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BUILDING MOMENTUM
FOR THE LONG-TERM CCS DEPLOYMENT
IN THE CEE REGION

Assessment of current state, past experiences and potential for CCS deployment in the CEE region

UKRAINE

Civitta Ukraine

Implemented by: WiseEuropa, Bellona Europa, EPG Energy Policy Group, Civitta, Institute for European Integration
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PROO

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Glossary

BFS	Blast-furnace slag
CBAM	Carbon border adjustment mechanism
CCS	Carbon capture and storage
CCU	Carbon capture and usage
CHPP	Combined heat and power plant
CLC	Chemical looping combustion
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
DRI	Direct reduction of iron
EAF	Electric arc furnaces
ETS	Emissions trading system
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
HPP	Hydropower plant
NPP	Nuclear power plant
RES	Renewable energy sources
SOE	State-owned enterprise
SPP	Solar power plant
SRI	Smelting reduction iron
TPP	Thermal power plant
WPP	Wind power plant

Disclaimer

The report initially presented a comprehensive analysis of the situation in Ukraine regarding the existing situation, past experiences, and potential for CCS deployment till October 2021. However, since the Russian invasion in February 2022, the situation in Ukraine has been significantly impacted in all areas of life, including those described in this report. Thus, it is clear that the lasting and entirely unpredictable effects of this war are expected to exert a strong influence on the situation further described in the report.

Following the stabilisation of the situation, an effort by the team in Ukraine was undertaken to update the relevant sections of the report to reflect the current state of affairs in 2023, taking into consideration the impact of the war. Thus, the current iteration of the report represents a synthesis of previous research done in this field and the analysis of the impact of the war in this field. Moreover, the updated report expands upon the existing research by considering Ukraine's recovery needs. It encompasses an extended scope of analysis, including an assessment of the various recovery scenarios for Ukraine, with a particular focus on the technological applications across industries, which also includes aspects of CCS. The results of this research will serve as a catalyst for a discussion on the most appropriate technologies to facilitate the restoration of Ukraine.

Chapter 1. The concept of CCS and CCU in the context of Ukraine

1. Carbon-intensive sectors of the Ukrainian economy

Industry accounts for almost 30% of Ukraine's gross domestic product (GDP) which is about 52 billion USD in 2023. In 2022, the export-to-GDP ratio in Ukraine was 87%, making the industrial sector a key source of foreign exchange earnings. Low processing-level and high energy-intensive production dominate the industry, primarily the production of alloys and the chemical industry[1].

Industry can be divided into two key blocks: mining and process manufacturing. The mining industry accounts for 6.6% of Ukraine's GDP, while the processing industry accounts for more than 22%[2].

From 1990 to 2022, industrial production in Ukraine decreased significantly in all key product groups due to the collapse of the USSR, which led to the breaking of strong trade and production ties between Soviet countries. For example, the steel production level in 2021 was only 37.6% of 1990 production; similarly, the cement production level in 2022 was 41.1% of 1990 values[3].

In 2022, Ukraine's production level fell by more than 35%. The war led to the disruption of production chains in most sectors of the economy, negatively affecting GDP. Also, one of the most significant factors in the reduction of production is the reduction in the working population, which occurred after February 2022. In 2023, depending on the pace of hostilities on the territory of Ukraine, GDP may decline further by 5-10%. The recovery of Ukraine's GDP and its return to positive values is expected as early as 2024. The recovery period of Ukraine's economy may take up to 5 years due to significant damage, primarily to infrastructure facilities. Considering these factors, the CO_2 emission volume for Ukraine in 2022 fell to around 40-45% or about 198 million tonnes of CO_2 equivalent (CO_2-eq)[4].

The introduction of new tariffs and non-tariff restrictions, including the Carbon Border Adjustment Mechanism (CBAM) in the European Union (EU), places additional pressure on producers through the carbon footprint of each product. Ukrainian companies are expected to lose a significant share of exports to the EU if they are not able to modernise from a mid-term perspective. Modernisation implies a considerable number of investments, and there is a lack of legally established public financial instruments in Ukraine to support the environmental modernisation of business. There is also no regulation in Ukraine on waste trade, exchange of emission quotas and other instruments that are popular in other countries.

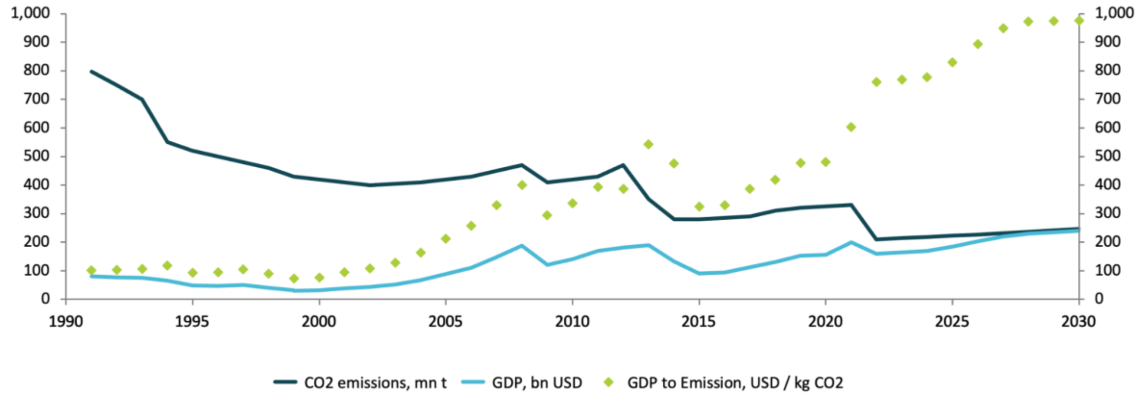
[1] Project team calculations based on the data from the State Statistics Service

[2] The processing industry, in turn, can be divided into metallurgy, mechanical engineering, chemical industry, construction materials production, light industry, food industry, woodworking and other sectors, based on the State Statistics Service classification

[3] Project team calculations based on the data from the State Statistics Service

[4] Project team calculations based on the data from the State Statistics Service

FIGURE 1. DYNAMICS OF GDP AND GHG EMISSIONS OF UKRAINE IN 1990-2030, CENTRE FOR ECONOMIC RECOVERY[5]



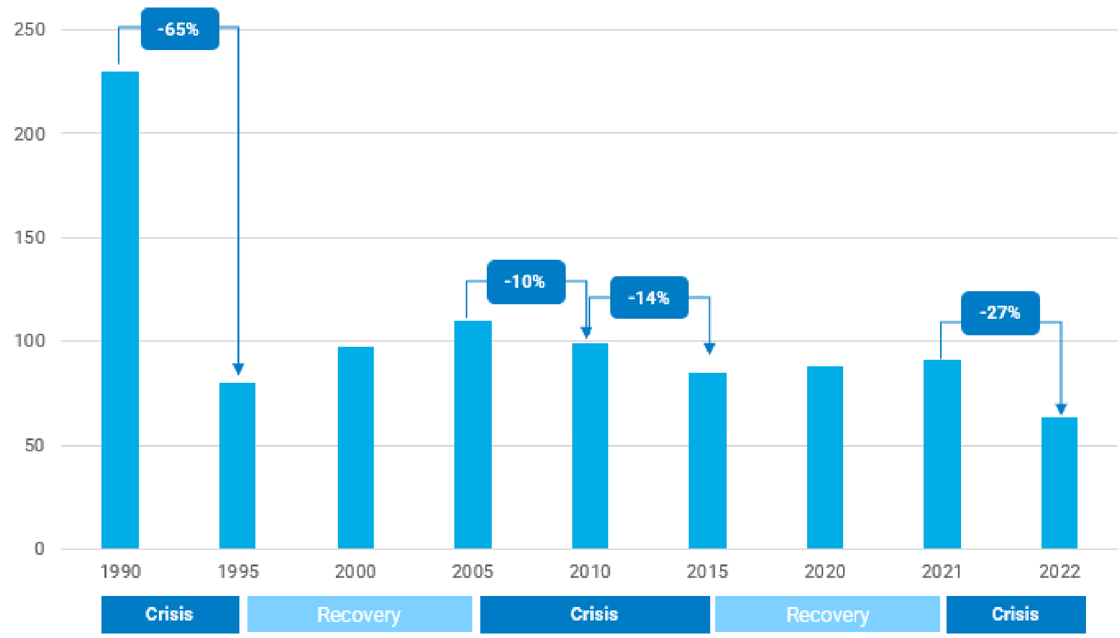
It is important to consider the overall dynamics of greenhouse gas (GHG) emissions in Ukraine because when analysing this parameter with GDP statistics, it is possible to draw some conclusions about their correlation. Over the last 30 years, GHG emissions in the industrial sector have decreased by 66%. It should be noted that the general trend involves several cycles of growth and reduction of GHG emissions:

- **1991-1995:** the post-Soviet period of production decline and the formation period of Ukraine's market economy. A decline in GDP output (trade with the USSR, logistics chains, production cooperation, workforce migration) of 48% caused an energy production decline, which mainly used coal and other energy resources. It caused an industrial production decline of 25%. All these factors reduced CO_2 emissions by more than 250 million tonnes or 36% from 1991[6].
- **1996-2007:** the phase of recovery and active production growth. GDP rose from 88 to 150 billion USD or almost 70% during this period. Such growth was caused by many reasons, which included agricultural production growth of more than 100%, international trading development, and the development of service sectors. In comparison, industrial production capacity continued to decline by 1-2% per year. During this period, CO_2 emissions decreased by almost 10%.
- **2008-2009:** the phase of production decline caused by the global financial crisis. During the global financial crisis, production in most sectors of the economy decreased significantly. In 2 years, GDP fell by 15% from 150 to 130 billion USD. The volume of GHG emissions showed a decline of 15% due to a drop in production in the metallurgical, chemical and energy sectors.
- **2010-2013:** exit phase from the global crisis, with a reduction in production in some sectors of Ukraine's economy. In the period after the financial crisis, most sectors of the economy began to recover. The level of industrial production grew by 4%, which, together with other economic growth sectors, increased GDP by 6%. Due to the growth of industrial production and the increase in electricity consumption, CO_2 emissions rose from 375 to 400 billion tonnes (7%).
- **2014-2016:** the phase of occupation of the Donbas region, the annexation of the Crimean Peninsula and the freezing of the conflict. During the first three years after the annexation of the territory of Crimea and the beginning of the war in the eastern regions of Ukraine, there was a significant reduction in production volumes in the extractive and processing industries. During this period, the GDP of Ukraine decreased from 135 to 120 billion USD, or by 8%. Due to the reduction in the volume of industrial production, the level of CO_2 emissions during this period decreased by 6%.
- **2017-2021:** slow restoration of production chains, gradual increase in production. GDP grew from 126 to 140 billion USD, or by 12% during this period. The sectors of the processing industry and the service sector showed the highest growth rates, up to 5% per year. At the same time, GHG emissions increased by 9%[7].

[5] Report On the Determination of the Second National Defined Contribution of Ukraine to the Paris Climate Agreement, 2021
[6] Ibid.
[7] Ibid.

- **2022-2023:** the period of active hostilities in the east and south of Ukraine, population emigration, and disruption of production chains. During the war, the total decline of GDP is expected to be up to 40%. This will happen primarily due to the reduction of production volumes in most sectors of the economy. The approximate level of CO_2 emission decline is expected to exceed 35%.[8]
- **2024-2030:** the expected period of post-war recovery of Ukraine. During this period, a significant increase in foreign investments in most sectors of the economy is expected, which will be an incentive for increasing production volume. The level of emissions in this period will depend on the specifics of state regulation, energy-efficient actions on the part of businesses, and the growth of electricity consumption rates.

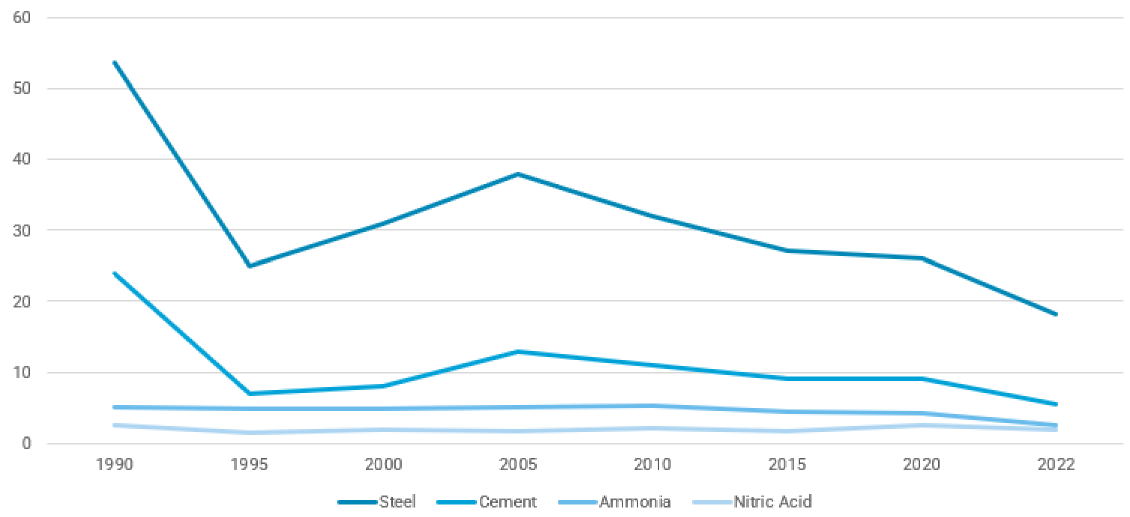
FIGURE 2. DYNAMICS OF GHG EMISSIONS FROM PROCESSING INDUSTRIES IN UKRAINE, KT CO_2-EQ, EUROSTAT[9]



Such cycles are firmly tied to the industry growth rate. Given the projected growth of such rates in the coming years, GHG emissions will also increase. It should also be noted that the Ukrainian economy remains energy-intensive (the energy intensity of GDP is, for example, 2.5 times higher than in Poland and 3.3 times higher than in Germany), which, in combination with the lack of energy-efficiency measures, contributes to higher GHG emissions[10].

[8] Project team estimates
[9] Project team calculations based on the data from the State Statistics Service
[10] Energy Balances, Eurostat, 2023

FIGURE 3. DYNAMICS OF PRODUCT OUTPUT VOLUME IN 1990-2022, THOUSAND KT, STATE SERVICE FOR STATISTICS OF UKRAINE[11]



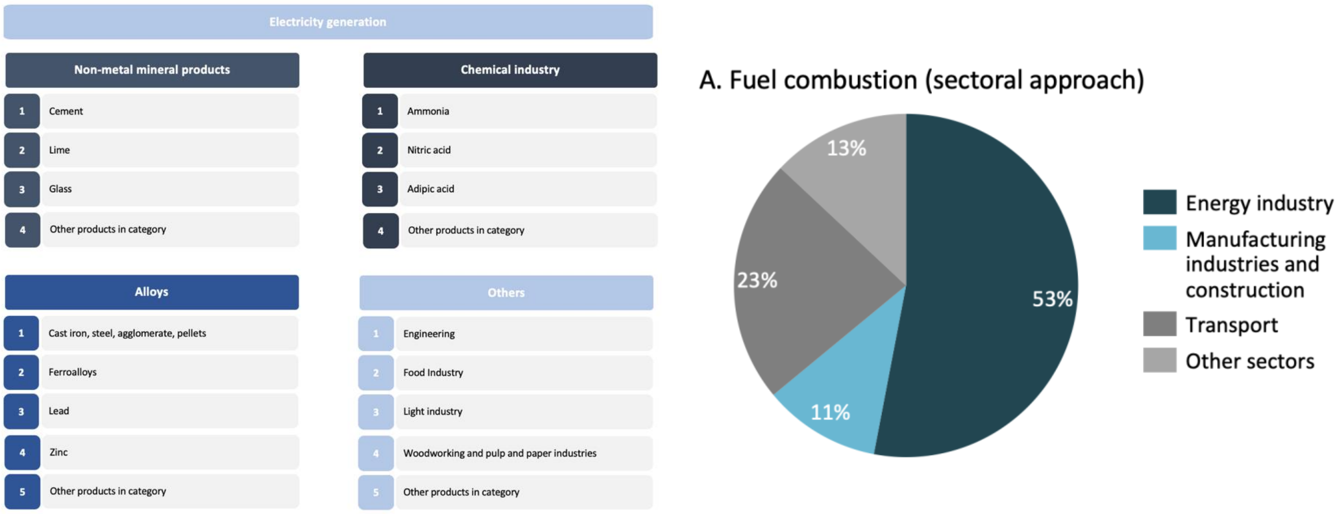
The financial crises, weak trade position, and lack of transparency in the privatisation process are factors that led to the further decline of the industries. In addition, constantly changing policies and government incentives forced companies to continue with the old technologies and use the advantages of a cheap workforce and relatively inexpensive energy resources, resulting in low energy efficiency in the production process.

When analysing the dynamic of other sectors, It Is possible to see that, for example, the production of nitric acid from 2015 to 2021 increased by 30% as Ukraine ceased the import of Russian fertilisers and agricultural companies shifted to Ukrainian fertilisers. In addition, the improved access to capital for small agricultural producers and farmers has improved, resulting in a 6% annual growth of fertiliser consumption over 2016-2021. The cement industry showed 7.6% growth from 2015 to 2021 as the government started a building renovation programme.

Following the outbreak of war in Ukraine in 2022, the destruction of production facilities, supply chain disruptions, and reduced electricity supply led to a decline of over 30% in the sector's production volume.

[11] Project team calculations based on the data from the State Statistics Service

FIGURE 4. MAIN INDUSTRIAL-EMITTERS OF CO_2-EQ[12], NATIONALLY DETERMINED CONTRIBUTION CALCULATIONS[13]



It is essential to analyse technologies that decrease CO_2 emissions in energy generation. The deep analysis of each technology effect is described in Chapter 2, but before that, it is necessary to analyse the dynamics of CO_2 emissions in Ukraine in the future. It will depend on several key factors:

- Economic recovery and growth will stimulate local Ukrainian producers and energy suppliers.
- Restoration and development of industrial production: after the beginning of the war, industrial production decreased by 30%. This sector will require large-scale financial resources for recovery and may take up to 3-4 years.
- Restoration of the energy system in Ukraine: the power distribution networks are worn out by 60-85%.
- The level of electricity consumption by the population and business: up to 5 million people emigrated in 2022.
- Implementation of energy efficiency measures. In 2022, measures to insulate premises became one of the most common methods of energy modernisation. This trend is expected to continue in 2023.

1.1. Power generation

KEY INSIGHTS:

- During the war, the distribution of energy generation sources did not change much. Ukraine still has a diversified energy system: electricity is generated from nuclear, thermal (coal and natural gas), hydro and other renewable energy. The total installed capacity of electricity generating facilities was more than 50 GW before the war, which allowed Ukraine to be a net exporter.
- As a result of the war, electricity generating and transmitting facilities suffered severe damages that caused power shortages. In 2023, coal and natural gas are dominant in thermal power plant (TPP) generation. Still, during the forecasted period (by 2060), usage of coal is expected to decrease almost two times compared to 2023 (from 50% to 25% in TPP generation).
- The Ukrainian energy sector has significantly reduced CO_2 emissions compared to 1990 due to economic decline and the development of renewable energy sources (RES) and nuclear energy share in the energy mix.

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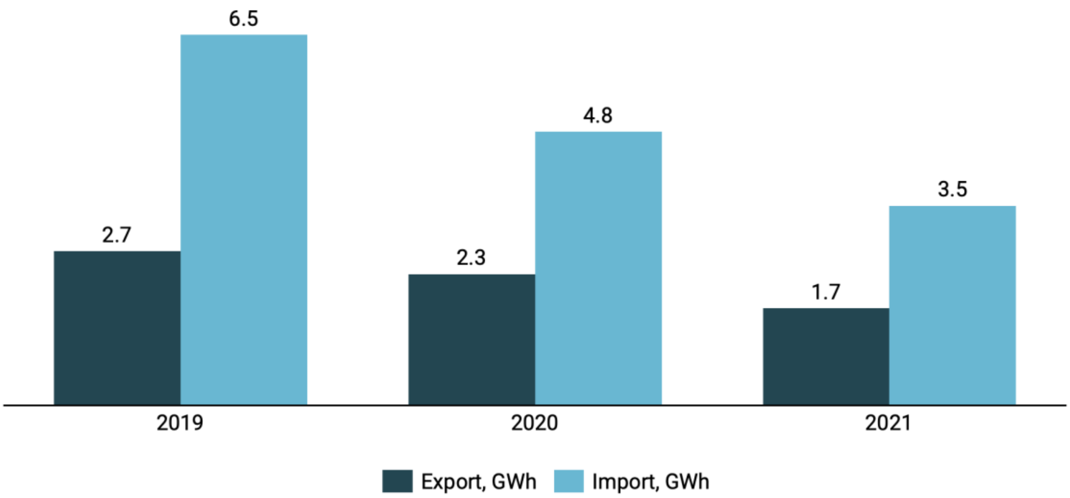
[12] Greenhouse gas inventory report, National Center for Accounting of Greenhouse Gas Emissions, 2022
[13] Report on the Determination of the Second National Defined Contribution of Ukraine to the Paris Climate Agreement, 2021

Sector description: The power system consists of 4 nuclear power plants (NPPs) with a total installed capacity of almost 14 GW; 15 TPPs and 43 CHPs (installed capacity of more than 21 GW); 8 large hydropower plants (HPPs) and three pumped-storage power plants (installed capacity – 7.3 GW). In 2021, 55% of electricity was produced by NPPs, 29.3% by TPPs and combined heat and power plants (CHPPs), 6.7% by HPPs, and 8% by RES. In comparison, in 2011, NPPs produced 42.9% of electricity, TPPs – 49%, and HPPs – almost 8%. The number of industrial solar power plants (SPPs) and wind power plants (WPPs) has increased significantly in the last decade. Most of them are located in the southern regions of Ukraine. The total installed capacity of RES reached 9.2 GW in 2021.

In 2020, the industry was the main final consumer in the total volume of final consumption (33.4%), closely followed by household consumers (28.5%) and transport (16.8%).

