UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

Rebuilding Ukraine with a Resilient, Carbon-Neutral Energy System

UNECE

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Disclaimer
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LIST OF ABBREVIATIONS

CBAM	EU Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCSU	Carbon Capture, Storage and Use
CHP	Cogeneration Plant
CN	Carbon Neutrality scenario
COP	UNFCCC Conference of the Parties
DAC	Direct Air Capture (technologies)
DSM	Demand-Side Management
DSO	Distribution System Operators
EBRD	European Bank for Reconstruction and Development
EBIDTA	Earnings before interest, taxes, depreciation and amortization
ENTSO-E	European Network of Transmission System Operators for Electricity
ESU	Energy Strategy of Ukraine by 2035
ETS	Emission Trading Scheme
EU	European Union
EUEA	European-Ukrainian Energy Agency
EV	Electric Vehicle
FC	Fuel Cell
FEC	Final Energy Consumption
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GVA	Gross Value Added
HPP	Hydro Power Plant
IAEA	International Atomic Energy Agency
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEF	Institute for Economics and Forecasting (Ukraine)
IRE	Institute of Renewable Energy (Ukraine)
IRENA	International Renewable Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial processes and product use
KSE	Kyiv School of Economics
LPG	Liquefied Petroleum Gas
LULUCF	Land Use, Land Use Change and Forestry
MRV	Monitoring, Reporting and Verification
NACE	Nomenclature of Economic Activities (EU statistical classifier)
NASU	National Academy of Sciences of Ukraine

NDC2	Updated Nationally Determined Contribution
NEEAP	National Energy Efficiency Action Plan
NMM	Non-Metallic Minerals (Industrial sub-sector)
NPP	Nuclear Power Plant
OECD	Organisation for Economic Co-operation and Development
PPA	Power Purchase Agreement
RDF	Refuse-Derived Fuel
RE	Renewable Energy
REF	Reference Scenario
RPI	Real Personal Income
SIDA	Swedish International Development Cooperation Agency
SMR	Small Modular (nuclear) Reactors
SOE	State Owned Enterprise
TIMES	The Integrated MARKAL-EFOM System (generator of energy system models)
TPES	Total Primary Energy Supply
TPP	Thermal Power Plant
TSO	Transmission System Operator
UAH	Ukrainian Hryvnia (currency)
UASA	Ukrainian Association of Solar Energy
UARE	Ukrainian Association of Renewable Energy
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
UWEA	Ukrainian Wind Energy Association
VAT	Value-Added Tax
ZNPP	Zaporizhzhya Nuclear Power Plant

EXECUTIVE SUMMARY

This study, prepared by UNECE experts, builds upon UNECE's work on Building Resilient Energy Systems and utilizes the UNECE Carbon Neutrality Toolkit.

The analysis presented here focuses on a carbon-neutral scenario for the post-war restoration of Ukraine's energy system. The findings aim to serve as a valuable source and tool for future horizon scanning efforts and broader foresight processes to support policymaking. The objective is to assist the Ukrainian government in exploring different pathways and rebuilding its energy system based on the concept of carbon neutrality.

Ukraine continues to heavily rely on fossil fuels, accounting for 70% of its Total Primary Energy Supply (TPES) in 2020. The Russian invasion of Ukraine had a significant impact on the energy sector, resulting in a 43% drop in energy demand in 2022 compared to 2013.

FIGURE 1

Total primary energy supply by energy source, million tonnes of oil equivalent (mtoe), Ukraine 2000-2020