FIGURE 5. IMPORT AND EXPORT OF ELECTRICITY, STATE STATISTICS SERVICE[14]

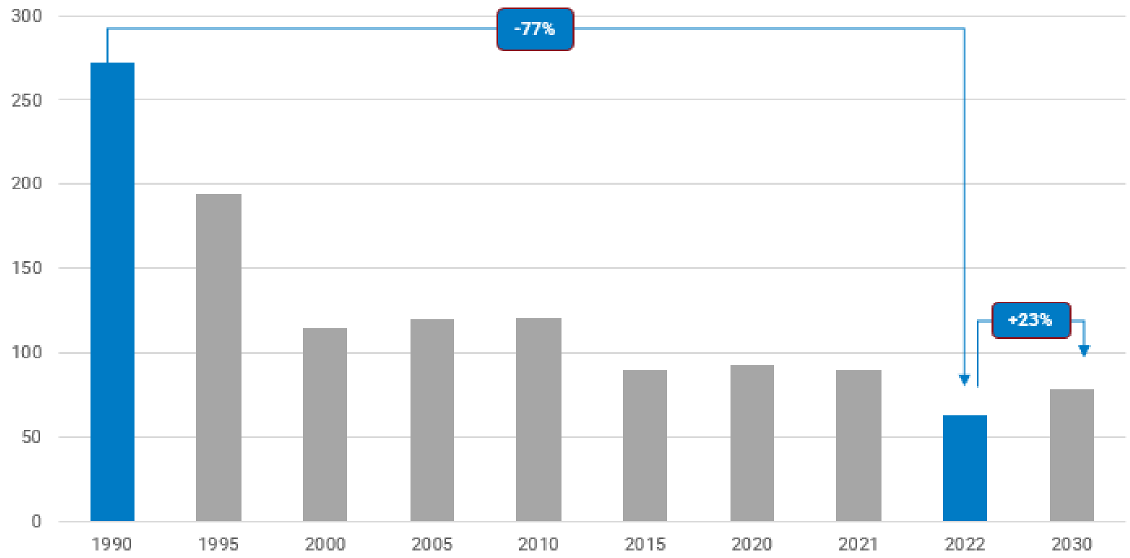


Before the attacks on the energy infrastructure, Ukraine was a net electricity exporter. For instance, in 2021, Ukraine exported 3.5 GWh and imported 1.7 GWh. In January 2022, the Ukrainian power system was synchronised with the European continental power system, and from July 2022, the commercial export of electricity to the EU was launched.

Due to the severe damage to energy infrastructure due to targeted Russian attacks, there is a profound power shortage in the energy system that reaches almost 30% (as of December 2022).

[14] State customs service, Energy map, 2023

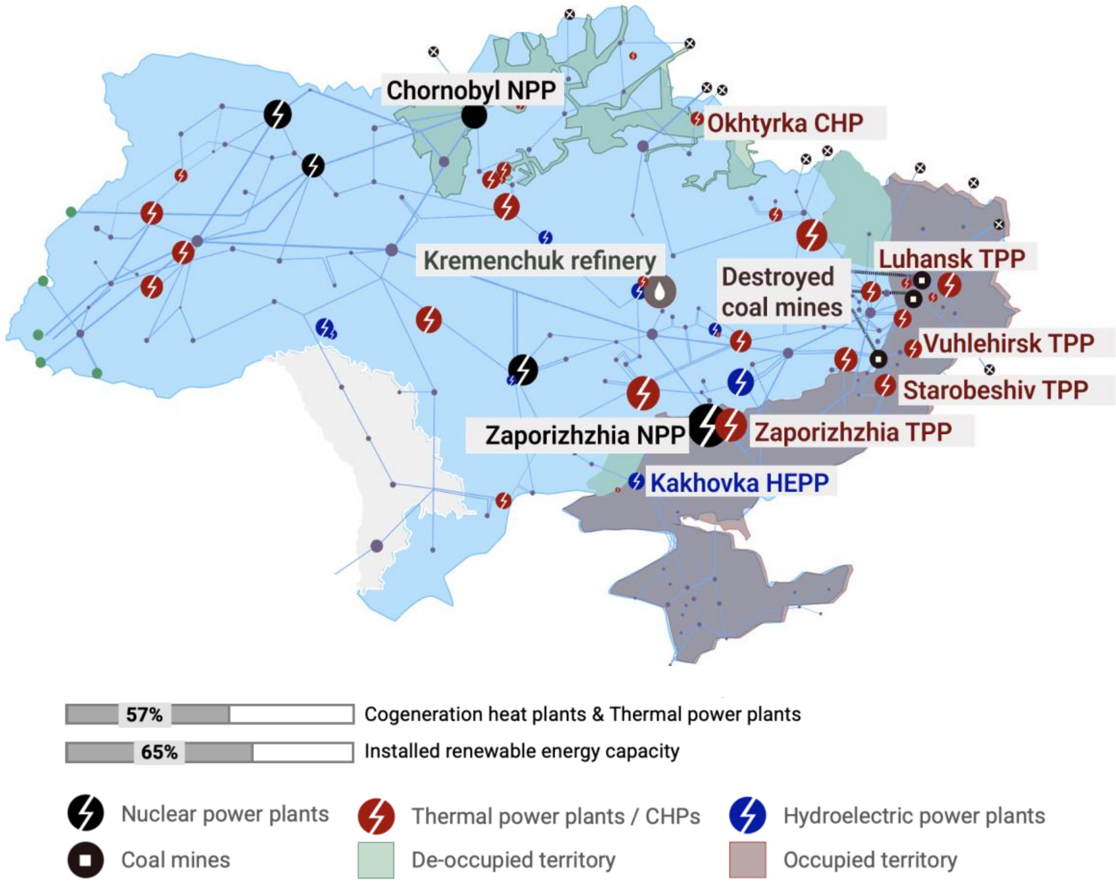
FIGURE 6. GHG EMISSIONS FROM ENERGY AND HEAT GENERATION IN THE UKRAINE, 1990-2030, UKRAINE'S GREENHOUSE GAS NATIONAL INVENTORY REPORT, 2022[15]



Influence of war: Due to intensive attacks on energy infrastructure, the sector has lost a considerable share of its capacities: more than 50% of thermal, 12% of solar, and 90% of wind generation have been damaged or occupied by the Russian military forces. Toshkivska i Zolota mines in the Luhansk region have been shut down due to the fact that they cannot be repaired. The Zaporizhzhia nuclear power plant has been under occupation since March 2022. Frequent shelling creates risks of reactor cooling system failure and damage to its backup power source, which can become an environmental disaster. In November 2022, due to another attack, the power lines were damaged, resulting in a complete cut-off of the station from the external power supply, and all 20 diesel generators were used to provide power to support the operation of NPP. The closed NPP in Chernobyl was occupied for over a month, which posed additional environmental damage since clouds of radioactive dust were raised, and the soil cover was disturbed in the radiation-contaminated areas of the exclusion zone. The damage has also been done to HPPs In Ukraine; for example, in June 2023, a significant portion of the Kakhovka dam was destroyed while it was under Russian control. The hydropower generation system lost about 334 MW, or about 4% of total HPP capacities, over the whole country. This demonstrates the challenges the HPP generation system will face in the upcoming years.

[15] Greenhouse gas inventory report, National Center for Accounting of Greenhouse Gas Emissions, 2022

FIGURE 7. THE MAP OF THE UKRAINIAN ENERGY SYSTEM CAPACITY AS OF JUNE 15, 2023, CENTER FOR THE ECONOMIC RECOVERY[16]



Significant damages will lead to a structural transformation of the energy system. According to preliminary Ukraine's Recovery Plan[17], which includes information about dealing with key sectoral problems and vectors of future development, deployment of RES generation is envisaged, as well as the development of such low-carbon technologies as biofuel and hydrogen production, energy storage application, increasing the flexibility of the energy system, development of power grids and energy infrastructure, natural gas extraction and transportation, development of oil transport and oil refining infrastructure.

Carbon capture and storage (CCS) and carbon capture and utilisation (CCU) are potential options to decarbonise energy systems that heavily rely on fossil fuels (coal predominantly). However, in Ukraine's case, where carbon-neutral generation resources reach almost 70%[18], other decarbonisation options are considered more attractive (such as introducing more energy efficiency measures, RES and small-reserve-capacity CHP construction).

[16] Visualisation of the Center for the Economic Recovery based on Ukrenergo data
[17] Ukraine Recovery Plan, 2022
[18] Power generation in Ukraine, Ukrenergo, 2021

1.2. Metal production

KEY INSIGHTS:

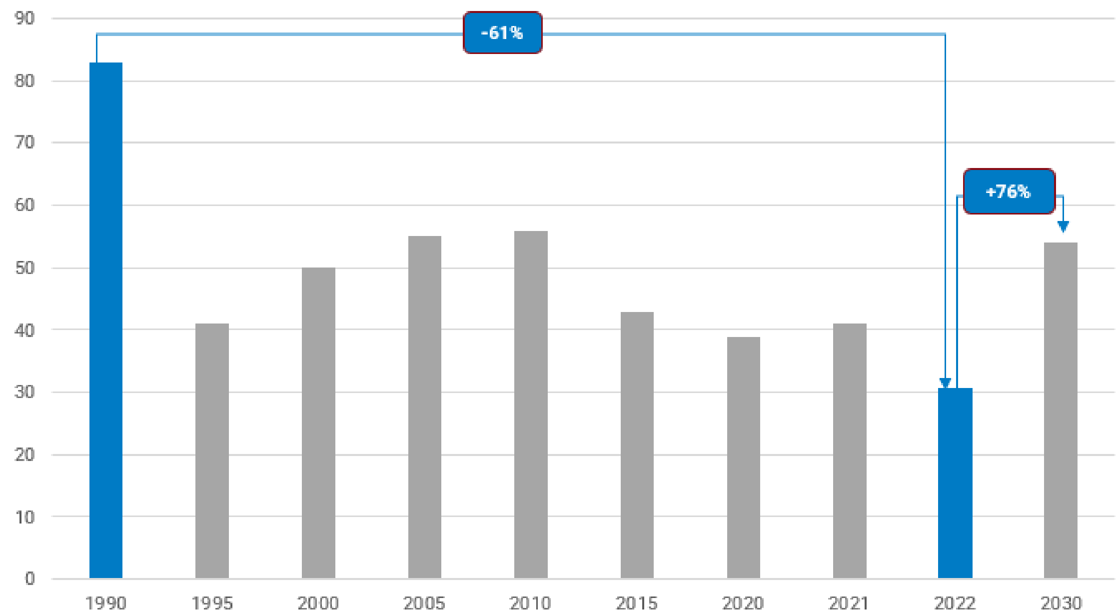
- Well-developed mining and metal production sectors have one of the highest CCS investment potentials. Their combined share in GDP was 12% as of 2022. The sector also has a significant role in Ukrainian foreign trade. In 2021, the export of iron ore and metal products accounted for the largest share of Ukrainian exports, equalling 20.46%[19].
- Even though the metallurgical sector is at 40% of pre-war capacities due to the occupation losses, the sector is eager to proceed with integration into carbon-free European markets.

Sector description: Metal production is one of the most important components of the Ukrainian economy. Steel production holds the top position in this sector. Every year, Ukraine produces about 21 million tonnes of steel, making it the 13th largest producer of this product globally. Steel accounts for over a quarter of Ukrainian exports and affects a significant part of domestic production.

The decline in emissions from the metal industry of 52% since 1990 has been primarily due to decreased production. After the beginning of military actions on the territory of Ukraine in 2022, due to the destruction of production facilities, supply failures and reduction in the supply of electricity, the production volume of the sector decreased by more than 30%. But still, metal production is a key pollutant in Ukrainian industry. This sector accounts for more than 71% of all industrial emissions. Steel is a key pollutant among metallurgical products. Ukraine is one of the few countries still using open-hearth furnaces, and the number of electric arc furnaces (EAFs) is less than 15%.

Metal production is one of Ukraine's primary sources of GHG emissions. In 2020, the share of this sector in the overall structure of emissions from processing was almost 71% and 12% of total emissions in Ukraine.

FIGURE 8. DYNAMICS OF CO_2 EMISSIONS FROM ALLOYS AND METAL REFINING, UKRAINE'S GREENHOUSE GAS NATIONAL INVENTORY, 2022[20]



19 [Project team calculations based on the data from the State Statistics Service]
20 [Greenhouse gas inventory report, National Center for Accounting of Greenhouse Gas Emissions, 2022]

Influence of war: Metal production suffers significantly due to the ongoing hostilities. As of October 2022, only 10% of metallurgical enterprises worked at more than 75% of their capacity compared to the pre-war period. Most production facilities are located in Eastern and Southern-Easter parts of Ukraine, so their work is constantly under threat. Thus, since April 2022, the Zaporizhstal steel plant has been operating at approximately 50% of its capacity. The Southern Mining and Processing Plant resumed its operation after four months of downtime and, in November 2022, produced 13.4% of the plan compared to November of the previous year.

The decrease in production level includes several factors, such as:

- The shortage of raw materials – the beginning of hostilities led to a 25% reduction in the supply of metal ores.
- The shortage of workforce – if active hostilities in Ukraine continue until the end of 2024, the potential deficit of workforce in the future years can amount to 4.5 million people[21].
- The impossibility of shipping goods by sea from the ports of Ukraine, which are now available only for grain transportation. Sea logistics in 2022 decreased by more than 70% due to the blockade of Ukrainian ports and attacks on port infrastructure. This caused the necessity to use other ports on the Black and Baltic Seas, which increased costs.
- The shortage of electricity has arisen since the beginning of October 2022.

For example, due to those factors, the steel plant ArcelorMittal Kryvyi Rih suspended most of its production processes in December 2022. The available amount of electricity is enough to support production at less than 20% of capacity. However, the company plans to return to full operation immediately after the renewal of the energy infrastructure. Other major metal plants, such as Azovstal Iron and Steel Works and Ilyich Iron and Steel Works, were entirely or significantly ruined due to heavy attacks and stopped their work.

CCS/CCU potential: Steel production is one of the key producers of GHG emissions. Emissions in steel production are divided into two key categories: blast furnace energy and the chemical process. In the latter, CO_2 emission reductions require significant investments that are not attractive based on the current regulatory framework and the environmental tax rate. Hence, CCS/CCU technologies are of interest to the industry. International practice shows that due to the method of production and the location of steel plants, CCU might be a more interesting technology than CCS.

However, Ukrainian companies note that emissions can be reduced much more cheaply and efficiently. The energy efficiency of the production process and the issue of Scope 2 emissions (emissions that occur during the production of energy, which is then used in the further industrial process) are the key focuses of industrial companies. Industry representatives emphasise that modernising these components will be the main source of CO_2 reduction in the near future (5-10 years). The metallurgy companies are expected to invest around 1.5 billion EUR annually into the modernisation of the blast furnaces (improvement of the filtration system, blower system replacement, blow supply device replacement) and, if the government will generate sufficient stimulus and a stable regulatory base for companies to consider investing, in reducing the emissions of sulphur and nitric oxides and dust, through the construction of new coke batteries with additional investments of around 2.5 billion EUR.

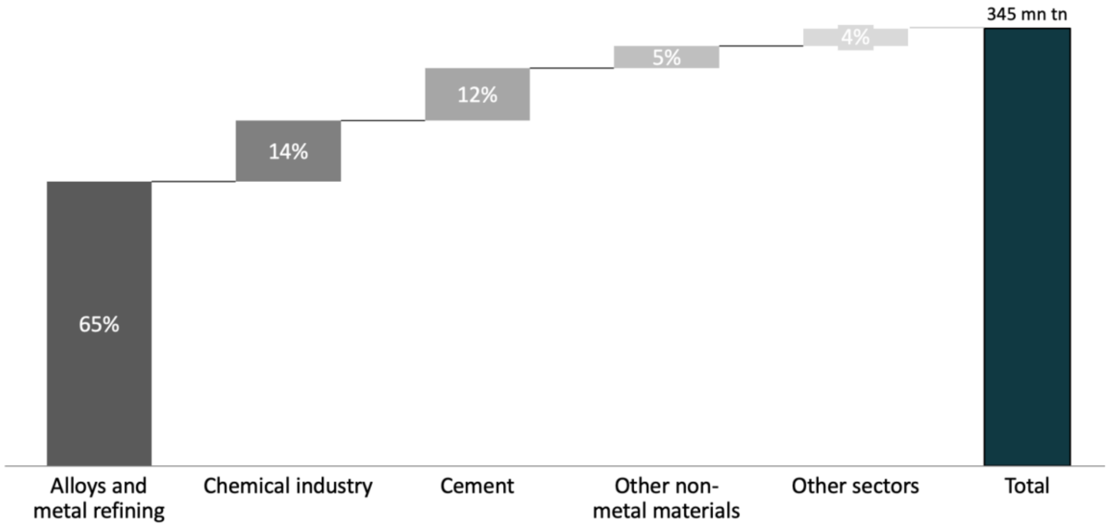
In addition, the process of CO_2 capturing in the production of metals is, to some extent, more complex than in the extraction of natural gas or the chemical industry. This means significant investment in carbon capture technologies.

Key challenges:

1. Proximity to the line of hostilities, significant destruction and shutdown of some metallurgical plants.
2. Expensive technologies that are less profitable than alternatives. The companies consider CCS/CCU technologies as a potential solution after 2030.
3. High cost of CO_2 transportation and storage infrastructure.

[21] Ukraine lacks 4.5 million workers. How to overcome the labor shortage, EP, 2023

FIGURE 9. STRUCTURE OF CO_2 EMISSIONS IN UKRAINE GENERATED FROM DIRECT AND INDIRECT EMISSIONS BY SECTOR (PROCESSING INDUSTRIES), UKRAINE'S GREENHOUSE GAS NATIONAL INVENTORY, 2022[22]



Although Ukraine does not currently have a single project using CCS or CCU technologies, many industries are already considering this option from a medium- or long-term perspective. Several large Ukrainian companies, both state-owned and privately owned (e.g., DTEK, Naftogaz, ArcelorMittal, etc.), have published their strategies to become carbon neutral by 2040-2050.

Given the specificities of production, energy efficiency, technology, and renewable energy, they cannot fully meet these goals. This means that companies are already considering CCS/CCU technologies, mostly gas production companies, TPP operators and metallurgy producers. The major industrial producers are in eastern Ukraine and are at a reasonable distance from potential CO_2 storage facilities. Companies such as Naftogaz and ArcelorMittal have indicated a strong interest in CCS and CCU technologies as part of the strategy that will ensure carbon neutrality.

At the same time, it is necessary to consider the factors that hinder the development and introduction of such technologies in Ukraine. Firstly, there is a low profitability of technologies for the Ukrainian industry. High costs, as well as a lack of financial incentives and available alternatives, reduce the interest of companies. However, this is not a feature of Ukraine alone. These factors indicate that CCS/CCU technologies may be of interest to large companies in some industries in the long run.

1.3. Crude oil and natural gas production

KEY INSIGHTS:

- As of 2020, Ukraine had 1.1 trillion cubic metres of discovered natural gas reserves and about 200 million tonnes of hydrocarbon reserves. For their extraction, CO_2 can be used as an enhancing instrument.
- Kharkiv and Poltava regions are the richest in natural gas deposits, followed by the Lviv region.
- A slight decrease in natural gas production (about 5%) is expected due to the war.

Sector description: Ukraine has low oil production possibilities but a significant and promising natural gas production industry. Annual natural gas production is about 21 billion cubic metres, and a positive development scenario (created before the Russian invasion)

[22] Greenhouse gas inventory report, National Center for Accounting of Greenhouse Gas Emissions, 2022

projected an increase in production to 30 billion cubic metres by 2030. The overall production potential is about 780 billion cubic metres. Almost 80% of natural gas production is extracted by the state-owned enterprise (SOE) Naftogaz.

TABLE 1. CO_2 EMISSIONS, NATURAL GAS AND OIL PRODUCTION, UKRAINE'S GREENHOUSE GAS NATIONAL INVENTORY, 2019

1990	1995	2003	2005	2010	2015	2019	1990-2019	2015-2019
3023.8	2013.8	1932.4	2259.2	2144.9	2132.5	2138.8	-30%	+0%

Influence of war: As of 2022, natural gas production has been at its lowest level in the last decade. Natural gas production was most affected in Kharkiv and Donetsk regions due to the vicinity of the front lines, and to a lesser extent in Poltava, Sumy and Chernihiv regions. The reduction in production is observed in the east of the country, while the production in the West is increasing. However, the de-occupation of the Kharkiv region allowed the resumption of mining in this territory and the carrying out drilling and well repair works. It is projected that natural gas production in Ukraine will be at about 18.7-18.8 billion cubic metres by the end of 2022, 5% less than the previous year.

Regarding crude oil production, the extraction potential is limited due to the blocked access to the Black Sea shelf, which is rich in oil deposits. In 2022, the estimated volume of crude oil production in Ukraine decreased by 10% due to a reduction in the level of employment in the industry, a disruption in logistics and supply chains, and a reduction in the volume of electricity supply. Reconstruction of the sector after hostilities ends may take 1 to 2 years. Another result of the hostile attacks was damage to the Kremenchuk Refinery, the biggest refinery in Ukraine responsible for processing up to 5 million tonnes of crude oil annually.

In November 2022, three special permits were sold at auctions for the use of land plots in the Poltava and Ivano-Frankivsk regions for the geological study of oil and gas-bearing subsoils, with subsequent extraction of oil and natural gas.

Ukraine's Recovery Plan proposes the following steps regarding the oil and oil products market of Ukraine: expansion of interconnectors between Ukraine and European oil refineries for the delivery of oil products to the Ukrainian market; the creation of stocks of oil and oil products in protected warehouses; completion of the Brody (Ukraine) – Adamova Zastava (Poland) oil pipeline for the bilateral operation – this project will allow Ukraine to gain access to Baltic ports, and Poland – to Ukrainian ports on the Black Sea.

CCS/CCU potential: The introduction of new restrictions on the purity of natural gas during its supply to the gas transmission system is currently being discussed, which will provide a much higher degree of purification in the future. Those restrictions will contribute to changes in CO_2 emissions within the gas processing industry – most of the CO_2 will be extracted before entering the gas transmission system. The amount of CO_2 that can be extracted from gas exceeds the demand by four times. In this case, storage is considered a strong option. As such emissions also mean additional carbon taxes for producers, companies are considering CCS/CCU technologies. The low cost of this process in the gas production industry simplifies the use of carbon capture technologies. In addition, high territorial concentration and the presence of large players in the market streamline the logistics of extracted CO_2. Most natural gas production wells are in the Poltava region, while Naftogaz owns around 70% of the gas production market.

The industry is primarily interested in CCS technologies. In the entire market, this is the only industry with a strong interest in using such technologies in the long run. In addition, there is also some potential for CCU technologies. This is mainly the case for using CO_2 in crude oil production. However, the CCU potential is much smaller because the amount of Ukrainian crude oil production is relatively low.

Key challenges:

1. Lack of regulation for CCS technologies – companies fear being penalised for using such technologies before any regulation specifies CO_2 storage aspects.

2. Expensive infrastructure requires state investments. Even though the potential CO_2 storage facilities are located within a reasonable distance from the key gas wells, transportation of CO_2 is one of the key challenges as it requires significant investments.
3. In the current situation, the location of the facilities does not allow for the deployment of such projects due to their proximity to the front line.

1.4. Chemical industry

Key insights:

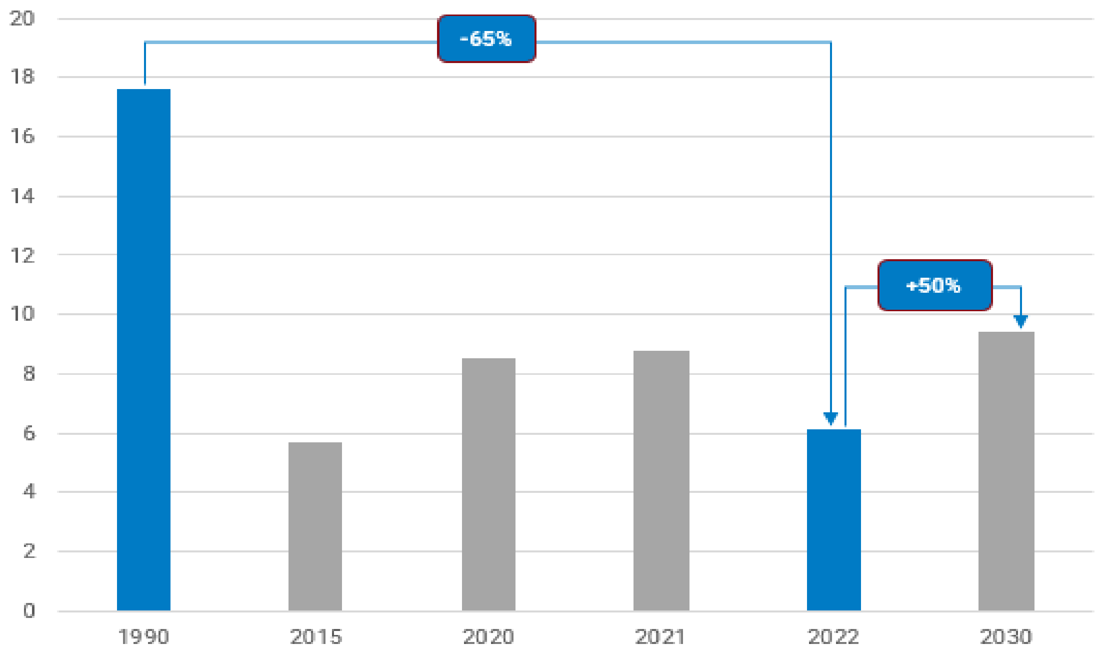
- The chemical industry's share in Ukraine's GDP is about 3% and almost 10% of the industrial production structure.
- The majority of chemical enterprises have suspended production, primarily because of the vicinity to the area of active hostilities and in temporarily occupied territories.

Sector description: Ukraine has a wide range of chemical industries, from oil refining to ammonia production. One of the key product groups is fertilisers: two-component and nitrogen. Even though the chemical industry had been demonstrating a significant decline in production, as most oil refinery production facilities were closed between 1990 and 2015, the military conflict with Russia has given a new push for substituting imported fertilisers with Ukrainian ones. Due to high demand from the agricultural sector, fertiliser producers are working almost entirely on the Ukrainian market. Over the last five years, fertiliser consumption by the Ukrainian agricultural sector has shown a compound annual growth rate of 7%. On top of that, the chemical industry (11.3%) and the production of non-metallic minerals (14.3%) significantly contribute to the overall structure of GHG emissions.

Influence of war: At the beginning of the invasion, most fertiliser production facilities near the front line were forced to stop their operational activity. Many of them experienced shelling. For example, the chemical industry plant Sumykhimprom was attacked, which led to an ammonia leak. The chemical industry plant Severodonetsk Azot Association (which provided 15.3% of nitrogen fertiliser production capacity in Ukraine) was destroyed by almost 70%. Another plant – the Odesa Port Plant (which provides 14.4% of nitrogen fertiliser production capacity in Ukraine) stopped operating at the beginning of the war and has not resumed its work as of October 2022. The production capacity of the chemical industry plant Rivneazot is less than 50%.

Additional constraints for the operation of fertiliser production enterprises are imposed by the disruption of supply chains that resulted in shortages of raw materials and power cut-offs.

FIGURE 10. DYNAMICS OF CO_2 EMISSIONS IN THE CHEMICAL INDUSTRY OF UKRAINE, UKRAINE'S GREENHOUSE GAS NATIONAL INVENTORY, 2022[23]



CCS/CCU potential: The chemical industry is interested in CCS/CCU technologies for two key reasons. First, the production of ammonia yields almost pure CO_2, which can be stored directly without additional purification. Existing production chains can produce sufficiently concentrated CO_2 at the output, and technologies to achieve a concentration of more than 95% while capturing more than 90% is relatively cheap (in comparison to other industries). Secondly, due to the existing production processes, the use of CCU technology can continue the production chains of the chemical industry itself, for example, in the production of biofuels. CCS technologies, which are already planned to be used in the Russian production of nitrogen fertilisers, are also considered in the chemical industry[24].

However, representatives of the Ukrainian chemical industry prefer other types of CO_2 reduction, which imply basic energy efficiency measures that lead to lower energy consumption per unit produced and reduce the product's carbon footprint. Industry representatives note the potential for the use of hydrogen and have their own proposals to reduce the cost of its production using renewable or nuclear energy.

Key challenges:

1. Proximity to the area of hostilities; some production facilities are currently located in occupied territories.
2. Cheaper decarbonisation alternatives are available (cogeneration with alternative power sources other than natural gas, heat recovery, energy management systems, etc.).
3. Businesses in the chemical industry consider other business models (e.g. biogas application) more profitable.

[23] Greenhouse gas inventory report, National Center for Accounting of Greenhouse Gas Emissions, 2022

[24] The development of ammonia and hydrogen production in Arctic and Eastern Russia can ensure its leadership in hydrogen energy by 2030, FANU "Vostokhosplan", 2023

1.5. Production of building materials

Sector description: The construction sector showed rapid growth between 2014 and 2018 due to delayed demand for real estate because of the 2013–2014 crisis and changes in the ease of doing business in the market, which caused a significant increase in new building supply. The main changes were simplifying the general scheme for obtaining construction permits, reducing the number of stages from 55 to 5, reducing the time for obtaining such permits to 60 days and reforming the State Architectural and Construction Inspectorate system.

The share of employment in the construction sector is 4.2%, employing 699 thousand people. The construction sector's share of GDP is 8% (5.2 billion EUR). The share of construction in tax revenues is 3.1% or 0.5 billion EUR.

Steady investment demand has contributed to the high growth rate of construction works in all segments. High growth rates of civil engineering and non-residential building construction are caused by active funding from the state and local budgets and funds from enterprises and international donors. During the war, a sufficient supply of free housing due to mass migration and the low effective demand of the population contributed to a gradual decline in construction volumes: business expectations of entrepreneurs from the sector finally exceeded 50% of the pre-war level only in April 2023[25], partially due to acute labour shortages and rise of construction material costs[26].

Under unstable economic conditions and exchange rate fluctuations, investors invest more in economy-class apartments. The most significant demand is for small apartments, as the number of square metres affects the total purchase price. As a result, the average area of apartments in Ukrainian newly erected buildings decreased from more than 120 square metres to almost 80 square metres in 8 years.

The construction sector can become a powerful multiplier for the economy, and 1 Ukrainian hryvnia (UAH) invested in construction gives 6 UAH of GDP growth. The industry creates demand for products from 5–7 related industries and stimulates investment inflow.

The growth of investment in construction can increase the annual growth rate of industrial production by 3–5% per year due to the multiplier of housing investment. The construction of new energy-efficient houses and the thermal modernisation of old ones will help reduce heat use by 30%. The state can create an additional almost 465 thousand jobs because of thermal modernisation by introducing energy audit procedures and jobs in related sectors of the economy (builders, administrators, construction material producers). Cement accounts for 8% of GHG emissions, and its share will gradually increase with the start of reconstruction initiatives. The sector has a considerable recovery potential since, due to hostilities, about 15.2 billion tonnes of waste was generated from the destruction of buildings and structures in Kyiv, Chernihiv, and Sumy regions alone[27].

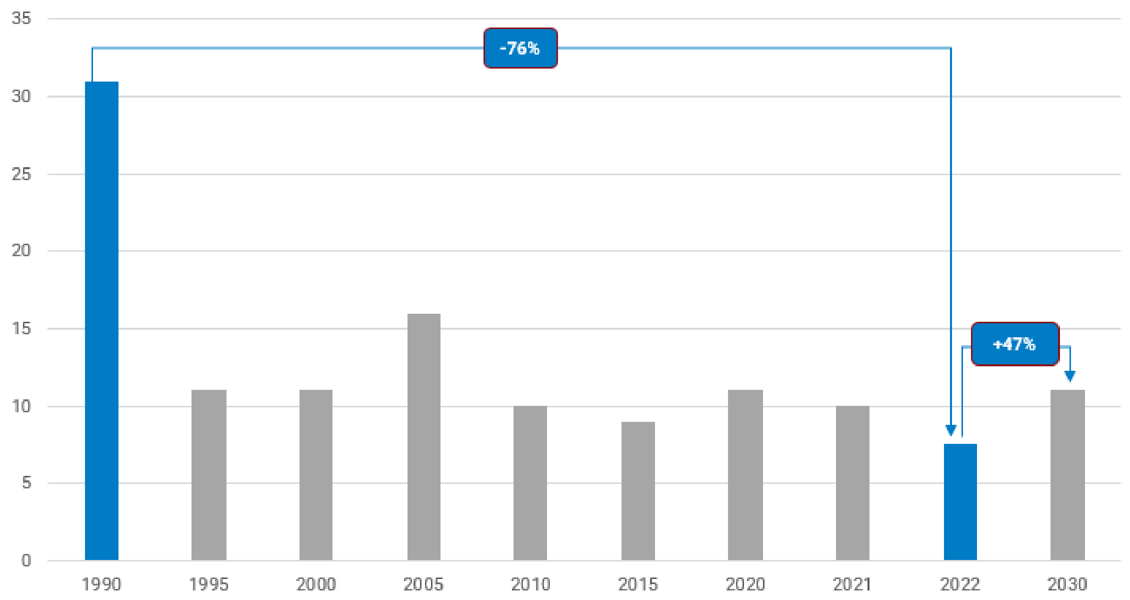
Influence of war: It should also be expected that the construction sector will grow significantly after the end of the war, as there is a considerable need for the reconstruction of residential, social and industrial infrastructure. Military actions caused damage to various categories of Infrastructure that will require restoration, mainly housing stocks, transport infrastructure, and public infrastructure.

As of October 2022, the number of infrastructure objects destroyed and damaged due to the war equals 136 thousand residential buildings, 978 medical facilities, and 616 administrative buildings.

Ukraine’s Recovery Plan envisages capital repair and reconstruction of 23.6 million square metres of housing that suffered significant damage due to Russian aggression and 13.3 million square metres that require ongoing repair. As stipulated in this plan, the reconstruction must be carried out considering energy efficiency standards.

[25] NBU provides new estimates of business expectations for June 2023, Market for Construction Materials, 2023
[26] What is going on in the construction sector during the war, Interfax, 2023
[27] Recovery of the Ukrainian construction industry under the conditions of war, Ukrainian Center for Sustainable Construction, 2023

FIGURE 11. CO_2 EMISSIONS, MINERAL MATERIALS, UKRAINE'S GREENHOUSE GAS NATIONAL INVENTORY, 2022[28]



CCS/CCU potential: A high share of potential CCS/CCU projects in the EU are concentrated in the cement sector. Like steel production, cement (clinker) production creates emissions in two ways: due to energy consumption and due to the chemical reactions involved. CCS/CCU technologies are often used to capture the carbon released during the chemical reaction in the production process.

Ukrainian cement producers show much less interest in CCS/CCU technologies, arguing that they are inefficient. Modernisation to reduce CO_2 emissions is achieved more cheaply and efficiently through more environmentally friendly energy production for the production process. Representatives of the cement industry emphasise that cement production can dispose of certain types of household and industrial waste without leftovers (and with zero CO_2 emissions). Prospects for using carbon capture technologies in the industry are low, even in the long run.

Key challenges:

1. Low efficiency and high prices with cheaper alternatives of input materials (such as RDFs from solid wastes instead of coal) are available.
2. High cost of CO_2 transportation and storage infrastructure.
3. Issues with biomass aggregation and transportation.

[28] Greenhouse gas inventory report, National Center for Accounting of Greenhouse Gas Emissions, 2022

2. Major CO_2 emitters in Ukraine

In terms of GHG emissions, three companies, Metinvest, ArcelorMittal and ISD, account for more than 50% of all emissions[7].

The biggest emitter is the heat and electricity generation sector, with the key emitters being the heat power plants that generate over 90 million tonnes of CO_2 from electricity and heat production. The key reason for high emissions is the dominance of coal in the energy mix of heat power plants, which has a high emission factor. Heat and electricity generation emissions are projected to decline by up to 75 million tonnes by 2030 because of the gradual phasing out of coal-powered generation. Considering those TPPs that were under the control of the government between 2014 and 2022, the distribution of emissions was the following:

1. Centerenergo (3 TPPs: Trypylska, Zmiivska, Vyhlehirska) – 8.2 million tonnes CO_2.
2. DTEK-Shidenergo (2 TPPs: Kurahivska, Luganska) – 10.69 million tonnes CO_2.
3. DTEK-Zahidenergo (3 TPPs: Burshtynska, Ladyzhynska, Dobrotvirska) – 15.53 million tonnes CO_2.
4. DTEK-Dniproenergo (3 TPPs: Zaporizhzka, Prydniprovska, Kryvorizhzka) – 15.9 million tonnes of CO_2.

As of December 2022, four TPPs (Vyhlehirska, Luganska, Kryvorizhzka, Starobeshivska) are located on occupied territories, and there is no available information on the level of damages caused to the facilities. Since the beginning of the war, all 15 TPPs have been attacked, resulting in damages of various degrees (thus, the information about their operation and emissions could change). The most severely damaged is Ladyzhynska TPP.

The introduction of CCS/CCU technologies for Ukrainian TPPs and CHPPs is not seriously considered, as Ukraine plans to phase out a significant number of power plants. The approved National Emissions Reduction plan has a schedule for phasing out TPPs and CHPPs in Ukraine[29]. In 2021, 8 blocks of Dniprovska CHPP and Khersonska CHPP were planned to be phased out. A significant number of power plants were expected to be closed by 2023 (7 094 MW). Over the next period until 2033, 21 245 MW had to be phased out according to the plan. Being a significant challenge by itself, the task has been further complicated by the destruction of the energy system capacities during the winter of 2022-23 as a result of the Russian cruise missile attacks. TPPs and CHPPs comprise the key balancing capacity within the Ukrainian energy system, ensuring the coverage of peaks and the deficit in winter when RES generate less energy – with the loss of a significant share of renewables (90% for WPPs and 30% for SPPs) and Zaporizia NPP, their role in balancing the system became even more critical. At the same time, the available manoeuvrable capacity, primarily at TPPs, decreased by 68% – from 14.3 GW to 4.6 GW[30]. Nevertheless, no official statement on the delay of the phaseout of CHPP capacities has been made so far.

The second biggest group of polluters after Ukraine's TPPs are its ferrous metallurgy plants. The key industrial pollutant plants (and their parent companies) as of 2021 can be distributed as follows:

1. Ilyich Iron and Steel Works (Metinvest): 2.04 million tonnes CO_2.
2. ArcelorMittal Kryvyi Rih (ArcelorMittal): 2.35 million tonnes CO_2.
3. Azovstal Iron and Steel Works (Metinvest): 2.1 million tonnes CO_2.
4. Dnieper Metallurgical Combine (Industrial Donbas Union): 1.28 million tonnes CO_2.
5. Zaporizhstal (Metinvest): 1.89 million tonnes CO_2.
6. Southern Mining and Processing Plant (Metinvest): 0.65 million tonnes CO_2.

As mentioned above, Azovstal Iron and Steel Works and Ilyich Iron and Steel Works were destroyed during the war, and their work was stopped. The rest of the plants were forced to temporarily stop their activities at the beginning of the invasion due to their proximity to hostilities. However, even though the operations were resumed, plants cannot work at full capacity due to several factors described above (power supply interruptions, lack of raw materials, inability to use sea routes, etc.).

[29] CO_2 emissions, 2021, Updated Nationally Determined Contribution of Ukraine to the Paris Agreement, 2021
[30] Survive the winter: energy officials report on readiness, engineers calculate possible risks, Interfax, 2023

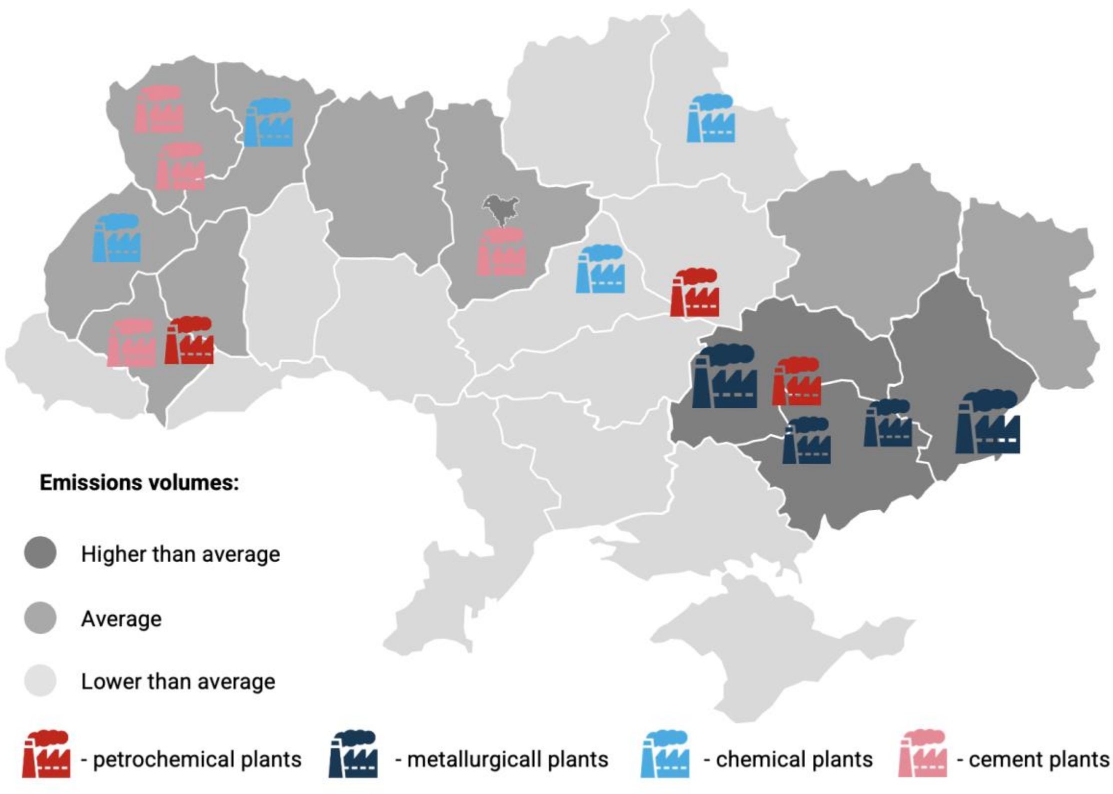
Most of the largest polluters are located in the Eastern and South-Eastern parts of Ukraine. Heavy industry is less developed in the Western and Central parts of Ukraine. The largest CO_2 emitters in those parts of Ukraine are the following:

1. DTEK-Zahidenergo (TPPs: Burshtynska, Ladyzhynska, Dobrotvirska) – 15.53 million tonnes CO_2.
2. Lvivvugillia – 0.29 million tonnes CO_2.
3. Kalush CHPP-Nova – 0.13 million tonnes CO_2.

Among others, significant polluters in the region can be named the following facilities:

1. Sirka (Lviv Oblast’).
2. Ukrnafta (Ivano-Frankivsk Oblast’).
3. Ivano-Frankivskcement (Ivano-Frankivsk Oblast’).
4. Rivneazot (Rivne Oblast’).
5. Consumers-Sklo-Zorya (Rivne Oblast’).
6. Volyn-cement, a branch of Dickerhoff Cement Ukraine (Rivne Oblast’).

FIGURE 12. MAP OF THE MAIN INDUSTRIAL CO_2 EMITTERS IN UKRAINE, UKRAINE’S GREENHOUSE GAS NATIONAL INVENTORY, 2019[31]



Most metallurgy plants are located in the eastern part of Ukraine had access to a developed sea and railway infrastructure, thus enabling the opportunity to transport the CO_2 from the source of emissions to the storage facility. Because of the occupation and

[31] Greenhouse gas inventory report, National Center for Accounting of Greenhouse Gas Emissions, 2022

naval blockade, this opportunity is lost, and the sector has to combat acute logistical problems caused by the limited exporting capacities of the western exporting routes[32].

3. Assessment of geological potential for CCS

Ukraine has several options for carbon storage. There is potential for storage by physical absorption and residual trapping mechanisms (whereas soluble absorption and mineralisation mechanisms are less likely). The reason for the most significant benefit of the first two is the potential of using natural gas wells as carbon storage methods.

In the Donetsk basin, there are Devonian saline aquifers in combination with impermeable salt deposits, which are best suited for CO_2 storage near large industrial and energy sources of CO_2 emissions. There is potential for the use of deep coal seams to store carbon in the western region.

GENERAL INFORMATION

In Ukraine, there are prerequisites for starting work and research projects on CCS. Depleted gas reservoirs within the eastern, western and, to a lesser extent, southern oil and gas areas should be considered possible carbon storage sites. Geological formations that have stored natural gas in their pores for millions of years can also serve to store CO_2.

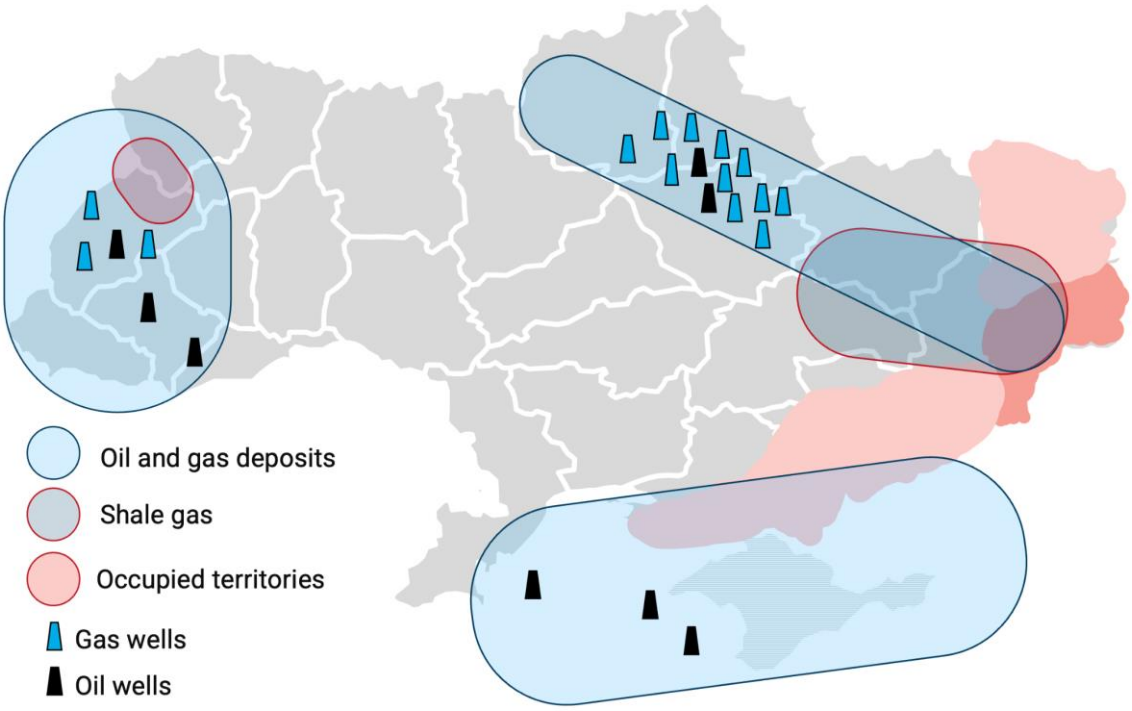
In addition, depleted reservoirs are already equipped with the necessary infrastructure for injection, including boreholes and pipelines. Also, one option to consider is the injection of CO_2 into deep and highly mineralised aquifers, which have a regional distribution, high filtration capacity and are reliably isolated from aquifers and oil and gas formations by regional reservoirs.