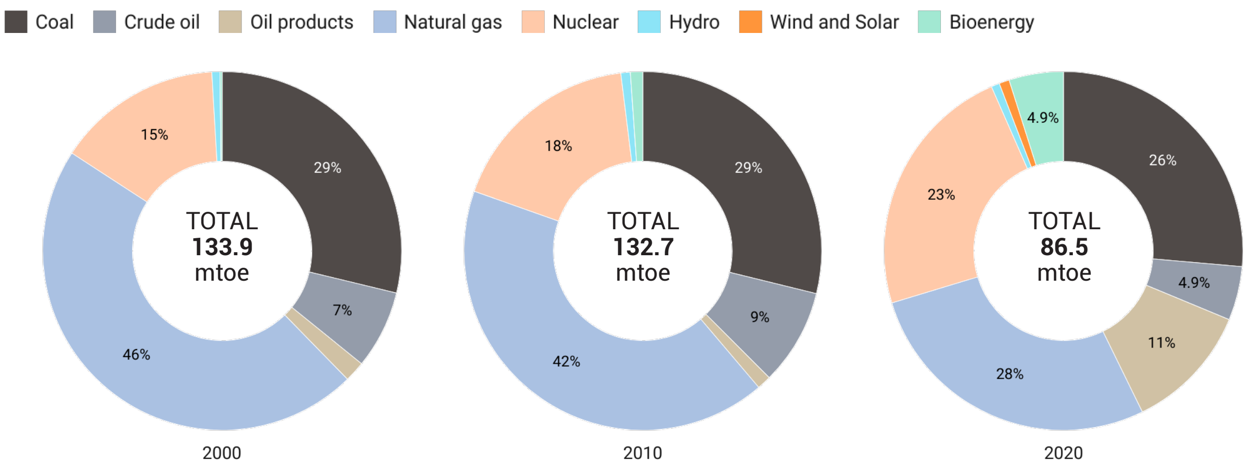
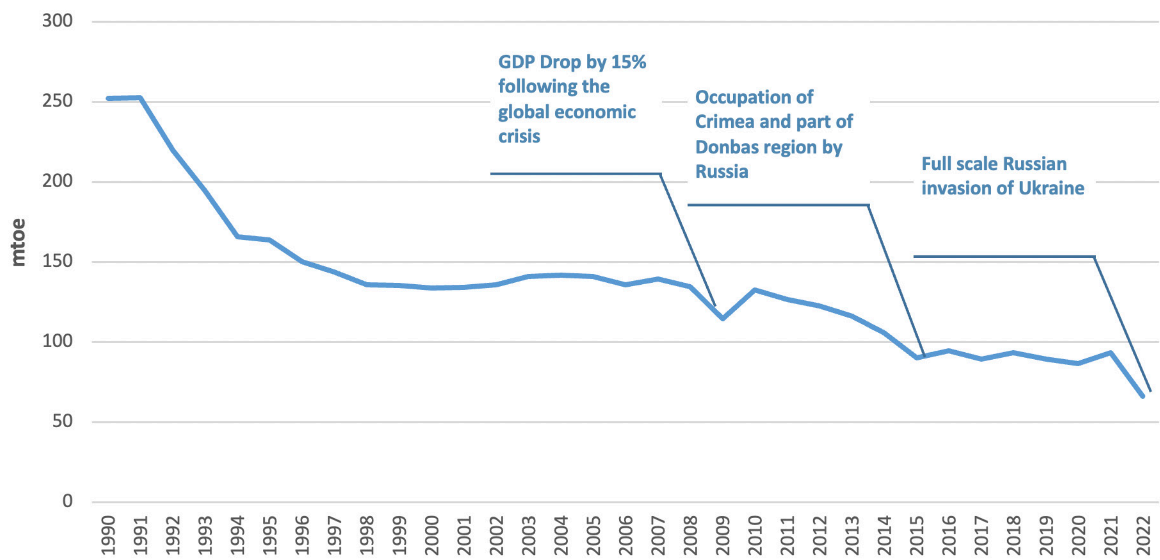