GEOLOGICAL FORMATIONS FIT FOR CO_2 STORAGE

According to the State Service of Geology and Subsoil assessment of Ukraine, the most appropriate carbon storage option for Ukraine is using depleted oil and gas reservoirs. Creating wells of this type will be the cheapest and most likely the safest and most scalable option. It will help achieve a faster technology spread without additional development costs.

[32] "Is it possible to resume exports during wartime?", Institute of Economic Research and Political Consultations, 2023

FIGURE 13. OIL AND GAS REGIONS IN UKRAINE: POTENTIAL FOR CARBON STORAGE, STATE SERVICE ON GEOLOGY AND NATURAL RESOURCES[33]



The use of depleted gas wells has several advantages:

1. The natural origin of the well with a sufficiently strong mineral cap and necessary infrastructure at the storage site.
2. Territorial proximity of the gas production basin (and potential carbon storage site) to major pollutants.
3. Existing gas transmission infrastructure (with direct access to wells) can be used for CO_2. The ability of the gas transmission system to transport CO_2 has not been studied yet. Currently, the gas transmission system operator is analysing the capability of the system to transport hydrogen.

According to estimates by the State Service of Geology and Subsoil of Ukraine, the best locations for carbon storage could be the depleted gas fields in Hlinsko-Rozbyshivsk, Novo-Hryhorsky, Sagaidatsky and Malosorochynsky. The estimated capacity of the depleted gas fields for CO_2 storage exceeds 2.4 billion tonnes of CO_2 stored.

In addition, alternatives to depleted gas sources may be using CO_2 to intensify oil production (for example, for the Myhyryn field with a complex production process) or storage in deep, highly mineralised horizons that do not contain drinking water.

However, taking into account the proximity of the region to the front line, which poses significant risks for the deployment of new projects, as well as the fact that some of the emitters have ceased their activities, the potential for CCS/CCU project development is shifting to the western part of Ukraine, where there are also suitable natural conditions for this. More than 40 deposits are located on the territory of five regions – Lviv, Ivano-Frankivsk, Volyn, Zakarpattia, and Chernivtsi. However, the resource base of the active deposits is depleted in some places by 90%. Due to this, Western regions provide only 5% of total gas production in Ukraine[34].

[33] Project team visualisation based on the State Service on Geology and Natural Resources data, 2021
[34] What is happening with gas production in Western Ukraine, EP, 2018

The gas transportation system (around 38 550 km) is considered a potential infrastructure to transport CO_2. The transmission system operator is currently studying the opportunity to transport hydrogen through this system. The ability of the gas transmission system to transport CO_2 has not been studied. Currently, the gas transmission system operator is analysing the capability of the system to transport hydrogen, with the primary analysis results showing the opportunity to transport a mixture of gas and hydrogen with only up to 3% of hydrogen within the mix. There are also well-developed underground gas storage facilities (12 in total) in Ukraine with a total capacity of 31 billion cubic meters that also can be used for hydrogen and CO_2 storage. In 2021, underground gas storage facilities operator Ukrtransgaz planned to study the possibility of repurposing Krasnopopivsk underground gas storage (Luhansk region) to store the hydrogen or its mixture with methane.

The regional gas infrastructure is also currently under assessment regarding hydrogen transportation potential. The Regional Gas Company (regional gas infrastructure operators) has managed to test, and the company plans to supply a mixture of gas and hydrogen in a test project.

Additionally, Ukraine has an ammonia transportation system. Ukrainian scientists claim that producing ammonia from hydrogen would allow for transporting more energy, as ammonia contains three times more energy per cubic meter.

Ukraine has a strong transportation system with strongly developed water transport, the cheapest form of transport, allowing unrestrained exports of refined oil and chemical products during peaceful times. Ukraine used to have 18 active seaports and 11 river ports, which ensured the transhipment of over 170 million tonnes of products annually. Sea transport is strongly developed as agricultural and metallurgy companies export their products to European and African countries. The war has reduced the number of effectively operating seaports to just 5 (and 9 for river ports)[35].

Even though throughout the years of independence, river transportation has shown a decline from 67 million tonnes annually to 8 million tonnes in 2019[36] due to the excessive regulation of the government-owned river ports that made the income accumulated on the parent company's balance and not reinvested in the development of river infrastructure, it was seen as prospective for the future development of Ukrainian agriculture and industry. During 2019-2021, the situation improved with the adoption of the strategy for the development of inland water transport in Ukraine for the period until 2031 by the government[37] as private companies started to work in the public-private partnership format and develop river infrastructure[38].

[35] Three ports in Ukraine receive and send cargo, Landlord.ua, 2022
[36] Ministry of Recovery of Ukraine, 2019
[37] Ministry of the Recovery of Ukraine, 2021
[38] Law on internal water transport: a month after starting, Ukrainian Shipping Magazine, 2021

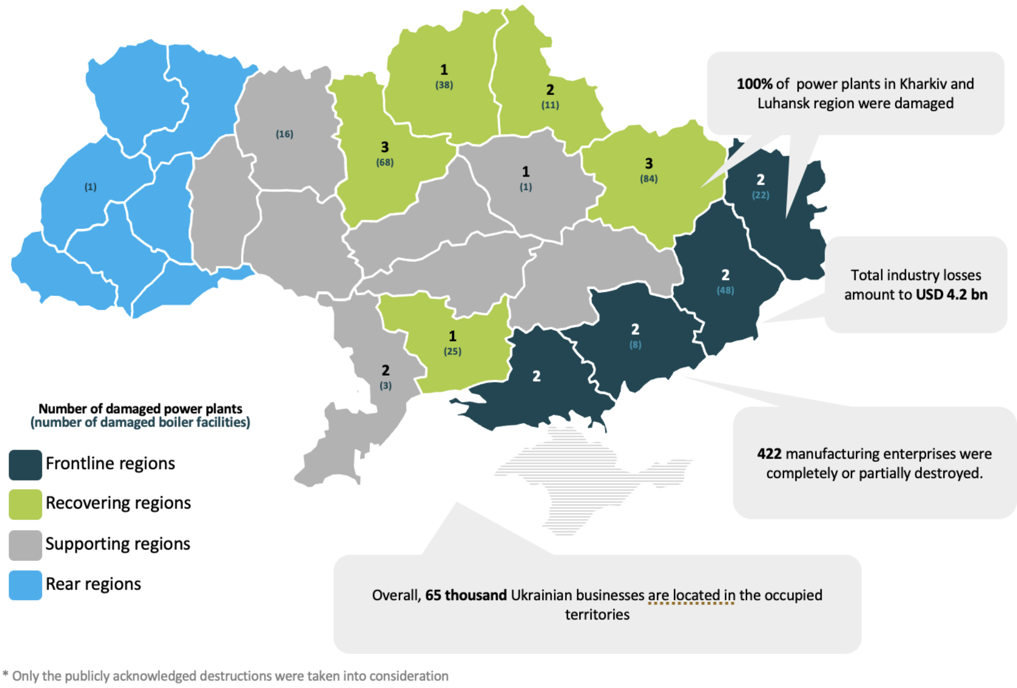
4. Impact of war

Overall, war has had a devastating impact on all sectors mentioned above. For the metallurgical sector (steel production), the war decreased export share from 30% to 18% (of total exports)[39]. The estimated change in volumes of emissions suggests at least a similar drop is plausible.

For the energy industry, war has significantly increased the usage of emissions-intensive sources of power generation: the loss of the Zaporozia NPP, 90% of total WPP, 30% of total SPP capacities[40] and continuous power outages due to the destruction of the grid distribution networks have shifted the consumption towards less sustainable energy solutions, such as petroleum and diesel generators and small-scale CHPP.

In terms of the regional distribution, the areas in the East of the country were most affected by such an effect, as seen in the figure below.

FIGURE 14. REGIONAL LOSSES AND DESTRUCTION OF ENERGY CAPACITIES, 2023, CENTER FOR THE ECONOMIC RECOVERY[41]



The losses can be analysed in terms of regions:

- Front-line regions: the most significant losses in housing – 99.1 thousand units, 82% and 11% of which are in the Donetsk and Luhansk regions. There are also substantial losses in energy (86 units) and agriculture (12.10 billion USD), where the Zaporizhzhia suffered the most (3.9 billion USD) and the Kherson region (2.1 billion USD) the least.

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[39] State Statistics Service
[40] Ukrinform, 2023
[41] Visualisation of the Center for the Economic Recovery based on Kyiv School of Economics, World Bank and Ukrenergo data

Recovering regions: significant losses in the energy sector (233 units). 40% of such destructions were in the Kharkiv region, followed by 30% in Kyiv and Kyiv region. The overall losses in housing are 41.2 thousand (60% of them in the Kyiv region and only 0.7 thousand in the Chernihiv region). In agriculture, the total losses are 12.2 billion USD. The most significant losses are in the Kharkiv region, at 4.2 billion USD; the Sumy region has the lowest losses at 1.6 billion USD.

Supporting regions: moderate losses in energy infrastructure (23 units) and housing (6.8 thousand) and significant losses in agriculture (12.2 billion. USD). In agriculture, Poltava and Vinnytsia regions were the most affected (2 billion USD each), and in the housing sector – Dnipropetrovsk region (3.1 thousand). Khmelnytskyi region suffered the least losses.

Rear regions: the lowest levels of total losses. Specifically, the Lviv and Rivne regions reported damage to 0.1 thousand housing units. In agriculture, the losses amounted to approximately 2.4 billion USD. Ternopil oblast incurred the highest losses, reaching 0.8 billion USD, while Zakarpattia experienced comparatively lesser losses at 0.045 billion USD[42].

5. Assessment of green technology potential in the recovery of Ukraine

5.1. Emission dynamics in the selected sectors

Energy, agriculture, and steel sectors produced 51% of CO_2 emissions in Ukraine in 2021. The energy sector produces as much CO_2 emissions as the agriculture and steel industries combined. Therefore, those sectors were the most promising candidates for further analysis. There is a visible trend in their emissions volumes – the decrease of CO_2 emissions in these sectors is slow.

Before the war, the agriculture and steel industries witnessed a gradual increase in CO_2 emissions, primarily due to the absence of modern equipment and sustainable production practices. Specifically, emissions in agriculture rose from 44 million tonnes in 2021 to 47 million tonnes in 2022, while the steel industry experienced a similar increase from 41 to 46 million tonnes.

Agriculture represents 10.8% of Ukraine's GDP and employs around 6% of the workforce. In terms of exports, the importance of the sector for the economy increased significantly because of the war: the sector experienced a notable increase of 7% from 2021 to 2022, reaching 41% of total exports. The primary sources of CO_2 emissions in the agricultural sector can be attributed to plant crop farming and animal farming.

The energy industry, although less significant in terms of GDP and employment figures, turned out to be crucially important for the stability of the entire economy. Before the war, the rapid growth of renewable energy capacities was a significant part of the industry transformation. In 2019, Ukraine was in the top 10 countries with the fastest-growing renewable energy sectors[43]. The energy industry accounts for 9.1% of GDP and employs approximately 3% of the workforce. The Russian invasion has led to a significant 95% decline in energy exports, reaching a mere 0.09% of total exports in 2022, in contrast to 1.85% in 2021. The primary sources of CO_2 emissions in the sector stem from the combustion of fossil fuels, including coal, oil, and natural gas, utilised for electricity generation, heating, and transportation.

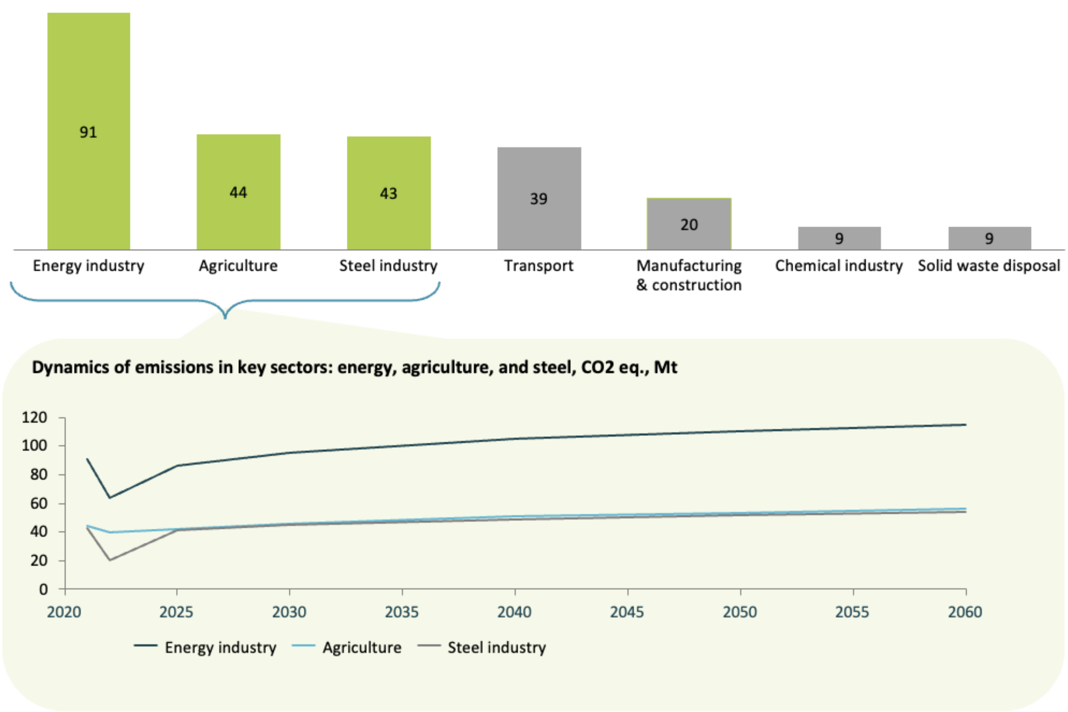
Even though the total production volume in the agriculture sector is expected to grow twofold by 2060, there is unlikely to be room for robust application of CCS technologies. The growth in exports is expected to mirror the increase in total production, with its share remaining stable at around 40% throughout the entire time period. Unless the EU moves forward with the proposal to include agriculture in the EU Emissions Trading System (ETS) and CBAM schemes[44], the probability of investments in these sectors in Ukraine remains low.

[42] Report on the direct damage to the infrastructure from the destruction caused by Russia's military aggression against Ukraine a year after the start of the full-scale invasion, Kyiv School of Economics, 2022
[43] Decarbonization of Ukraine’s Energy Industry, Razumkov Centre, 2022
[44] Putting a price on emissions and rewarding carbon removals in the land sector, European Commission, 2023

For the rest of the sectors, in the context of recovery by 2060, the assumptions include a massive increase in energy production volume, with an almost three times increase in power generation. The share of exports will grow insignificantly, meaning that most of the newly generated energy is expected to be consumed within the country. The manufacturing industry is expected to quadruple its production, reaching 103 million tonnes of steel and other byproducts by 2060. The increase will be primarily due to domestic consumption, driven by the reconstruction and modernisation measures. The share of exports will remain around 29%.

The metallurgy industry makes up 4.9% of the Ukrainian GDP: due to the ongoing war, the industry experienced a significant 2.5% decline in its contribution, which used to be around 12%. Furthermore, the industry's export level also sharply decreased, dropping to just 10.5% of total exports compared to 19.5% in 2021. The sectoral contribution to the employment rate was and remains relatively small – just 1.16%[45].

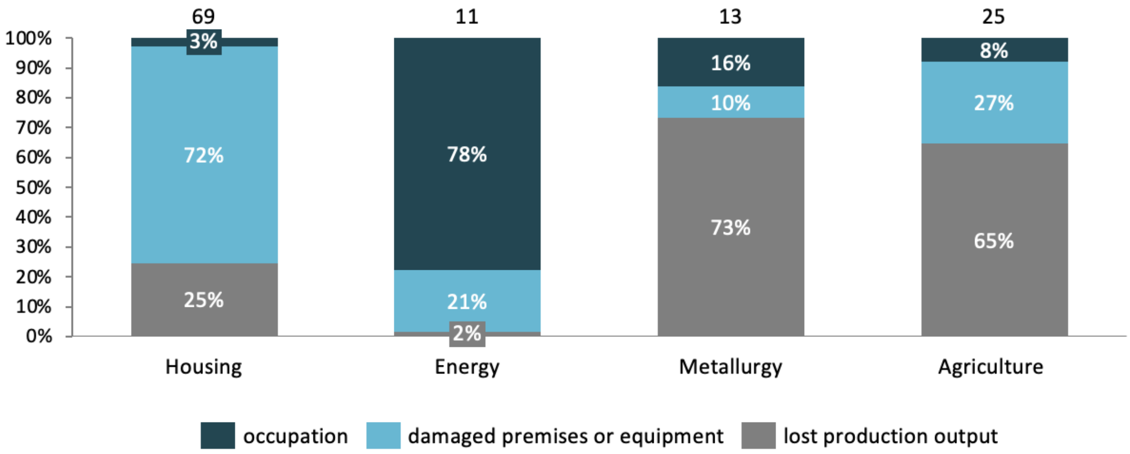
FIGURE 15. GENERAL AND SECTORAL ECONOMIC GROWTH ON EMISSIONS, PROJECT TEAM CALCULATIONS[46]



However, most verifiable (direct) losses for the three outlined sectors differ. As shown in the figure below, the recovery needs in the energy sector are the highest compared to the estimated losses, as is the share of damages. Partially, this is explained by the higher recovery standards attributed to EU environmental standards in the case of electricity exports and the possibility of ultimate land loss with currently non-damaged or mildly damaged power generation capacities. The overall share of occupied supply sources in the breakdown of losses amounts to 78%, which is achieved through the occupation of 70% of WPP (primarily located in the Zaporizhia, Kherson and Mykolaiv regions – partially reclaimed down from 90% after the right bank de-occupation at the end of 2022) and Zaporizhia NPP which comprises six reactors.

[45] Project team calculations based on the data from the State Statistics Service
[46] Ibid.

FIGURE 16. BREAKDOWN OF THE VERIFIABLE LOSSES IN EACH SECTOR, BILLION USD, CENTER FOR ECONOMIC RECOVERY, 2023[47]



The share of production loss is the highest for the metallurgy sector due to the significant decrease in capacities due to limited supply, power outages, and logistical bottlenecks. It constitutes up to 73% of the total verifiable losses compared to 65% in agriculture. In comparison, the net loss of the production capacities is significantly smaller – just about 4 billion USD[48].

Housing has the largest amount of direct losses. Most damaged residential units are in Donetsk, Kharkiv, Luhansk, Kyiv, and Mykolaiv regions. Over one-third of the damaged units are destroyed (499 056 units), while two-thirds are partially damaged. Of partially damaged units, 285 257 have minor damage (up to 10%), and 787 779 have moderate damage (between 10% and 40%)[49].

Since the recovery processes will require large amounts of concrete, for the purposes of future analysis, the cement industry is outlined from the entire construction sector to provide a more precise estimate for the total output forecast and changes in technology usage.

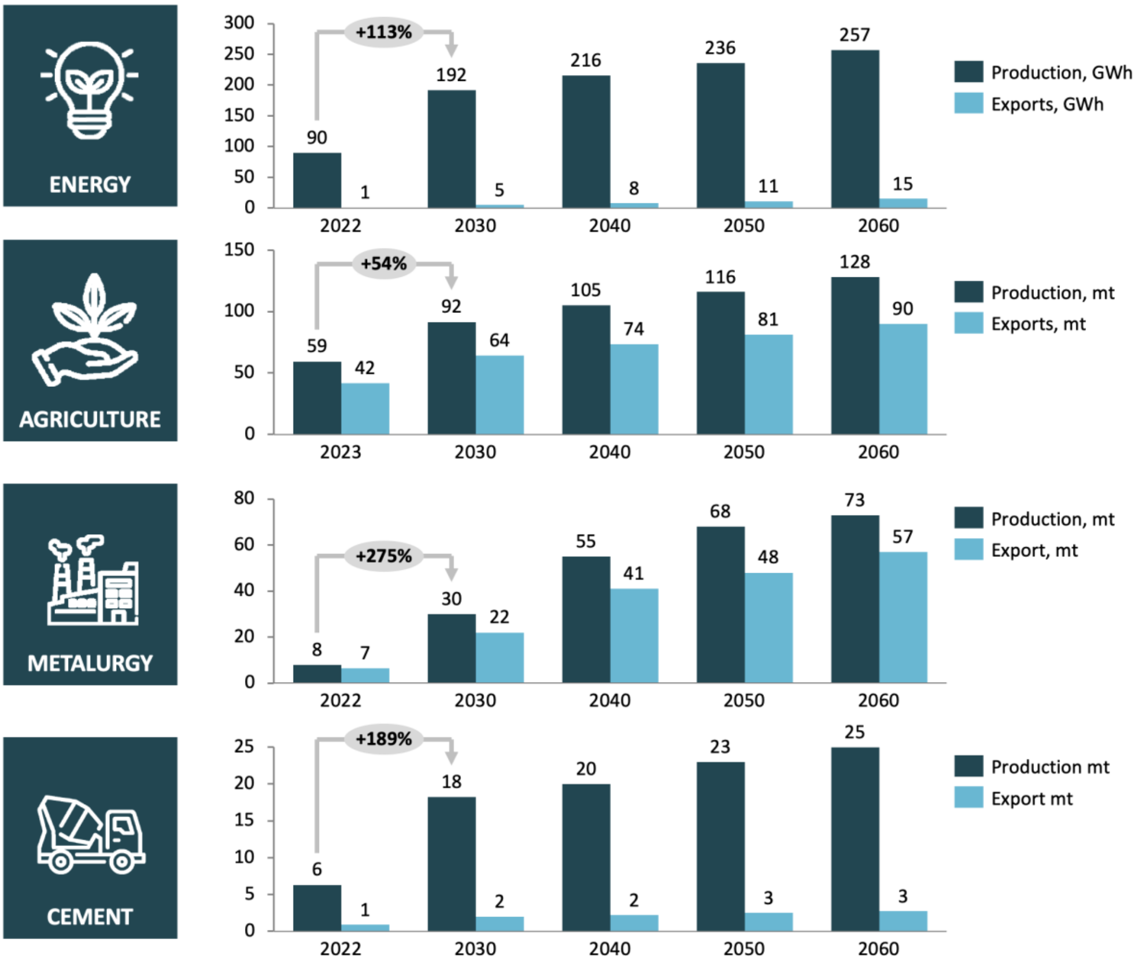
As shown in the figure below, in the case of a successful and undisturbed recovery process, all studied sectors are expected to increase production volumes significantly.

[47] Calculations and visualisation of the Center for Economic Recovery based on Kyiv School of Economics, World Bank and Ukrenergo data

[48] Ibid.

[49] Ukraine Rapid Damage and Needs, World Bank, 2023

FIGURE 17. PROJECTED PRODUCTION AND EXPORT VOLUMES FOR THE KEY OUTLINED SECTORS UP TO 2060, CENTER FOR ECONOMIC RECOVERY, 2023[50]



Driven by the increased needs in domestic consumption, the output growth in the metallurgy sector is expected to be the largest one: a nearly six-fold growth in steel production up to 2030 has the potential to continue in future driven by further exploration of foreign export markets and development of the derivative industries (machinery manufacturing and appliances assembly).