FIGURE 2

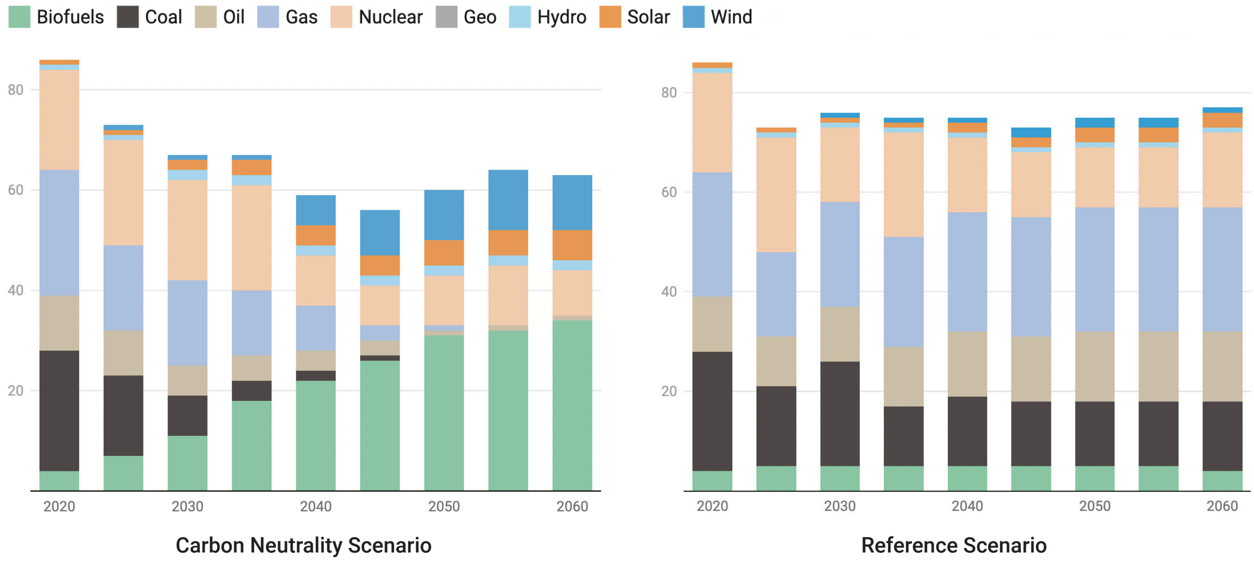
Total primary energy supply (mtoe), Ukraine 1990-2022



Achieving carbon neutrality necessitates a radical transformation of the energy supply mix, emphasizing the importance of harnessing the potential of modern bioenergy and phasing out unabated fossil fuels.

FIGURE 3

Total primary energy supply (mtoe), carbon neutrality & reference scenarios, Ukraine 2020-2050



Extensive decarbonization, according to this study, could lead to a doubling of electricity demand. Solar and wind generation could take the lead, becoming Ukraine's primary sources of electricity and increasing the share of renewables in total generation from 12% in 2020 to nearly 80% by 2050. These renewable sources are complemented by nuclear, hydro, and bioenergy in the analytical model.

FIGURE 4

Power generation capacity (gigawatts, GW), reference & carbon neutrality scenarios, Ukraine 2020-2050

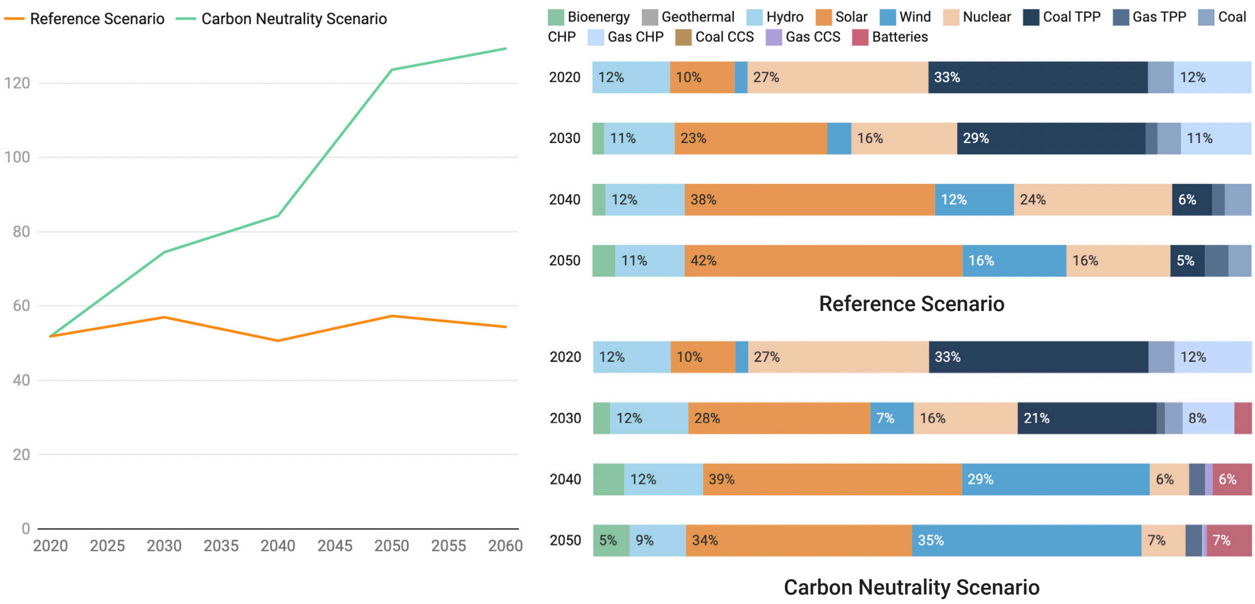
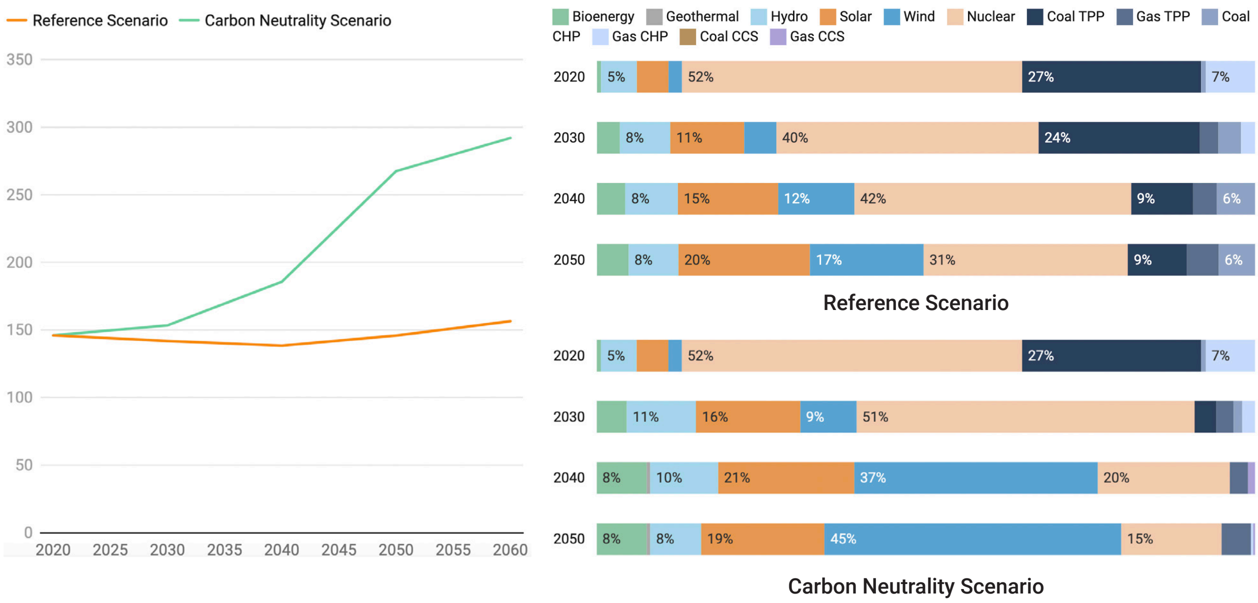