The second-best performance is projected for the cement industry, which is expected to demonstrate a nearly three-fold growth up to 2030, driven by the same recovery and reconstruction demand. As seen from the chart above, production growth is expected to slow down significantly after 2030.

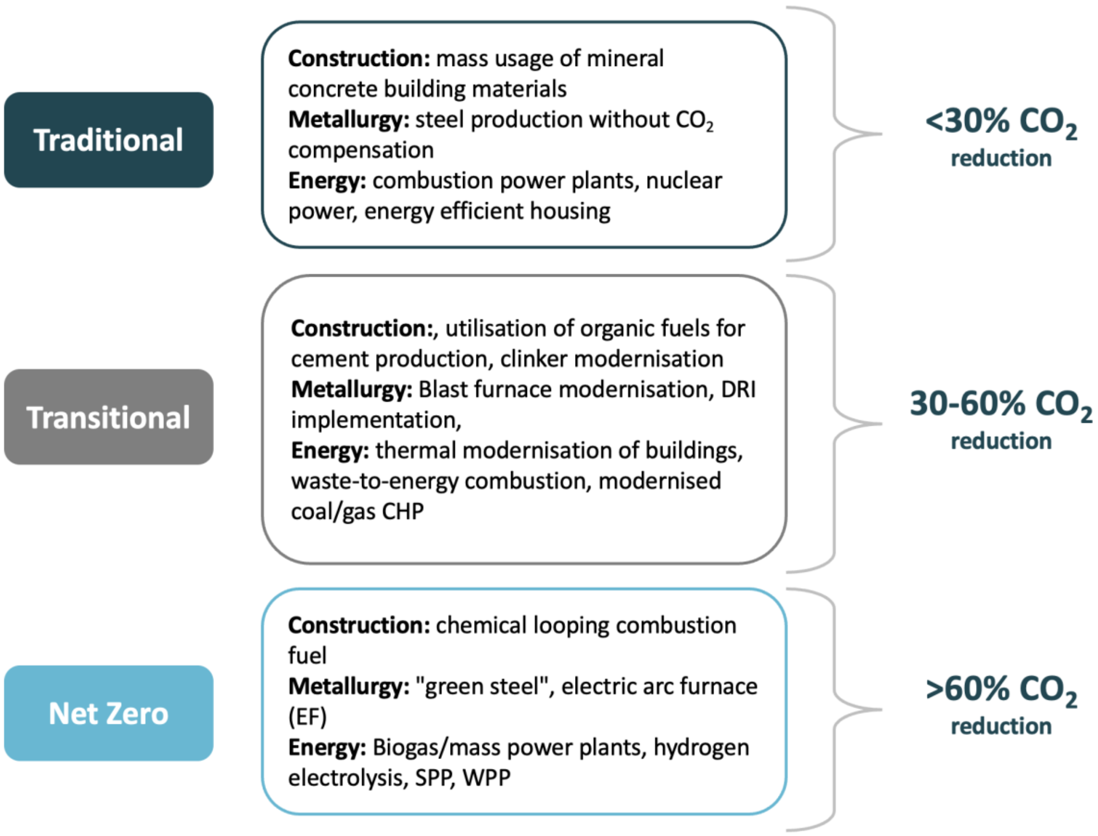
Despite demonstrating the lowest production growth projections, the energy industry is expected to grow sustainably for the rest of the forecasted period, increasing production volumes from 82 GWh to 257 GWh per annum.

[50] Project team calculations based on the data from the State Statistics Service

5.2. General sets of technologies for recovery

Key sets of CCS and CCU technologies include three broad groups: traditional, transitional, and Net Zero technologies, which are generally distributed in terms of their impact on emissions reduction, as seen from the figure below. As mentioned, agriculture technologies were not included in this framework due to the difficulties with CO_2 reduction estimation.

FIGURE 18. KEY TECHNOLOGY ASSUMPTIONS FOR THE OUTLINED SECTORS, PROJECT TEAM CALCULATIONS

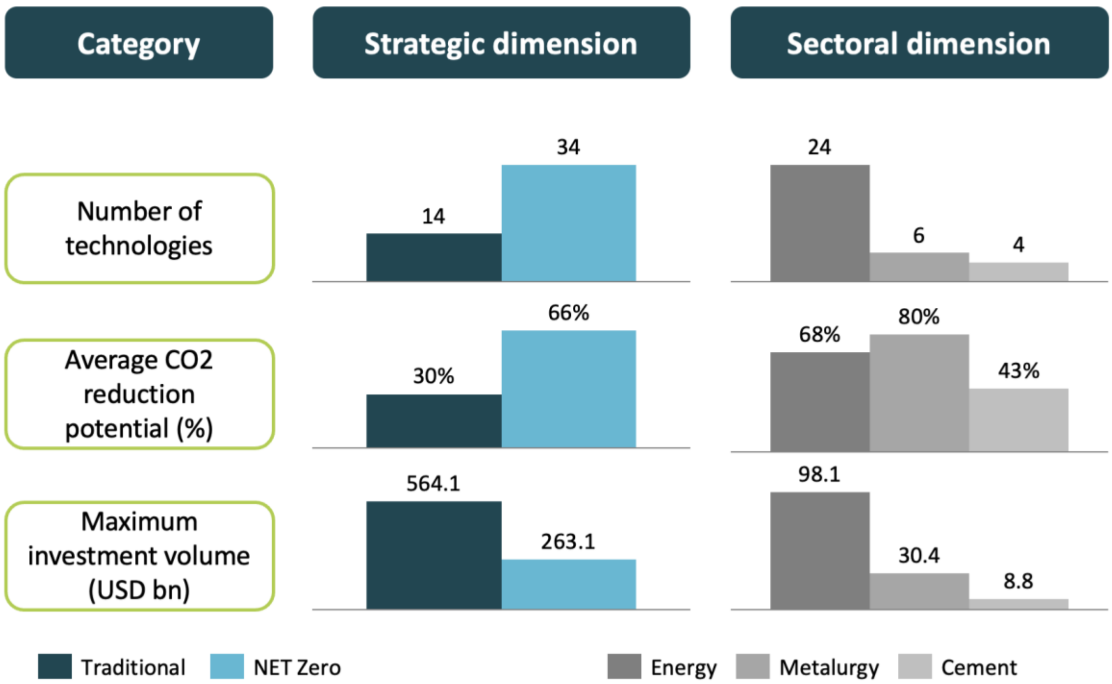


As can be seen from the figure above, the technologies are divided into three categories based on their emissions reduction potential. Although the variance of estimates may differ based on the particular aspects of their application, the emission reduction estimates were calculated based on several assumptions: replacement of alternative fossil fuel power generation sources with renewables (energy sector), application of substitution or performance-enhancing technologies (metallurgy) and usage of techniques aimed at efficiency improvement (cement industry).

5.3. Investment assessments

To effectively reduce CO_2 emissions as part of the recovery, attracting investments to use Net Zero technologies is necessary. On average, Net Zero technologies are both the most expensive and effective in terms of CO_2 reduction. The category of Net Zero technologies includes technologies or solutions that produce zero or close to zero CO_2 emissions or are designed to neutralise emissions already produced. Deployment of new technology requires from 3 to 6 years on average, and in some cases, more than ten years (for example, hydrogen-based direct reduction of iron (DRI) in metallurgy or new nuclear capacities in the energy sector). Net Zero technologies require 53% more investments than traditional technologies. In terms of CO_2 reduction, the Net Zero technologies are expected to reduce 66% of emissions compared to just 30% in the case of traditional technologies.

FIGURE 19. KEY TECHNOLOGY COMPONENTS OF THE SUSTAINABLE RECOVERY, PROJECT TEAM CALCULATIONS



Technologies implemented in the metallurgy sector have the highest CO_2 reduction potential. This is explained by the assumption of the ~100% modernisation of existing production capacities in Ukraine, where all existing pants would be modernised. Energy sector technologies significantly dominate other sectors in terms of total required investment volume due to their larger numbers (24 technologies vs 6 and 4 in metallurgy and cement sectors) and generally larger scale (e.g., power plant construction). For the cement sector, the technologies in question are primarily based on the changes in fuel usage and clinker modification, which can ensure smaller volumes of emissions during the process of concrete production.[51] The traditional set of technologies was excluded in this assessment case due to the difficulties in estimating the maximum CAPEX volumes due to the absence of the relevant investment projects planned.

5.4. List of scenarios for technological implementation

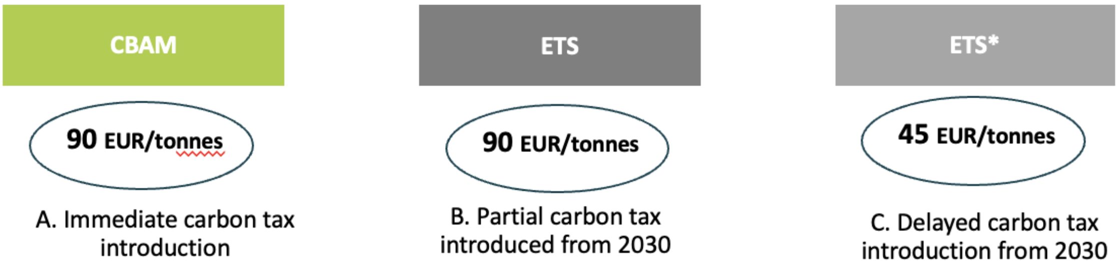
Overall, the research outlines three possible policy scenarios which might significantly impact not only the implementation of the CCS/CCU technologies but the entire dynamics in the three outlined sectors (metallurgy, energy and cement):

1. The scenario is based on the assumption of the introduction of CBAM regarding all Ukrainian exports to the EU.
2. The scenario without the introduction of the CBAM due to the timely implementation of the national ETS in Ukraine.
3. Delayed deployment of the ETS in Ukraine, preceded by CBAM application.

The visualised summary of all three scenarios is provided in the figure below.

[51] Alternative Clinker Technologies for Reducing Carbon Emissions in Cement Industry: A Critical Review, Antunes et al., 2021

FIGURE 20. CLIMATE POLICY SCENARIOS, PROJECT TEAM CALCULATIONS [52]



The detailed description of the scenario assumptions is provided below:

- **CBAM** – "As-Is" type of scenario, where Ukraine has not introduced ETS and the environmental tax is 1 EUR per ton of CO_2 CBAM is applied towards Ukrainian products (taxation under CBAM scenario – 90 EUR/tonne of CO_2); for the energy sector – state programs to reduce coal generation, new nuclear hydrogen production facilities; for metallurgy – production of 2.5-5 million tonnes of "green" steel is made available with EAFs. The absence of the ETS means that exports to EU countries of such goods as electricity, aluminium, mineral fertilisers, hydrogen and iron and steel will be taxed within the scope of the CBAM; a significant part of the products produced by these sectors will be directed only to meeting domestic demand, which will lead to substantial losses of the sectors. Carbon-neutral technologies will be partially implemented only in the most EU export-oriented sectors, particularly electricity and metallurgy.
- **ETS** – "Ukrainian context" type of scenario, where Ukraine introduces ETS in 2030 (Phase 6 – including transport and agriculture) with CBAM terminated until 2030. Due to the adverse taxation under CBAM (90 EUR/tonne), a decrease in energy consumption is projected: insulation of buildings, modernisation of heating equipment, and full energy modernisation of public and household lighting will take place under Ukraine's Recovery Plan. Consequently, ETS introduction in the energy and metallurgy sector encourages manufacturers to implement low-carbon and energy-efficient technologies and allow these goods to be exempted from additional taxation; modernisation of blast furnaces and coke production at metallurgical facilities occurs, transition to oxygen-converter and electric steelmaking technologies is partially carried out: Ukrainian steel makers and fertiliser producers substitute Russian exports at European markets.
- **ETS*** – delayed ETS scenario, where Ukraine introduces ETS in 2030 (Phase 6 – including transport and agriculture) with CBAM terminated until 2030 (ETS in Ukraine – taxation levels are 45 EUR/tonne, relevant to the EU ETS. Due to the full-scale war, reporting on emissions remains optional, becoming obligatory only three months after the lifting of martial law). Therefore, the expansion of ETS to other sectors of the economy will contribute to the application of the largest number of decarbonisation initiatives. The energy sector can expect a significant increase in heat-generating capacities based on RES and biofuels and a transition to Net Zero heat production.

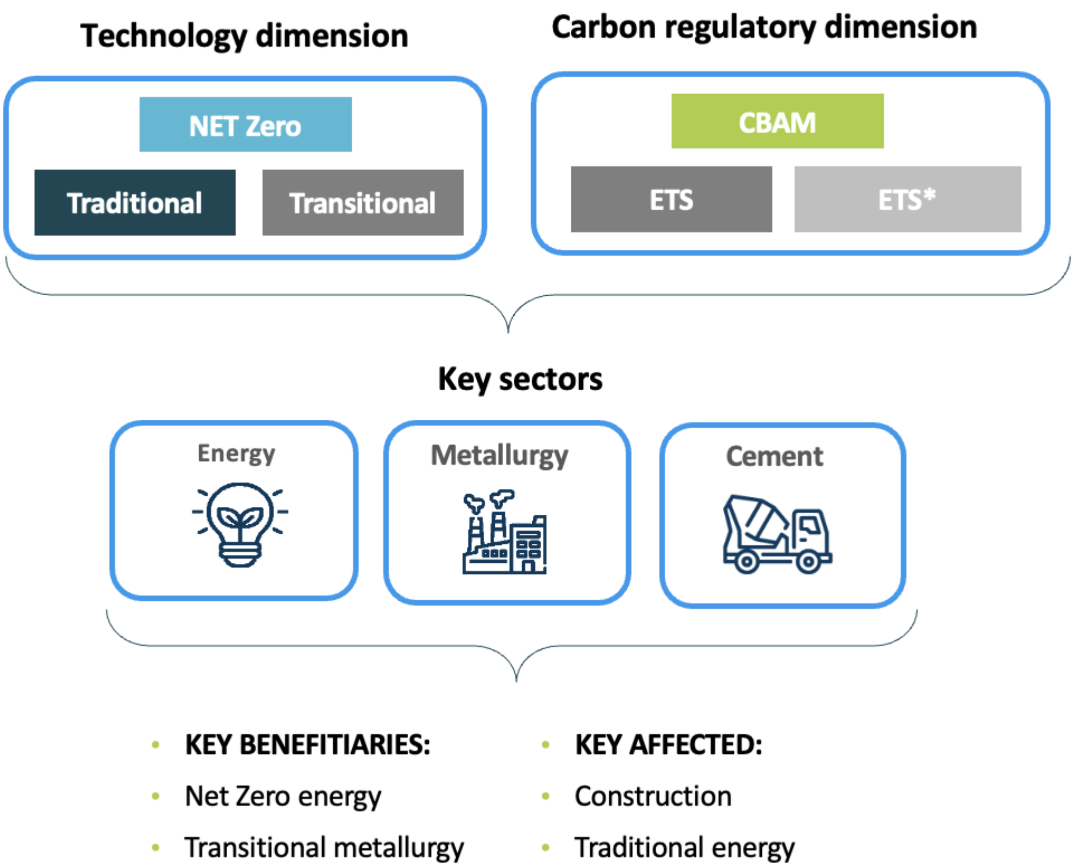
In the case of the CBAM scenario, transitional technologies might remain more attractive and widespread than Net Zero technologies across all regions. The corresponding volume attracted investments will also be dependent on the scenario. Under the ETS scenario, a set of NET Zero technologies might become much more attractive, allowing for significantly reduced CO_2 emissions. It is also expected to be implemented at the level of at least 20% across all three reviewed sectors, including agriculture. In the case of the ETS* scenario, Net Zero technologies are expected to matter less for all sectors. The predominant volume of investment in agriculture, energy, and metallurgy industries will continue to go to the traditional and transitional technologies. As Ukraine already mostly uses traditional technologies, most of the studied technologies belong to the category of novel technologies to explore the potential gains and losses from CO_2 reductions and activation of CBAM and ETS mechanisms.

[52] Project team visualisation based on the EU/UA legislative documents

6. Estimated investment effect

In this section, the aforementioned technology and scenario dimensions are combined to provide estimates for the average investment prognosis: the study projects the impact of technologies for each sector and estimates their implementation effect for the entire industry.

FIGURE 21. ANALYSIS FRAMEWORK, PROJECT TEAM INSIGHTS



The matrix above provides the visual estimates for the general forecasting framework as well as includes the list of key findings in relation to the most and least affected sectors based on the outlined scenarios. According to the assumptions, CBAM, ETS, and ETS* scenarios will have a significant impact on the development of the Ukrainian economy.

In the case of the CBAM scenario, transitional technologies might remain more attractive and widespread than Net Zero technologies across all regions. The corresponding volume attracted investments will also be dependent on the scenario. Under the ETS scenario, the set of Net Zero technologies might become much more attractive and allow for a significant reduction in CO_2 emissions. It is also expected to be implemented at the level of at least 20% across all three reviewed sectors, including agriculture.

In the case of the ETS* scenario, Net Zero technologies are expected to matter less for all sectors. The predominant volume of investment in agriculture, energy, and metallurgy industries will continue to go to the traditional and transitional technologies. As Ukraine already uses traditional technologies, most of the studied technologies belong to the novel technologies category to explore the potential gains and losses from CO_2 reductions and activation of CBAM and ETS mechanisms.

Below, the analysis provides a breakdown of average cost estimates for each of the studied sectors under the conditions of a consolidated scenario. Under its provisions, the technologies are combined for each sector under the assumption of their 20% implementation across the entire industry. The following chart provides a visualisation of those costs: current costs for the implementation of key technologies in the reconstruction and recovery initiatives of Ukraine (within energy, metallurgy and cement sectors), costs in case of implementation of most ecology efficient technologies (Net Zero technologies), as well as cost efficiency of technology bundles (combinations on Net Zero and traditional technologies, such as DRI/SRI and blast furnaces for metallurgy or combined biogas/natural gas CHPs in energy sector)

FIGURE 22. TOTAL SCENARIO COSTS FOR DIFFERENT TECHNOLOGY IMPLEMENTATION, BILLION USD, PROJECT TEAM CALCULATIONS

The general idea behind such a summary is that Ukrainian producers are currently seeking technologies both for direct reconstruction of pre-war capacities and technological modernisation bundles to allow for new development. The potential technology sets, which will combine the utilisation of old capacities with new technologies, are expected to be most ecologically efficient in terms of the smallest emissions volume but potentially the highest reconstruction and repair cost.

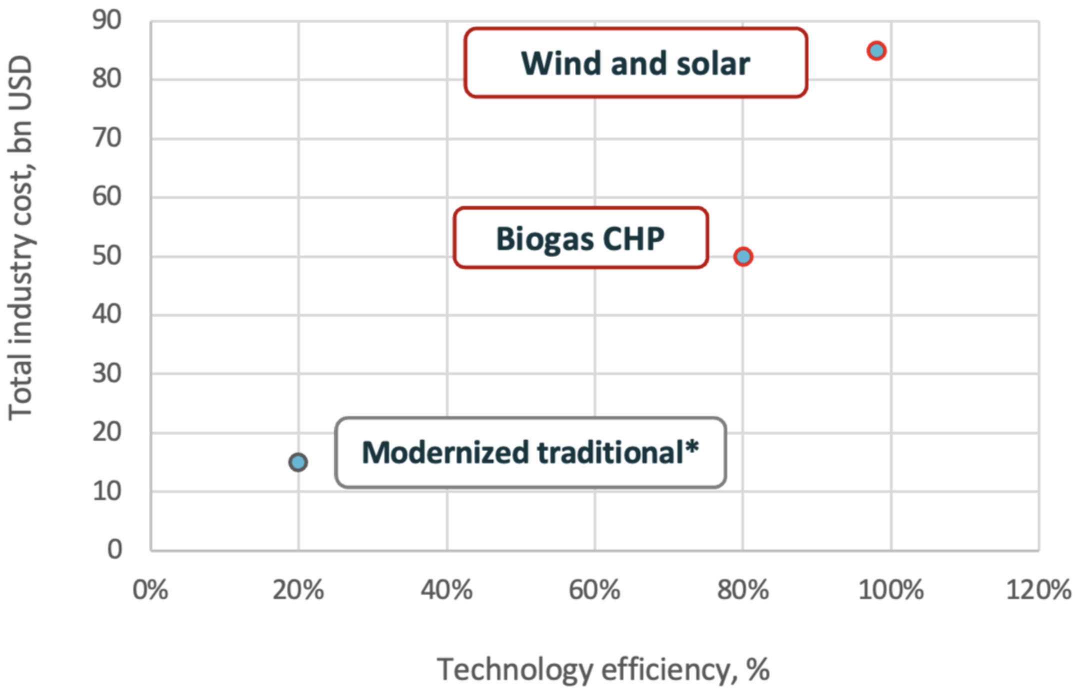
It is also important to mention that these numbers do not include the effects of related sectors, potentially amounting to about 10 billion USD. In this number, infrastructural, industrial manufacturing, and industrial parks are included: all of them can be seen as potential objects for foreign direct investments and domestic government and private investments upon the country's recovery.

6.1. Energy sector

Overall, Net Zero technologies will dominate the investment landscape in the energy sector. To form a comparative base for nine years, three types of power generation were chosen: coal, renewables (wind and solar energy), and natural gas combined with RES. The total installed capacity in each scenario is 1000 MW. The share of exports in the CBAM scenario is projected to be 20%, as will be the share of the technology implementation in the sector.

The calculations show that despite being the cheapest and most rapid to implement, transitional technologies (combustion power generation from gas and coal) won't be investment-attractive since, under all policy scenarios, the amount of CO_2 released is almost four times higher for natural gas and ten times for coal in comparison with RES sources (depending on the type of energy source, combustion power generation can produce the volume of emissions ranging from zero to 9.5 kg of CO_2 for one kWh in case of coal).

FIGURE 23. TECHNOLOGIES IN ENERGY SECTOR COMPARISON DIAGRAM, PROJECT TEAM CALCULATIONS



The performance efficiency of the three outlined sets of technologies is depicted in the figure above. As can be seen, modernised traditional technologies for the energy generation sector are one of the most expensive and one of the lowest for CO_2 change. On the other hand, using such technologies as “Coal (CHP)” gives a five times bigger CO_2 efficiency level with lower costs but in a longer perspective.

In addition to the outlined technologies, there is a set of technologies that, although not directly related to mass-scale power generation, are specifically designed to reduce the amount of CO_2 emissions. Technologies based on circular economies and energy efficiency principles, such as biogas production from organic waste and biomass combined heat and power, not only emit less while generating electricity but also reduce potential CO_2 that could be produced at landfills. In the case of Ukraine, in the current situation, the most probable way to decarbonise the sector is the application of natural gas-fired plants with permanent deployment of renewable generation. In the long run, such technologies as battery energy storage can be deployed as flexibility capacities and smart grids to increase energy efficiency while transmitting electricity.