FIGURE 5

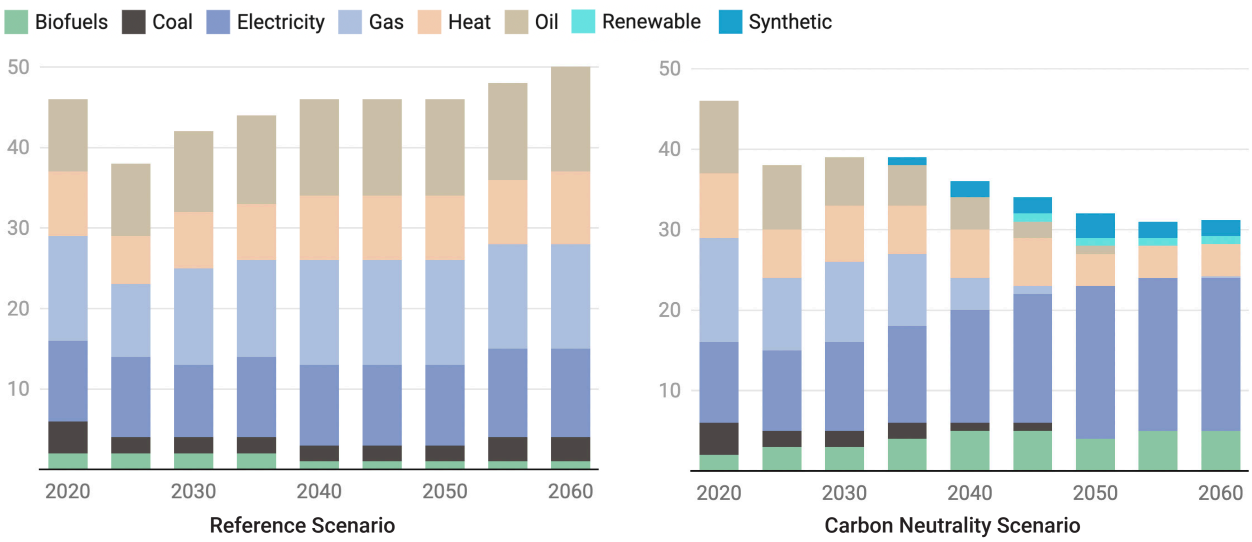
Electricity production (gigawatt hours, GWh), reference & carbon neutrality scenarios, Ukraine 2020-2050



The decarbonization process allows for a maximum shift towards electricity, heat, and renewable energy in final consumption. Primary fossil fuels could decline in final energy consumption from 60% in 2020 to around 2% in 2060, while electricity's share rises from 20% to over 60% of overall demand.