With regards to the impact of scenarios, although the CBAM scenario will also introduce significant differences in usage of net zero and traditional technologies, in the case of ETS and ETS* scenarios, the difference will remain significant, which is explained by the fact that the design of ETS is majorly aimed at targeting the energy sector. Due to low export share, the energy sector will be most resilient to CBAM/ETS application.

Since the application of Net Zero technologies means the lowest carbon emissions, even though their introduction period is the longest, they present the most reasonable technologies for CO_2 emission reduction. The share of free allowances for emission in ETS and ETS* Scenarios was taken at the level of 85%, which made some transitional technologies relatively competitive with Net Zero technologies under the CBAM scenario.

Key challenges:

- System imbalances caused by the war are likely to persist, posing a challenge to the widespread adoption of renewable energy installations.
- Implementing methanol production through CO_2 emission reduction demands energy efficiency and sustainable hydrogen sourcing while navigating scale-up complexities.
- Balancing CO_2 emissions, catalyst efficiency, and regulatory compliance is challenging in CO_2-emitting power generation processes.
- Managing coal combustion residuals requires environmentally responsible disposal techniques, containment assurance, and adherence to diverse regulations, adding complexity to the coal industry's environmental impact.

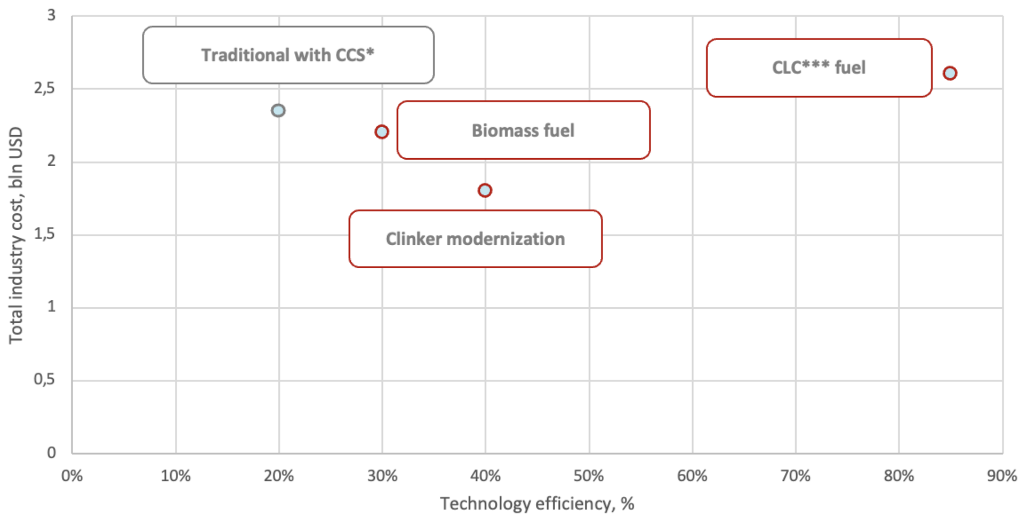
Key features:

- The production of biogas from excess agriculture output serves as a key feature, offering a potential solution for local grid balancing and electricity generation.
- Methanol production via CO_2 reduction contributes to carbon utilisation, enabling net-zero potential when powered by renewables and offering economic viability through potential carbon credit generation.
- Efficient CO_2 conversion diversifies methanol production feedstocks, enhancing sustainability and reducing dependence on traditional sources.
- Properly managed coal combustion residual sites can be repurposed, showcasing a feature that aligns with environmental sustainability and the responsible use of industrial byproducts.
- Biogas and methanol production via CO_2 reduction drive innovation through the use of advanced catalysts and recycling methods, contributing to sustainable energy and chemical production practices.

6.2. Cement sector

In the case of the cement sector, the differences in the effects of the introduction of CBAM and ETS scenarios variations are insignificant. Both scenarios mainly affect exports, and since the majority of cement sector produce will be diverted towards domestic markets, only a small fraction of the sector will be affected (only a 16% difference in costs) in case their exports to the EU countries. Transit options might also become extremely limited due to scrutinised check-up procedures and queues at the border. Cement sector losses will be highest from the introduction of ETS due to fuel price increases.

FIGURE 24. TECHNOLOGIES IN THE CEMENT SECTOR, COMPARISON DIAGRAM, PROJECT TEAM CALCULATIONS

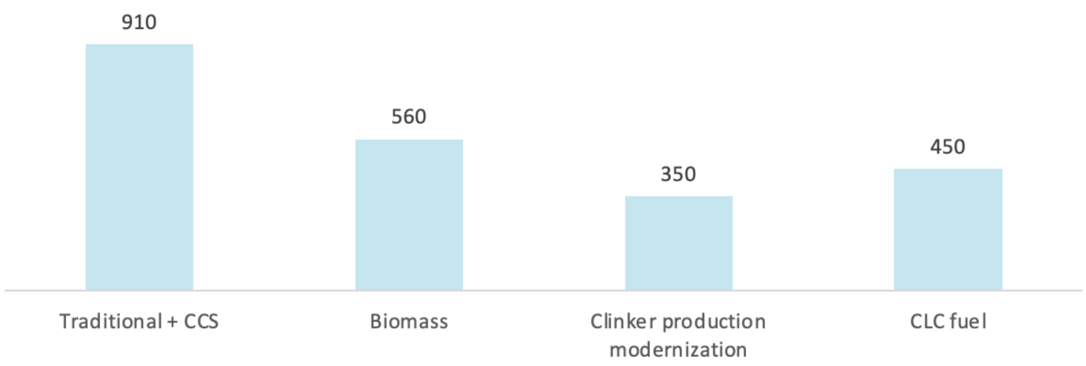


**** - Chemical looping combustion*

Overall, in the cement industry, transitional technologies are more investment-efficient under the CBAM scenario since their utilisation implies the recultivation of the large volumes of construction processes on the war-affected land. In the case of ETS implementation, the assumption for the share of ETS quotas will primarily affect fuel consumption since the list of green technologies includes the usage of biogas fuel and other technologies that can potentially allow significantly decreased emissions in the cement sector.

The most reasonable way to minimise an investment volume is using “Clinker production modernisation” and “CLC fuel” based technologies.

FIGURE 25. TECHNOLOGIES IN THE CEMENT SECTOR COMPARISON BY CO_2 REDUCTION COSTS, USD/KG CO_2, PROJECT TEAM CALCULATIONS



Key challenges:

- Potential costs continue to increase during each day of the war. The war has created an environment of instability, with daily fluctuations in various economic factors such as energy prices, transportation costs, and labour expenses. Frequent disruptions in supply chains, damaged infrastructure and heightened security concerns also contribute to rising operational costs.
- High dependence on government and international funding. The Ukrainian cement sector heavily relies on government support and international funding sources, posing a significant challenge until 2030 and later. The ongoing war has strained the country's economy, making it challenging for the government to allocate funds to develop and modernise the industry.
- Increasing technology implementation cost. Advanced technologies that help reduce CO_2 emissions often require significant upfront investments, which can strain the already financially constrained cement producers. The cost of acquiring and installing equipment for emission reduction, energy efficiency, and automation can be unpredictable.
- Combining the need for technological upgrades with limited financial resources. Finding such a balance is a complex challenge, and cement producers must carefully plan and prioritise their technology investments to maximise their return on investment while complying with environmental regulations.

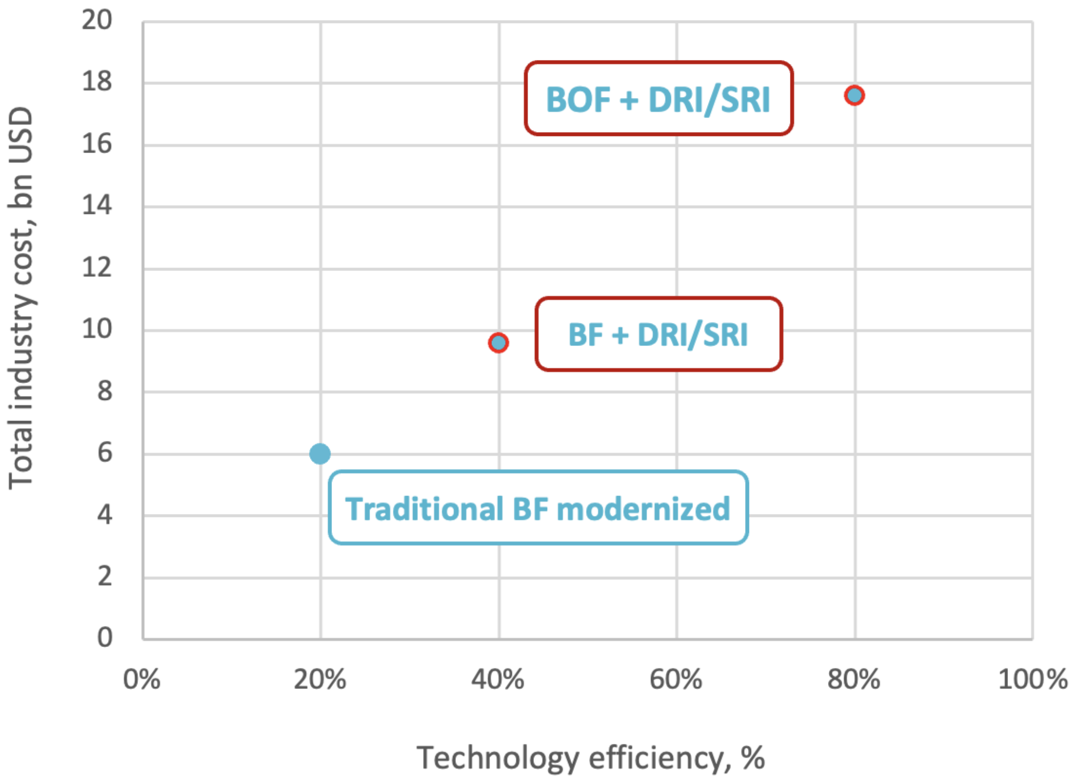
Key features:

- CCS can help cement producers to cut production costs. To remain competitive and sustainable, cement producers must find innovative ways to mitigate these escalating costs while maintaining the quality and reliability of their products.
- Attraction of foreign investments in CCS under the auspices of the general reconstruction. The ongoing war has strained the country's economy, making it challenging for the government to allocate funds to develop and modernise the industry. Cement producers could attract foreign investment through subsidies, grants, and low-interest loans to invest in essential infrastructure upgrades and environmental compliance measures.
- Cement sector producers can diversify their revenue streams and develop more self-sustaining financial models to reduce reliance on external sources, ensuring long-term viability. This can potentially help mitigate the rising costs of implementing modern technologies in the main production activities and provide new opportunities for horizontal business development.
- Potential cooperation of the enterprises from the sector under Article 6 of the Paris Climate Agreement. As the industry seeks to improve efficiency, reduce environmental impact, and meet evolving regulatory standards, the producers can provide proof of emissions reduction to obtain credible verification from international partners to boost exports.

6.3. Metallurgy sector

Regarding the metallurgical sector, the highest difference in tax-related costs will be observed for the CBAM scenario: traditional technologies will be 80% more expensive than Net Zero technologies. Concerning ETS scenarios, the average costs will be four times lower than under the CBAM scenario, which makes them relatively more preferable. Metallurgy will suffer greatly from the CBAM scenario but significantly less under other scenarios, making it resistant to tax implications under different scenarios – the sector will be equally affected.

FIGURE 26. TECHNOLOGIES IN THE METALLURGY SECTOR, COMPARISON DIAGRAM, PROJECT TEAM CALCULATIONS



As shown from the figure above, within the scope of metallurgy technologies, blast furnaces with the addition of CCS are less investment efficient than EAFs, which provide minimal emissions under the assumption that power generation is derived from RES. However, since the set of traditional technologies demonstrates an even lower level of efficiency, blast furnace modernisation (via the addition of direct reduction processes such as MIDREX or COREX) is still comparatively efficient and preferable[53].

For the metallurgy sector, it was possible to outline a selected set of CCS technologies which can be compared to each other. The comparison of different technologies by their cost for CO_2 reduction provides the following conclusions:

- **Technologies with CCS:**
    - **Cost for CO_2 reduction:** 1089 USD/kg CO_2
    - **Description:** Technologies incorporating CCS in the metallurgy sector come with the highest cost for CO_2 reduction at 1089 USD per kilogram. This reflects the substantial investment required to implement and maintain CCS infrastructure. While the expense is significant, it is essential to recognise the long-term environmental benefits of CCS. Ukraine's metallurgy sector, like many others globally, is under increasing pressure to lower its carbon emissions. The high cost of CCS may present initial financial challenges, but it offers a robust solution to meet emission reduction targets while preserving the industry's viability.
- **Blast Furnaces:**
    - **Cost for CO_2 reduction:** 519 USD/kg CO_2
    - **Description:** Blast furnaces have long been a staple in the metallurgy sector due to their cost-effectiveness in producing iron and steel. However, this technology's relatively high cost of 519 USD per kilogram of CO_2 reduction

[53] Energy and Technology Systems Analysis Brief, The Energy Technology Systems Analysis Program of the International Energy Agency, 2010

underscores its inefficiency in terms of emissions reduction. As Ukraine's metallurgy sector confronts environmental regulations and international climate commitments, companies may find it increasingly challenging to justify the continued use of blast furnaces without supplementary emission-reducing measures.

- **Blast Furnaces with CCS:**
    - **Cost for CO_2 reduction:** 662 USD/kg CO_2
    - **Description:** Blast furnaces with CCS represent an intermediary approach for reducing carbon emissions in Ukraine's metallurgy sector. By integrating CCS technology with the conventional blast furnace process, emissions can be captured and stored, leading to a reduction in CO_2 emissions. However, 662 USD per kilogram of CO_2 reduction cost is notably higher than using blast furnaces alone. This approach offers a compromise between cost efficiency and emissions reduction, allowing metallurgy companies to make strides toward environmental sustainability while managing financial implications.
- **Electric Arc Furnaces:**
    - **Cost for CO_2 reduction:** 230 USD/kg CO_2
    - **Description:** EAFs emerge as the most cost-efficient option for CO_2 reduction in the metallurgy sector, costing 230 USD per kilogram of CO_2 reduction. EAFs use electricity to melt scrap steel and produce new steel, reducing the reliance on carbon-intensive raw materials and emitting fewer GHG emissions. This lower cost makes EAFs an attractive choice for Ukrainian metallurgy companies seeking both economic and environmental benefits. It aligns well with the global trend towards sustainable steel production, positioning Ukraine's metallurgy sector to be more competitive internationally while reducing its carbon footprint.

Key challenges:

- Metallurgical processes generate various byproducts and emissions, which might be dangerous. Ensuring compliance with safety regulations and standards related to waste management, environment, and emissions is essential.
- While blast-furnace slag (BFS) is a valuable resource, managing and handling slag can be challenging due to its abrasive and sometimes hazardous nature. Proper slag storage, handling, and disposal are crucial to prevent environmental contamination.
- Implementing DRI technology will require more skilled and semi-skilled jobs in the local economy, which will require fostering employment efforts. DRI technology requires specialised technical expertise for operation and maintenance, which may be lacking in regions with limited skilled labour.
- Implementing DRI technology will lead to the creation of more skilled and semi-skilled jobs in the local economy, which will also require an effort to foster employment opportunities. DRI technology involves specialised technical expertise for operation and maintenance, which may be challenging in regions where skilled labour is limited.
- The setup costs for DRI units in metallurgy plants can be relatively high, posing a financial challenge for economies with limited capital resources. While DRI plants generally have lower infrastructure demands, adapting existing infrastructure to accommodate this technology can be logistically challenging.
- Transitioning to DRI technology may require time for the workforce to adapt, which can cause disruptions during the implementation phase. DRI plants are operationally complex, requiring stringent control measures and specialised knowledge for efficient and safe production.
- While DRI is deemed more environmentally friendly than traditional methods, it still results in CO_2 emissions, contributing to climate concerns. Dependency on alternative iron ore sources may be constrained by their availability and quality, affecting the stability of the production process.

Key features:

- Incorporating BFS into cement production is beneficial for a byproduct that might otherwise be disposed of in landfills, which will be useful during the reconstruction of Ukraine.
- By using BFS in cement production, the demand for natural resources such as limestone and clay, typically used as raw materials in cement, can be reduced.

- Incorporating BFS and other alternative materials can contribute to cost savings in cement production, potentially making the process more economically viable.
- The implementation of DRI technologies can offer several key advantages, like input efficiency (reducing the dependency on high-quality iron ore), long-term cost-effectiveness (over time, smelting costs become lower than in traditional blast furnace methods), reduced energy usage (might be relevant in the war-damaged regions where energy resources will remain to be scarce or expensive immediately after the end of the war).
- DRI facilities can be started up and shut down relatively quickly compared to traditional blast furnaces. This flexibility allows for better adaptability to market demand fluctuations and can contribute to a more agile and responsive metallurgical industry. Furthermore, DRI plants generally have lower infrastructure demands compared to traditional blast furnaces.
- Adopting DRI technology often involves collaboration with technologically advanced partners or suppliers. This can facilitate technology transfer, skill development, and knowledge enhancement within the domestic workforce, promoting long-term industrial growth.
- The implementation of DRI technologies can enable a developing economy to diversify its iron and steel products, potentially opening up EU markets under CBAM and attracting new foreign direct investment streams.

7. Summary of technology implementation possibilities

Under the current situation, the chances of implementing CCS technology in Ukraine seem low. The uncertainty regarding the political and policy scenarios significantly undermines the ability to conduct an investment feasibility study for two main reasons:

- Firstly, the war has significantly impacted the potential scope of CCS technology applications in Ukraine. Some of the key industries which were supposed to lead the CCS implementation have been significantly affected, which reduced their capacity to take the initiative in implementing such projects. Moreover, due to territorial losses and increased risks in certain regions, the implementation of some planned projects (such as CCS application in the oil and gas wells in the Dnipro-Donbas gas basin) has become physically impossible for now.
- Secondly, CCS projects have a low prioritisation level among key stakeholders due to the lower perceived impact on sectoral development in the context of prolonged war. High set-up costs of CCS technologies, combined with the significant level of associated risks, also impact implementation possibilities.

Nevertheless, due to the existence of the recovery and reconstruction prospects, several key technology sets can be outlined as most promising for the energy, metallurgy, and cement sectors under the current circumstances:

- For the energy sector, biogas production from biomass and methanol production with CO_2 usage can be considered as the two promising technologies in terms of the associated costs and emission reduction efficiencies. Furthermore, their implementation can improve the energy security for local Ukrainian communities by providing them with a local source of stable power generation opportunities and the society on a national level by establishing prospects for potential smart grid development.
- For the metallurgy sector, two promising technology sets include BFS application and DRI. Although DRI technology has numerous advantages, its cost-related disadvantages underscore the importance of careful consideration and strategic planning when introducing this technology in the context of a developing economy.
- The reviewed technologies in the cement industry can aid in making the reconstruction and development of unoccupied regions more sustainable in terms of short and long-term CO_2 emission reductions. However, due to the lack of a regulatory basis for their implementation, the businesses engaged in the industry without the provision of additional incentives are unlikely to prefer such technologies compared to the traditional ones for cost reasons.

Even though the current war-related challenges and low political prioritisation of CCS projects in Ukraine pose significant barriers to their development, there are still some promising prospects for the energy, metallurgy, and cement sectors, offering the potential for emission reduction, energy security, and sustainable development in the face of upcoming recovery and reconstruction efforts.

Chapter 2. CCS and CCU: current state and past experiences in Ukraine

1. Description of implemented and planned projects

There are currently no implemented or planned carbon storage projects in Ukraine. At the same time, several industries (ferrous metallurgy and gas production) are considering plans to implement CCS/CCU projects in the long run (the strategy of ArcelorMittal implies the consideration of CCS/CCU after 2030). In July 2021, one of the biggest steel producers, Metinvest, signed a memorandum of cooperation with the Austrian research centre K1-MET, which is focused on the decarbonisation of metallurgy and possesses strong expertise in CCS technologies. Cooperation was planned to be focused on implementing projects that ensure a reduction in carbon footprint; however, with the start of the full-scale invasion in 2022, implementation plans were put on hold.

In March 2021, the United Nations Economic Commission for Europe developed the Roadmap for Hydrogen Infrastructure in Ukraine, which sees the development of CCS technologies as an opportunity to reach carbon neutrality by producing hydrogen using carbon capture technologies.

Bellona's earlier research (2012-2013) regarding the development of CCS technologies in Ukraine defined the potential CO_2 storage regions in Ukraine. It also developed the model for CO_2 transportation from production facilities to potential storage capacities in the eastern part of Ukraine. On the governmental level, during the visit of the President of Ukraine to the US in August 2021[54], Ukraine established strategic dialogue in the sphere of Energy and Climate, and one of the points of cooperation is the CCS/CCU.

According to the Association of Gas Companies and the European Business Association, some companies are launching projects to study the profitability and affordability of CCS technologies. While these studies show high costs, carbon capture technologies could become cost-effective in the next 10-15 years due to effective energy modernisation, regulatory change, cheaper technologies, and other factors.

2. Legislation and regulation relevant for CCS deployment

CCS/CCU DEPLOYMENT REGULATION

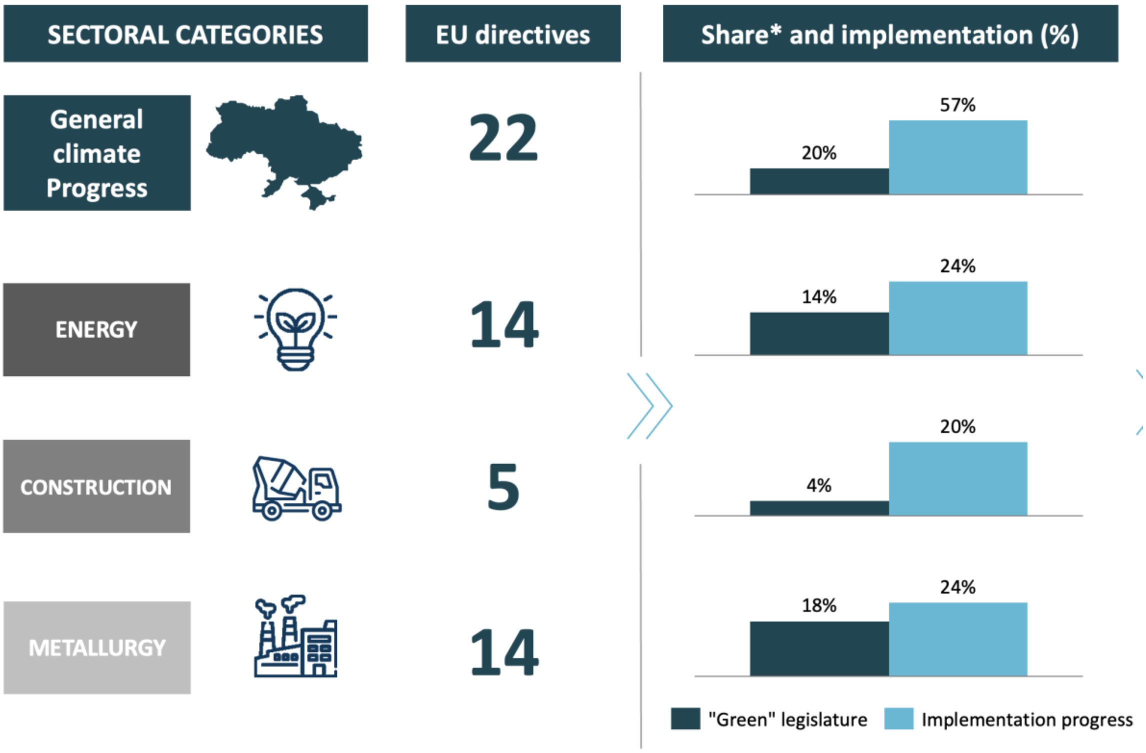
In 2019, the President's Decree emphasised the need for urgent action against climate change: the three most key documents in this field that remain relevant to this day are the Concept of Implementation of State Policy in Industrial Pollution, which aims to enhance institutional capacity and compliance with environmental legislation. The law on GHG emissions defines the legal and organisational principles of their monitoring, reporting and verification and paves the way for a national emissions trading system. The State Environmental Policy until 2030 focuses on five goals:

1. Formation of environmental values, sustainable consumption and production principles.
2. Ensuring the sustainable development of natural resources.
3. Integration of environmental policy into decision-making processes.
4. Reducing environmental risks.

[54] Office of the President of Ukraine, 2021

5. Improving the environmental management system.

FIGURE 27. ASSESSMENT OF THE POLICY READINESS ACROSS SECTORS, PROJECT TEAM CALCULATIONS



** considering the total number of all directives and regulations that need to be adopted as part of the EU integration processes*

As can be seen from the figure above, most of the EU policy integration aspects remain incomplete despite taking a significant share of the whole body of integrational legislature. Currently, the main tasks in legislation are developing draft laws on packaging, batteries and their waste, waste of electrical and electronic equipment, mining industry waste management, and developing draft laws on the use of pesticides and non-organic fertilisers. Also, within the framework of policies and legislative changes, it is crucial to liberalise energy exports and gas prices, make institutional investments into the national grid and power distribution, introduce the ETS system with the establishment of the Innovation Fund for the industry, which will be replenished with revenues from the CO_2 emissions trading system.

To date, there is no framework legislation on CCS, carbon trading, technological and geological qualities of carbon capture equipment, carbon well safety, etc. The Ministry of Environmental Protection and Natural Resources, after appropriate consultations with the State Service of Geology and Subsoil of Ukraine, concluded that it is necessary to introduce separate legislation that regulates the subjects of capture, storage, and disposal of carbon. According to the analytical note of the State Service of Geology and Subsoil of Ukraine, such regulation should be based on similar European regulations and features of the Ukrainian landscape (based on research of the Ukrainian Geological Institute).

It should be noted that Ukraine has now implemented some documents of international law that indirectly relate to the issue of CCS. For example, Directive 2006/32/EU, European Green Deal to establish an emissions monitoring and reporting system; Annexes XXVII, XXX, and XXXI of the Association Agreement and Conditions for the Status of a Candidate for Member of the EU where Ukraine committed to aligning its national legislation with the EU acquis on environmental protection, climate change, ozone layer protection, industrial pollution, and air quality). Although these documents do not determine the direct legal status of participants in the process and the CCS market, they form a conceptual framework that simplifies the further development of legislation.

LOW CARBON DEVELOPMENT STRATEGY OF UKRAINE UNTIL 2050

One of Ukraine's key strategic documents in reducing GHG emissions is the Low Carbon Development Strategy of Ukraine until 2050. The document covers several strategic measures to reduce carbon emissions and bring certain sectors of the economy to carbon neutrality. In the section on support for design and technological developments, the strategy includes "support for research, development, projects, and implementation of advanced demonstration projects". This also includes support for CCS/CCU technologies.

The document emphasises that the introduction of innovative technologies (in particular, smart grids, innovative nuclear energy technologies, technologies for the capture, storage, and reuse of carbon, industrial production and the use of hydrogen, and the latest agricultural technologies), in addition to policies and measures in the field of energy efficiency and renewable energy, will allow GHG emissions to be cut by 35 million tonnes of CO_2-eq annually in the period 2020-2050. In the National Economic Strategy until 2030, Ukraine announced its net zero target by 2060 in its revised Nationally Determined Contribution.

NATIONALLY DETERMINED CONTRIBUTION TO THE PARIS AGREEMENT

Another important medium-term strategic document – Nationally Determined Contribution of Ukraine to the Paris Agreement – notes the importance of CCS/CCU technologies. The document defines Ukraine's climate targets that the country plans to reach by 2030. The target is a reduction in emissions from the base year (1990). Ukraine has set an ambitious goal to reduce CO_2 emissions by 65% from 1990 levels. The document identifies the key measures that can support the transition to clean technologies. However, the document only identifies CCS/CCU technologies as potential tools and does not further assess the effects and cost of implementation.

NATIONAL EMISSION REDUCTION PLAN OF MAJOR POLLUTANTS FROM LARGE COMBUSTION PLANTS

The National Emission Reduction Plan implies the phase-out of coal power plants. The plan clearly defined the years when the block of a power station should be closed throughout 2018-2033. In 2021, the closure of Dniprovska CHPP and Khersonska CHPP was scheduled; however, due to the damages of other power generation sources during the winter of 2022, there are reasons to suggest that this plan might have been temporarily delayed. Such changes in the energy system require new investments to substitute the closed power generation with the new ones. In addition, the Ukrainian energy system is characterised by a deficit of balancing capacities. TPPs play a crucial role in ensuring the flexibility of the energy system as they can quickly increase the generation volume. Another problem is that due to the system imbalances caused by the war, the government might be forced to extend the operational terms of the closed plants and maintain the high share of operational combustion plants to compensate for potential losses of baseload power.

As a result, the National Emission Reduction Plan is currently under revision. It is expected to be updated based on the financial opportunities of Ukrainian energy companies and the need for new generation capacities.

TECHNICAL REGULATION OF THE NATURAL GAS IN THE TRANSMISSION SYSTEM

The new technical regulation of the natural gas in the gas transmission system implies that the concentration of CO_2 in the gas transmission system must not exceed 2.5% after 2025, thus raising a significant issue for national gas mining companies that expect to supply at least 6 billion cubic meters of gas that do not meet the criteria of the CO_2 share. The regulation is introduced as European traders require such technical parameters of gas, and the transit contract with the EU possesses the same parameter. Such a challenge drives mining companies to consider various options for CCS/CCU.

CCS IN STRATEGIES OF SOES (NAFTOGAZ)

The inclusion of CCS technologies in some SOE strategies is worth mentioning. The key one is the strategy of the Naftogaz group of companies (the group includes the production, transportation, and sale of natural gas and has a monopoly in the gas production market of Ukraine) released in 2021. Naftogaz is the only SOE considering implementing CCS technologies in the future. The other SOEs do not have long-term strategic planning with a horizon exceeding 5-7 years.

The company's strategy in the environmental safety section includes using CCS technologies. As the company plans to achieve carbon neutrality by 2040, and gas production and purification technologies provide for large volumes of CO_2, the use of CCS technologies is indeed an unavoidable option in the company's toolset in the long run.

UKRAINE'S RECOVERY PLAN

No official Recovery Plan has been approved so far. The preliminary document developed from the Ukrainian side in 2022 offers a comprehensive approach to the post-war reconstruction of Ukraine and is designed for ten years[55]. The estimated budget equals 750 billion USD. The plan is divided into two stages: most reconstruction projects are planned to be launched during the first stage (from 2023 to 2025) and finalised during the second stage (from 2025 to 2032), as well as supplemented with further development initiatives.

Overall, as can be seen from the figure below, the national plan consists of 17 programs aimed at different sectors and areas. Three of them can potentially include programs that utilise CCS/CCU technologies:

- Program 5) "Clean and protected environment".
- Program 6) "Energy independence and the green deal".
- Program 13) "Regional infrastructure and housing". Restoration and modernisation of housing and infrastructure are the most expensive programmes, and they will require 150-250 billion USD. At the same time, the energy independence and decarbonisation program will require 130 billion USD.

FIGURE 28. SUMMARY OVERVIEW OF UKRAINE'S PRELIMINARY RECOVERY PLAN, PROJECT TEAM CALCULATIONS

55 The Analysis of Carbon Dioxide in Natural Gas, Fuller

Noteworthy, the share of projects which can potentially be included in CCS/CCU-related initiatives is relatively high: the sheer number amounts to 210 projects: 45% of those included in Program 5), 23% for Program 6) and 17% for Program 13). The total approximate volume of investments needed to finance the planned green projects amounts to 400 billion USD.

The supporting materials for the preliminary plan offer a number of measures to reduce carbon footprint. In particular, residential, social, and educational infrastructure reconstruction and settlements at all stages must comply with energy efficiency standards. The restoration of critical infrastructure and enterprises must be carried out considering the possibilities of decarbonisation (however, the Plan does not directly mention the development of CCS/CCU infrastructure) and the future abandonment of fossil fuels. Also, most of the provided materials exclude the possibility of industrial facility reconstruction that relies on fossil fuels with a significant period of operation[56].

In addition to Ukraine's Recovery Plan, the EU has created the Ukraine facility – the 50 billion EUR instrument consisting of three key pillars:

1. Ukraine Investment Framework designed to attract and mobilise public and private investments.
2. Financial support in the form of grants and loans to the State.
3. Technical assistance and other supporting measures, including mobilisation of expertise on reforms, support to municipalities, etc.), which is expected to provide financing for Ukrainian reconstruction projects up to 2027[57].

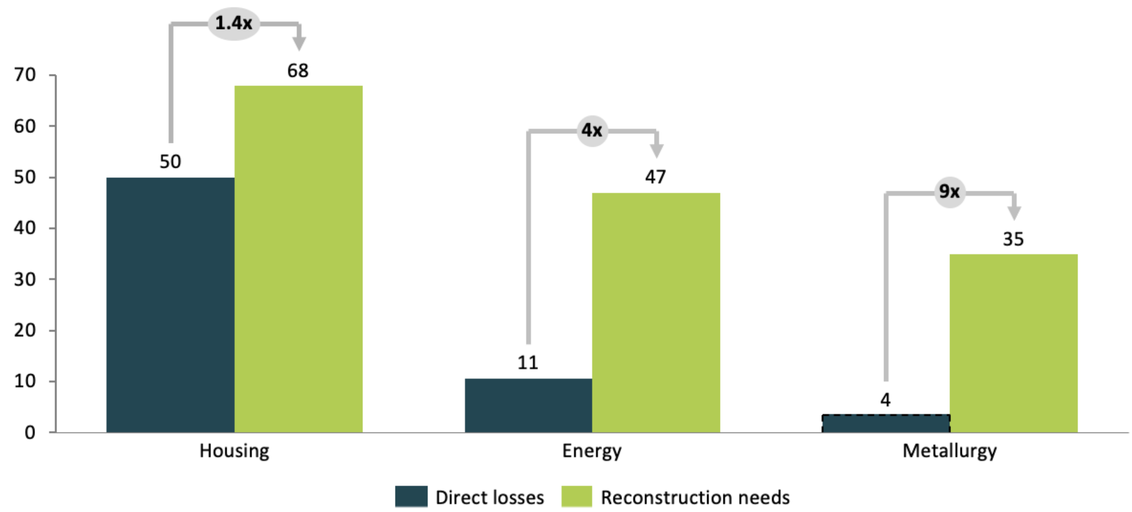
As of October 2023, the detailed structure of finance distribution is still being developed from the Ukrainian side – for this reason, the potential scope of environment-related projects remains unknown.

3. Sectoral investment effect on the recovery

Overall, the recovery within the three previously analysed sectors will require significant volumes of investments. The general existing recovery estimates suggest that the volume of necessary investments will be substantial for the housing, metallurgy and energy sectors.

[56] Ukraine Recovery Plan materials, Ukraine Recovery Conference, 2022
[57] A new Ukraine Facility, European Commission, 2023

FIGURE 29. DIRECT LOSSES VS RECONSTRUCTION NEEDS IN TERMS OF THREE KEY INDUSTRIES, 2022-2023, BILLION USD, PROJECT TEAM CALCULATIONS[58]



As can be seen from the figure above, for all three outlined sectors, the reconstruction needs significantly exceed the estimated direct losses, which can be explained by the higher costs of new technologies and materials used for reconstruction purposes.

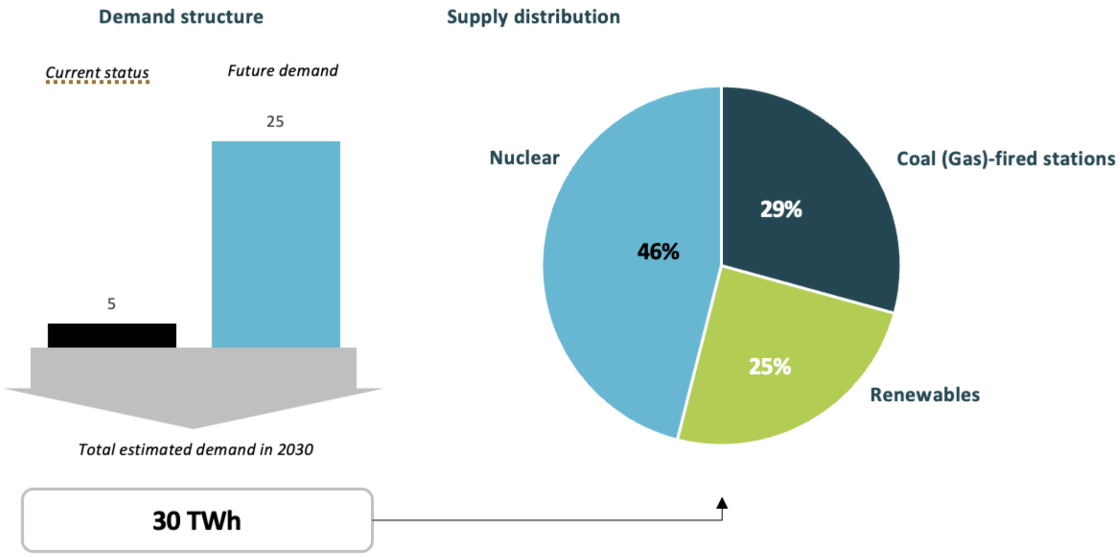
Since the recovery needs include both sustainable and non-sustainable sets of technologies, there is a sense of taking a deep dive into the precise needs of each of the aforementioned industries to analyse the structure of the required demand for investments.

3.1. Energy sector

For the energy industry, the research demonstrates insignificant changes in the energy supply structure: the majority of power will still be generated from NPPs, while the rest will be generated by a combination of coal and natural gas CHPPs and RES (WPPs, SPPs, and Biogas CHPPs).

[58] Based on Kyiv School of Economics damage assessment reports, 2023

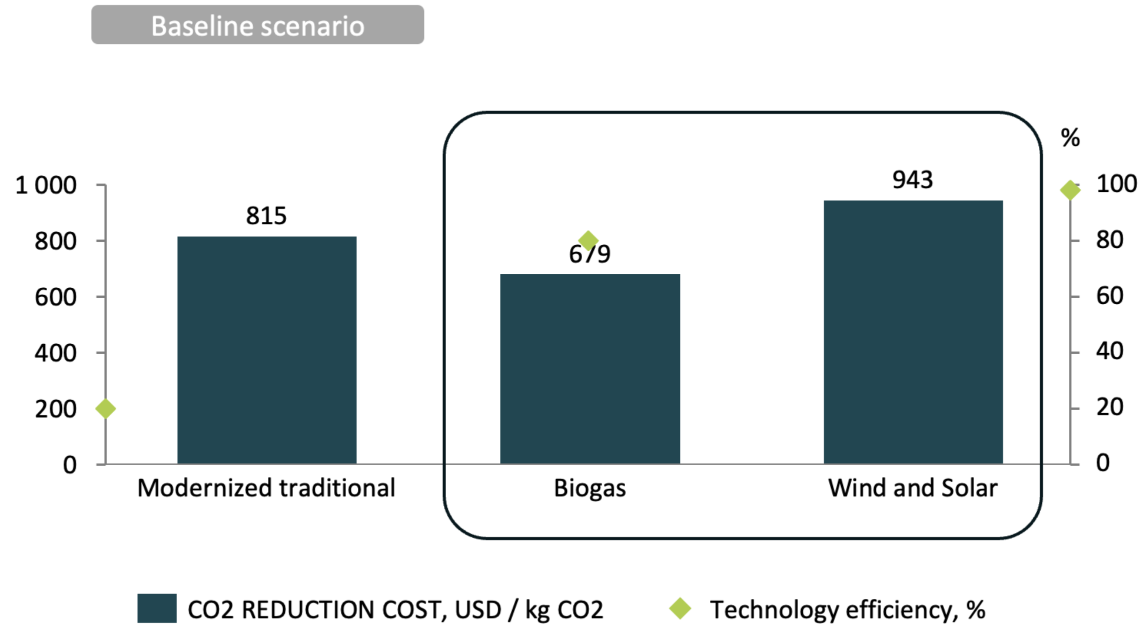
FIGURE 30. DEMAND STRUCTURE AND SUPPLY DISTRIBUTION IN THE ENERGY SECTOR, PROJECT TEAM CALCULATIONS



The demand structure, however, will change drastically. Based on the targeted GDP growth assumptions, the forecasted change is estimated as a five-time increase (up to the year 2030) due to the rise in electricity exports and domestic consumption (both for production and consumption purposes).

In terms of efficiency, the industry is expected to progress to the point where CO_2 emissions volumes for the Traditional technologies will be around 91 million tonnes per annum while applying CCS technologies can potentially reduce it by ~30%.

FIGURE 31. COMPARISON OF REDUCTION COST FOR TECHNOLOGIES IN THE ENERGY SECTOR, PROJECT TEAM CALCULATIONS

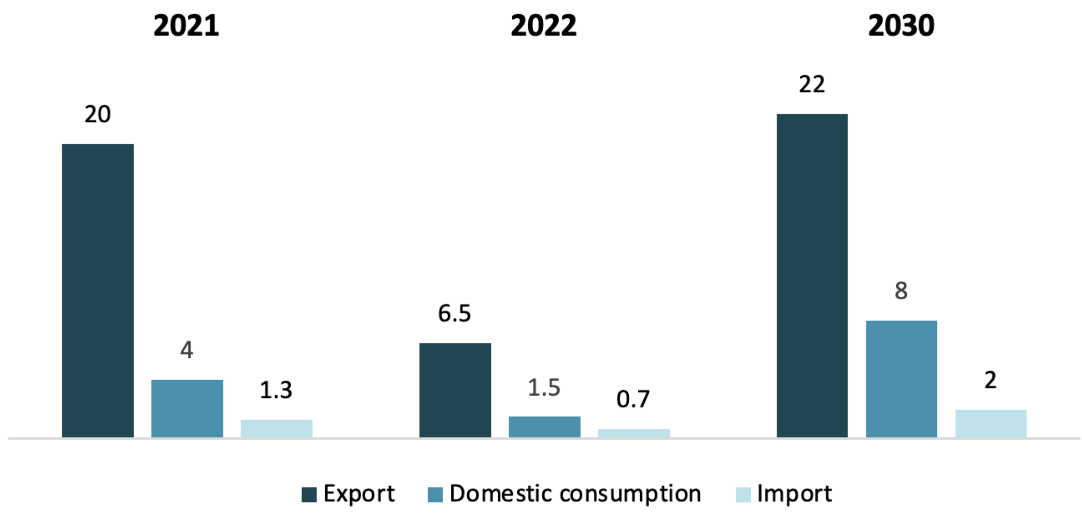


Within the structure of traditional technologies, the reconstruction and modernisation of the traditional power generation sources (coal and natural gas combustion power plants) require the largest volumes of investments (~ 8 billion USD) – which is, nevertheless, insignificantly higher than the costs of construction for new, more sustainable biogas technologies (+12%) and only slightly lower than the costs of introducing new solar and WPPs and SPPs (+33%).

3.2. Metallurgy sector

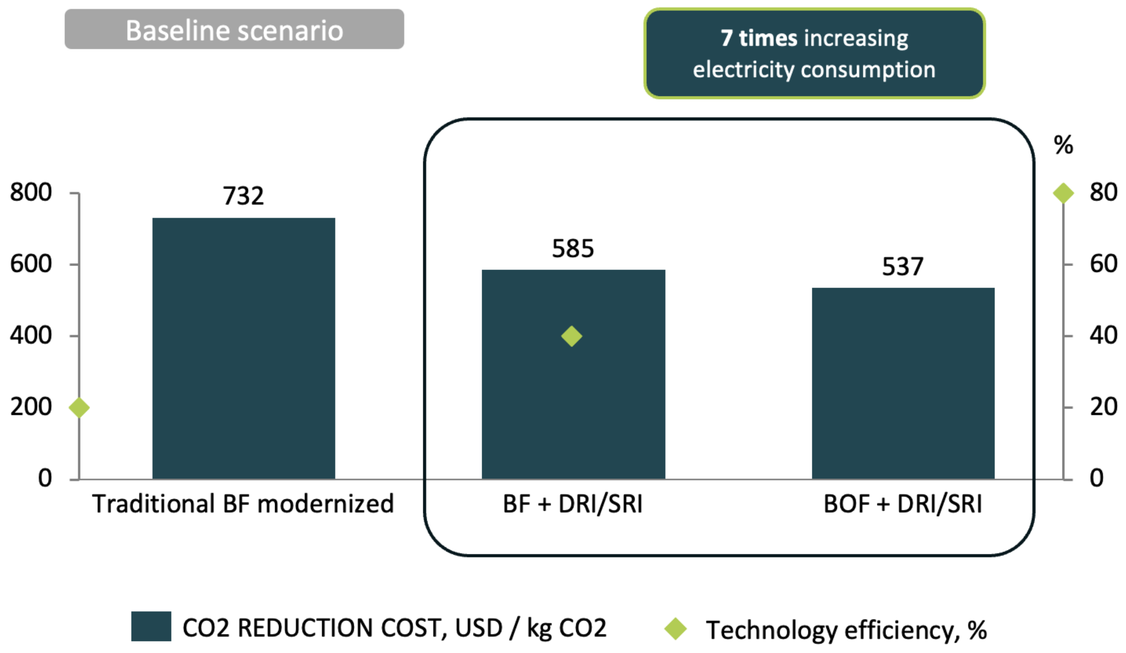
In the case of the metallurgy sector, the forecasted changes in future supply volumes are significant. By 2030, the sector is expected to produce 32 million tonnes of steel annually: the dynamics of changes in expected production volumes based on the key driving factors are demonstrated in the figure below.

FIGURE 32. STRUCTURE OF CONSUMPTION IN THE METALLURGY SECTOR, PROJECT TEAM CALCULATIONS



Overall, by 2030, the demand for steel products is expected to grow by 73% compared to the 2022 levels. The export-to-domestic consumption ratio, estimated based on the combination of imports + domestic production, is expected to change from one-fifth to roughly two-fifths. The key driving force behind such an increase would be the rise in foreign demand unrestricted by CBAM application under the conditions of timely ETS introduction in Ukraine.

FIGURE 33. COMPARISON OF CO_2 REDUCTION COSTS OF EACH TECHNOLOGY IN THE METALLURGY INDUSTRY, PROJECT TEAM CALCULATIONS



In the case of the particular technology application, as seen from the figure above, the sector's production growth can be driven by the upgrade and utilisation of existing production capacities with available CCS technologies. Regarding emissions reduction, EAFs are the most efficient, although their application is limited to scrap metal smelting (damaged equipment and rubble from war damages).

With regards to the regular iron ore processing and smelting, Blast furnace modernisation with the help of DRI technologies based on MIDREX and COREX processes can potentially be more efficient compared to the reconstruction of plants on the occupied territories within the scopes of traditional technologies.

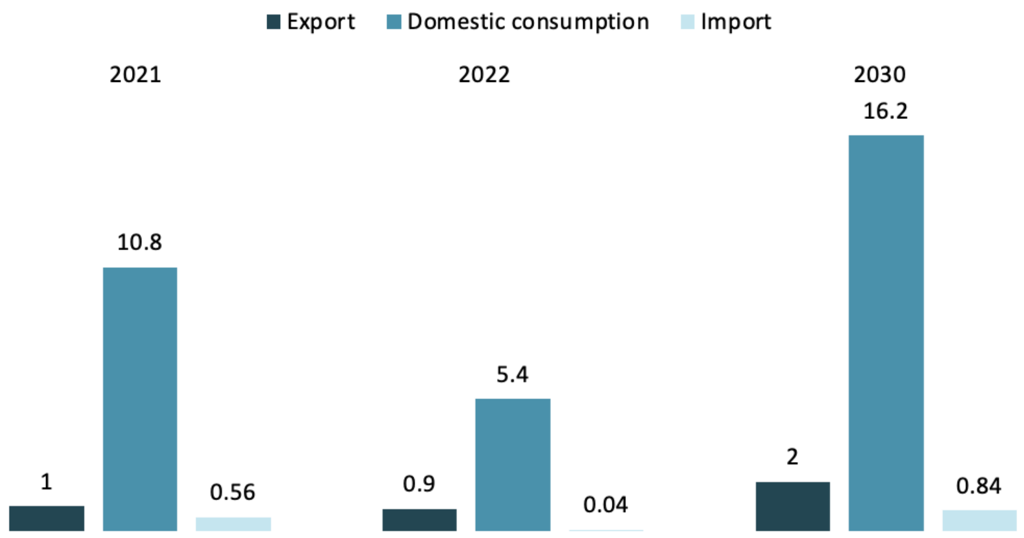
As research results demonstrated, the application of CCS technologies as a way to reduce emissions from the existing blast furnaces appears to be most expensive when applied for the sake of total industry reconstruction (14 billion USD), more costly than the regular blast furnace modernisation (based on DRI technologies).

Nevertheless, the introduction of CCS, in addition to blast furnace modernisation, will be much more efficient compared to the application of traditional smelting procedures with CCS technologies (DRI/SRI) as an additional component for the industry's operations, as the reduction in CO_2 emissions will be 60% lower than the volume expected in case of the regular CCS application and 66% lower compared to the baseline scenario (no transformation).

3.3. Cement sector

In the case of the cement sector, the forecasted changes suggest slow growth in the general future demand volumes. Despite the generally significant reconstruction and recovery needs in terms of roads and housing, the long-term growth for the sector suggests the total growth in production volumes from 7 million tonnes to 16 million tonnes per year in 2030. Domestic consumption is projected to remain the key growth driver for the sector, as seen in the figure below.

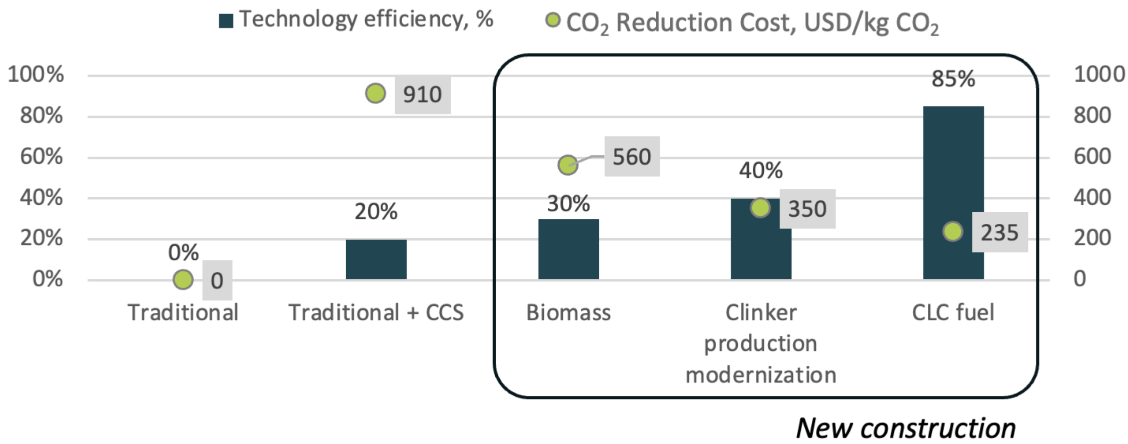
FIGURE 34. DEMAND STRUCTURE AND SUPPLY DISTRIBUTION IN THE CEMENT SECTOR, PROJECT TEAM CALCULATIONS



The total production volume for cement is expected to grow from about 11 billion tonnes to almost 17 billion tonnes per annum in 2030. The export share is expected to grow slightly (from 9% to 12%) due to the UA-EU integration processes and increased demand for infrastructure projects in the neighbouring European countries.

In terms of the selected technology efficiency, however, those few technologies available for sector modernisation cannot demonstrate high emissions reduction performance. In the case of the traditional CCS application for the purpose of concrete production, the CO_2 reduction costs per kg of emissions soar dramatically: the most cost-effective way to reduce CO_2 emissions appears to be confined to clinker production modernisation, which can allow significant emissions reduction (-40%) with a relatively low application cost (USD 350 per kg), which is 37% cheaper than the closest expensive option (biofuel application). CLC presents a lucrative option for the purpose of cement preparation as it demonstrates the highest emission reduction efficiency (85%) but remains limited to wide-scale application within the sector.

FIGURE 35. COMPARISON OF CO_2 REDUCTION COSTS OF EACH TECHNOLOGY IN THE CEMENT INDUSTRY, PROJECT TEAM CALCULATIONS



In addition to the cons mentioned before, CLC fuel production is also expected to be the most expensive for the entire industry (2.6 billion USD) while being the most efficient in emission reduction (85% lower than with the application of traditional technologies). At the same time, the biomass application for cement production can be potentially useful in the mass-scale recovery processes, which require a high share of concrete utilisation.

With regard to the total required industry investments, needs are similar: CLC fuel production technology requires the most significant investment volumes, with a significant CO_2 reduction effect (down to the level of 2.2 million tonnes). Clinker production modernisation provides the second most significant CO_2 reduction volumes (7.7 million tonnes).

Chapter 3. Ukraine's outlook for CCS and CCU

1. Summary of stakeholder engagement

Most of the information about the interest of stakeholders had been collected before the war. After the start of the full-scale invasion, not all of the stakeholders were actively engaged. According to responsibility, the interest in and potential impact on the stakeholder sector can be divided into three key categories:

- **Government bodies.** Responsible for introducing effective regulation, creating incentives for the development of the industry, and balancing the positions of the public and business. The group includes the Ministry of Environmental Protection and Natural Resources, State Service of Geology and Subsoil of Ukraine (under the Ministry of Environmental Protection and Natural Resources).
- **Business representatives**. Form demand for the introduction of CCS technologies, develop industry strategies, studies and incorporate technologies, and attract funding (including national and international). The group includes GMK Center, the Union of Chemists of Ukraine, Ukrcement, and the Association of Gas Production Companies of Ukraine).
- **Civil society and activists.** Form environmental requirements for business and government, as well as monitor the safety of technology implementation. The group includes the non-governmental organisation Ecodiya.
- **Academic and experts.** Provide expertise on the potential technology solution that may be applied. The group includes Naftogazbudinformatyka and Ivano-Frankivsk National Technical University on Oil & Gas.

2. CCS and CCU: public acceptance in Ukraine

The interest in CCS technologies has shown robust growth in 2020 and 2021 since the Ukrainian media started covering those topics. Several companies (Metinvest, DTEK, Naftogaz) publicly expressed interest in studying CCS/CCU technologies and their development in Ukraine. In addition, the government of Ukraine established strategic dialogue with the US on cooperation in the energy sector and environmental issues, also mentioning the CCS/CCU technologies as a point of collaboration.

The most significant attention of the media has been paid to the coverage of projects and initiatives worldwide and showing the CCS project as a potential solution in decarbonisation. The overall tone of the articles can be considered neutral, with scepticism related to the high price of the technologies and the low efficiency of their application.

The most discussed document has been the report of the International Energy Agency, where CCS technologies are considered an effective solution to ensure carbon neutrality.

During the interview, the State Service of Geology and Mineral Resources of Ukraine are ready to publicly express support for the development of CCS/CCU technologies. The Service sees clear opportunities for the development of CO_2 storage and claims that providing tax incentives to industrial producers would stimulate the capture and storage of CO_2.

On the other hand, there is opposition from environmental experts who strongly support a much cheaper solution for Ukraine. A reputable non-governmental organisation on environmental policy, Ecodiya, has expressed a public position criticising the introduction of CCS/CCU projects in Ukraine.

The association of gas mining companies, meanwhile, has publicly stated that the technologies of CCS/CCU are the only option for gas production companies as they need to align the quality of the gas produced with the technical regulation, which from 2025 requires that gas does not exceed 2.5% containment of CO_2.

Ecodiya stresses renewable energy and energy efficiency as the top priorities for Ukrainian decarbonisation. The key argument is that Ukraine has considerable potential for decarbonisation via energy efficiency measures and a significant increase in renewable energy, which is cheaper than CCS/CCU technologies.

The primary reason is that carbon storage does not stimulate industrial producers to reduce fossil fuel consumption, "The key threat in the use of carbon storage technologies is that they do not stimulate the abolition of the usage of fossil fuels, and as a result, we cannot consider such measures as a sustainable solution."

In addition, Ecodiya claims that the carbon capture process quite often requires a significant amount of water (CO_2 capture, in general, requires additional water for cooling and make-up), and Ukraine struggles with sufficient amounts of water, holding 32nd place among 40 European countries regarding water supply per person.

The final argument is that there is a significant risk of CO_2 leakage, which can have a negative impact on the environment.

3. Stakeholder positions on CCS and CCU

The majority of the stakeholder positions have been collected before the Russian full-scale invasion of Ukraine, which leaves certain reservations regarding their relevance to this date. Still, there are reasons to consider their positions because most of the stakeholders detailed in the table below have been preoccupied with more urgent issues of war impact mitigation.

TABLE 2. POSITIONS OF STAKEHOLDERS IN UKRAINE ON CCS AND CCU

Stakeholder	Description	Position
State Service of Geology and Subsoil of Ukraine	Governmental body. The State Service operates the access to mineral resources in Ukraine. The service conducts auctions and monitors and controls mining in Ukraine.	The State Service of Geology and Subsoil of Ukraine supports the idea of storing carbon in depleted oil and gas wells. In addition, the organisation supports the concept of providing fiscal incentives to enterprises for CO_2 emissions if they store carbon in geological formations (or use it to intensify oil production from wells). At the same time, the organisation emphasises the problem of financing these facilities and the need for scientific and technological cooperation with European countries to develop the technology in Ukraine rapidly. The Service suggests the need to establish proper regulation for the CCS and underlines the importance of introducing the ETS or increasing the carbon tax. Clear government support and long-term guarantees would help to implement CCU/CCS technologies. The Service announced an interest in creating an official working group on the development of CCS technologies.
Ministry of Environmental Protection and Natural Resources	Governmental body.	The Ministry also supports the idea of carbon storage in highly mineralised formations (to minimise the risk of leakage). The problem of funding and the need for international cooperation for the implementation of effective pilot projects are also noted.

GMK Center	Think tank with a focus on metallurgy.	Representatives of the association noted that carbon storage projects are interesting but not a priority. It is noted that even with the accelerated pace of energy modernisation, CCS/CCU technologies will only become interesting for the industry from a 10-20-year perspective.
Union of Chemists of Ukraine	Business association. The leading association that represents the biggest chemical producers in Ukraine.	The Union emphasises the long-term interest in CO_2 storage and use technologies. Now, such innovations are not profitable from the point of view of the EUR invested in reducing emissions. In this sense, energy modernisation will be at least 3-4 times cheaper.
Ukrcement	Business association. The leading association that represents the majority of building material producers in Ukraine.	Ukrcement considers CCU technologies as an option from a long-term perspective, as they are currently able to reduce their CO_2 emissions by reducing the amount of coal used and by using RDF (Refused Derived Fuel), thus reducing the amount of CO_2 emissions from coal burnt and increasing the reuse of processed wastes that would otherwise be stored and emit CO_2. Ukrcement does not consider CCS to be the best solution to reduce the amount of CO_2 emissions. In contrast, they see potential in using the CO_2 for purposes such as methanol production. In addition, Ukrcement considers CCS to be an initiative that does not stimulate emissions reduction within the production process.
Association of Gas Production Companies of Ukraine	Business association. The leading association of gas mining companies covers over 92% of gas mined in Ukraine. The association is actively looking at opportunities to reduce CO_2 emissions and store CO_2 in exhausted mines.	Representatives of the gas industry are interested in carbon storage technologies. This is prompted by the new technical regulation on gas quality within the gas transmission system, which forces companies to clean the natural gas from CO_2 at the entrance to the gas transmission system and the proximity to potential carbon storage wells. At the same time, the industry is waiting for government decisions on the regulation and financing of the sector and is wary of possible negative perceptions by citizens.
Ecodiya	Activists, think tank. Ecodiya is one of the leading environmental think tanks in Ukraine.	The non-governmental environmental organisation Ecodiya made a statement about the negative attitude towards prioritising the topic of CCS. According to the organisation, the state is not able to guarantee the safety of such wells. In addition, the cost of the technology and additional emissions during the implementation process raise doubts about the long-term potential of CCS technologies.
Naftogaz	Public, government-owned company. The leading gas mining company, which operates the largest number of mines, is actively seeking opportunities to mine shale gas in the Black Sea and is the biggest holder	Naftogaz sees a big opportunity in CCS as a business as the company is the biggest operator of abandoned gas mines suitable for storing gas. According to Naftogaz, technologies for capturing CO_2 from the atmosphere provide a great opportunity for the oil and gas industry in the context of decarbonisation of production. The company sees the promising use of wells, particularly oil wells, which can be used to inject captured CO_2. Also, according to the company valuation, this process can increase oil production.

	of the exhausted or closed mines in Ukraine.	
DTEK	Private. The leading energy sector company that covers gas, oil and coal mining, power generation, electricity infrastructure, and distribution.	DTEK is the most innovative energy company in Ukraine. The company announced climate ambitions to reach carbon neutrality by 2050. They were the first to introduce battery storage capacities, and now they are leading the development process of hydrogen technologies in Ukraine. In addition, they consider CCS/CCU technologies as a potential solution to reach carbon neutrality. The introduction of the ETS or increase of the carbon tax, regulation of CO_2 storage, clear government support, and long-term guarantees would help implement the CCU/CCS technologies. The company sees a perspective in the construction of bioethanol plants – production with high added value and hundreds of highly qualified jobs. These processing facilities also produce the high-protein feed additive DDGS and liquefied CO_2. However, due to military operations on the territory of Ukraine in 2022, this initiative is forced to move in time.
Metinvest	Private. The leading vertically integrated holding focused on metal and ore mining and metallurgy production. The vast majority of Metinvest products are exported to the EU.	Metinvest is considering various options to reduce CO_2 emissions, as they must export products to the EU, and there is a serious threat of getting under the CBAM. The key short-term measures that Metinvest will implement are focused on energy efficiency measures. On the other hand, from a long-term perspective, Metinvest is searching for innovative solutions that can be scaled to industrial use, as most innovative solutions are currently pilot projects. The most prospective are hydrogen technologies that will help reduce burnt fuel emissions. The company expresses strong interest in CCU/CCS technologies as well. However, as a regulatory framework is still not established and the ETS has not been introduced, the company is considering implementing such technologies after 2030. In 2021, the company planned to reduce CO_2 emissions using hydrogen technologies. The company planned to open a technological platform for this in Mariupol, but the start of hostilities in early 2022 prevented the implementation of the project.
Naftogazbudinformatyka	A leading organisation providing technical services to gas production and gas infrastructure companies. The organisation is currently assessing the gas pipelines for hydrogen transportation.	Naftogazbudinformatyka currently sees significant potential in the implementation of new technologies. The primary focus is now on hydrogen, and the organisation claims there is a need to develop infrastructure to transport hydrogen locally (from the internal market). The organisation sees potential in producing green hydrogen using renewable energy generation. The organisation points out that the market of CO_2 is relatively small and that storage of the captured CO_2 is required. The organisation also mentioned that the high level of CO_2 in the gas system leads to the erosion of gas tubes. The organisation expresses a strong interest in

		studying the transportation opportunities of CO_2 to ensure the implementation of CCS/CCU technologies.
Ivano-Frankivsk National Technical University on Oil & Gas	A leading educational institution specifically focusing on the gas production and gas transportation industry. The university has a strong research department as well as high-quality educational programmes.	The university sees significant potential for CCS development in Ukraine as Ukraine will have to reach carbon neutrality, given the fact that Ukraine has many big polluters such as power generation, metallurgy, fertiliser producers and the cement industry. The captured gas should be utilised and stored in depleted gas fields. The university claims that there is currently no regulation on the usage of CCS technologies, and there are no fiscal incentives for the companies to capture and store CO_2.

4. In-depth stakeholder perceptions of the CCU and CCS landscape

OVERALL PROSPECTS FOR CCU/CCS IN UKRAINE

Before the outbreak of the war, most of the experts interviewed were interested in CCS/CCU technologies, but note that the technologies are only interesting in the long run. The lack of a description of specific projects for these technologies, even in long-term strategic documents (for example, companies' plans for carbon neutrality until 2040), suggests a cautious attitude and observation of the dynamics of such projects in other countries.

Sectors are divided in their attitudes towards the following technologies. While some note strategic prospects, others are sceptical and see the technology as problematic due to potential public perception and regulation difficulties. Most sectors consider CCS technologies, while CCU is only considered in certain types of production (in particular, the chemical industry).

The accounting of emissions for environmental tax is much lower than in EU countries. Few companies in Ukraine have calculated their carbon footprint and have never really focused on the climate agenda. Ukraine plans to introduce the ETS in around 2024, but currently, there is no clear vision of how the system will work and where finances generated from ETS will be directed.

The destruction caused by the war and uncertainty about its duration also hinders the development of new large-scale infrastructure projects. The conducted analysis shows that the most favourable conditions for deploying the CCU/CCS technology are in the northeastern region of Ukraine. The area is now close to the front line, making this region unattractive for investments.

Enterprises that are the biggest polluters suffered severe damage, and some are not subject to restoration. In general, enterprises are focused on ensuring their operation in war conditions and are forced to postpone development projects for an uncertain period.

THE ROLE OF CCU/CCS IN SECTOR INTEGRATION

CCS/CCU technologies look promising for production clusters (due to the strongly developed Ukrainian gas transportation system and potential CO_2 storage sites).

It is essential to note the potential for developing industrial parks, which is included in the current National Economic Strategy of Ukraine 2030. CCS/CCU infrastructure can be an additional bonus for members of industrial parks.

AWARENESS OF EU POLICY AND FINANCIAL INSTRUMENTS FOR CCU/CCS

Even though Ukraine is not a member of the EU, most industry representatives focus on the EU regulation of CCS/CCU technologies. The lack of even initial regulation of the sector in Ukraine encourages businesses to consider European practices as most appropriate in the medium and long term.

At the same time, Ukraine has limited access to EU funding instruments in the field of CCS. The tools available for Ukraine now and in the next five years are focused on carbon and energy modernisation in production. On average, investments in such modernisation in Ukraine are 4-5 times more efficient than in CCS/CCU technology.

PERCEIVED DEPLOYMENT BARRIERS AND RISKS

Despite significant issues in project profitability compared to energy efficiency measures, the most considerable risk remains the lack of appropriate regulation in this field. Companies do not want to take the risk of even planning such projects before understanding the rules and potential limitations of the system. On the other hand, large companies are ready to publicly support CCS/CCU technologies and address the need for regulation and incentives to the government.

5. Stakeholder recommendations for CCU/CCS

REGULATION

The lack of framework legislation in the field of carbon management (as well as transparent regulation of trade in industrial waste) creates uncertainty in the market. It is necessary to develop framework legislation to regulate the field and clear rules (technical, environmental, social) for the creation, maintenance, and storage of potential wells. In addition, clear and transparent regulation of carbon trading is needed. Ensuring that CCS/CCU technologies lead to the exemption of environmental tax on the amount of CO_2 captured and utilised/stored or regulated within the ETS would create a stimulus for developing such technologies.

Business representatives believe that the “default solution” may be the implementation of European directives, which can be further finalised in terms of the Ukrainian market.

TECHNOLOGY

Technologies for injecting carbon into used natural gas wells, aquifers and coal seams are absent and costly for Ukraine. Representatives of the companies emphasise the need for cooperation with the EU and other countries (for example, Norway and the USA) to apply such technologies effectively in Ukraine.

Carbon capture technology is also an important issue. While in some areas (natural gas production and the chemical industry), they are simpler, in others (ferrous metallurgy), they require significant costs and additional development.

INFRASTRUCTURE

All the company representatives interviewed note that the issue of transport infrastructure and carbon storage infrastructure should be an exclusively governmental issue. Ukraine has significant potential to use the existing gas transportation infrastructure (pipelines, gas storage facilities, distribution points) with moderate investments.

MARKET

First, it is necessary to legalise carbon trading and regulate such relations. In addition, market incentives need to be considered for companies that use (recycle) purchased carbon.

FINANCIAL FRAMEWORKS

Companies expect to receive certain preferences through fiscal and other government measures. At the same time, the main stimulus for industry will be public investment in CO_2 transportation and storage infrastructure. Grants or other financial incentives are expected to establish carbon capture installations in the production process.

Other financial incentives may include easing environmental taxes for companies implementing next-generation carbon technologies (including CCS/CCU technologies).

INTER-SECTORAL AND REGIONAL COLLABORATION

Gas companies point to the potential for cooperation within the sector. The joint use of infrastructure due to regional and technological proximity will help reduce the cost of individual projects (however, it should be noted that in Ukraine, the natural gas industry is concentrated within one large and several medium-sized companies).

In the long run, the chemical industry may use CO_2 to produce fuels, polymers, or raw materials for certain chemical products. However, now the sector is not ready to use even its own captured carbon emissions (due to the high price of capturing technologies).

There is potential for cooperation with the agricultural sector, which is growing rapidly in Ukraine. There are technologies for the use of CO_2 as fertiliser in greenhouses (the CO_2 is captured from the air and injected into the greenhouse to stimulate the productivity of fruits and vegetables).

There is potential for connection to new industrial parks' CO_2 capture and transport infrastructure. This will reduce the cost of transportation and attract more medium-sized enterprises.

SOCIAL ASPECTS

Some business representatives point to the risks of negative public perceptions of technology. This risk can be crucial for the gas industry, where most of the market is held by an SOE.

Environmental organisations and activists are sceptical of CCS technologies and pessimistic about introducing such technologies into existing strategies for developing a carbon-free economy.