FIGURE 6

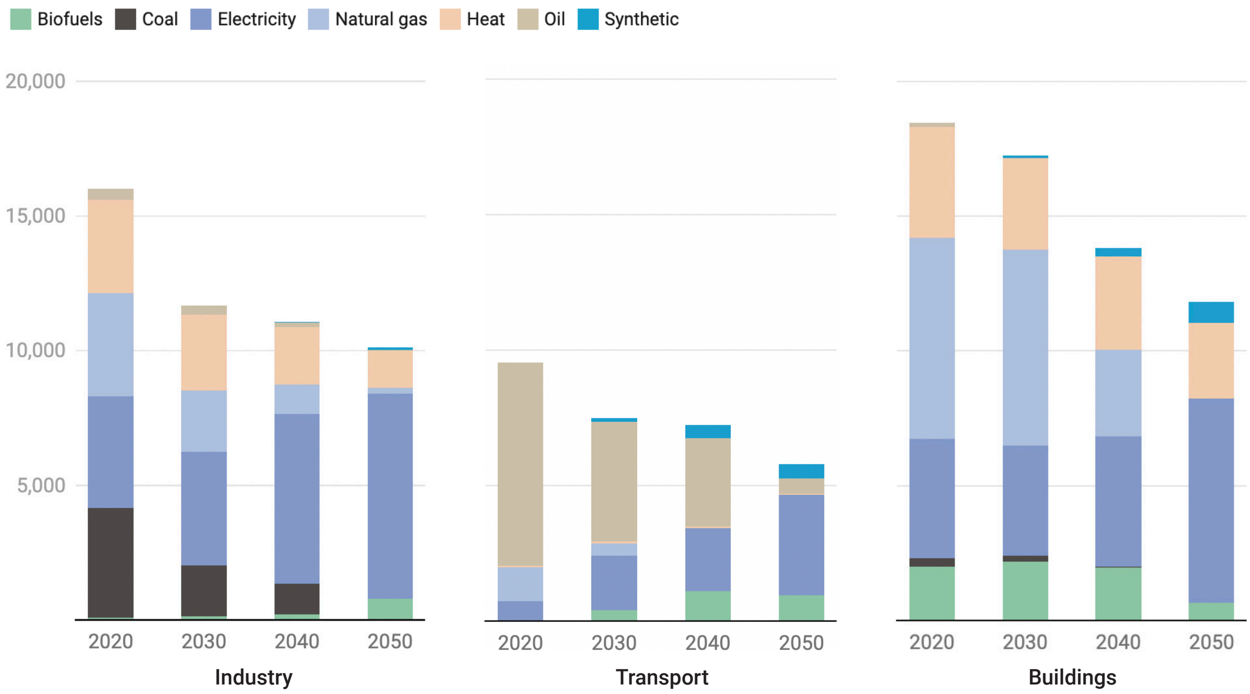
Final energy consumption by fuel (mtoe), reference & carbon neutrality scenarios, Ukraine 2020-2050



Energy efficiency improvements and electrification efforts could dampen demand growth, facilitating a gradual phasing out of unabated fossil fuels in various sectors. By 2050, transport is projected to reduce its reliance on fossil fuels by 93%, industry by 97%, and buildings by nearly 100%.

FIGURE 7

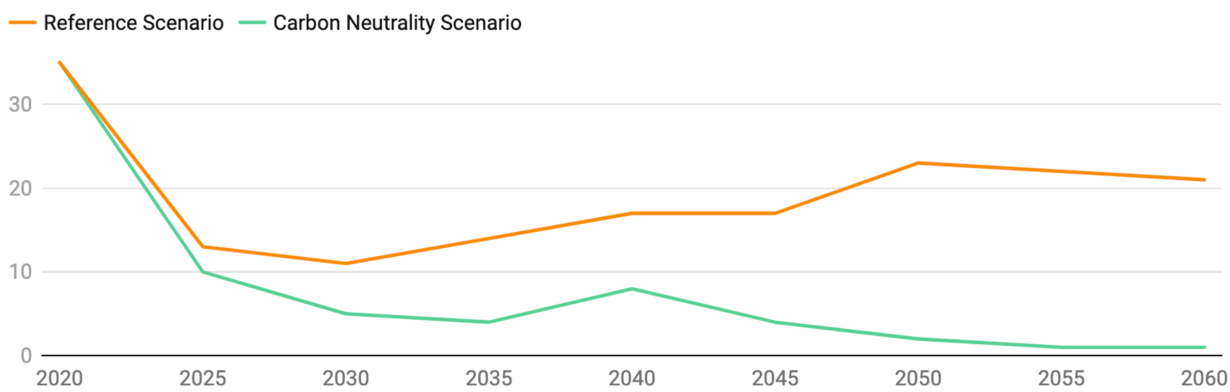
Final energy consumption by sector (kilotonnes of oil equivalent, ktoe), reference & carbon neutrality scenarios, Ukraine 2020-2050



Achieving the carbon-neutral pathway could not only provide Ukraine with energy independence but also enhance its energy resiliency. A significant shift towards domestic renewables and low-emission technologies would make Ukraine self-sufficient in terms of primary energy, reaching 98% by the mid-century (excluding nuclear fuel).

FIGURE 8

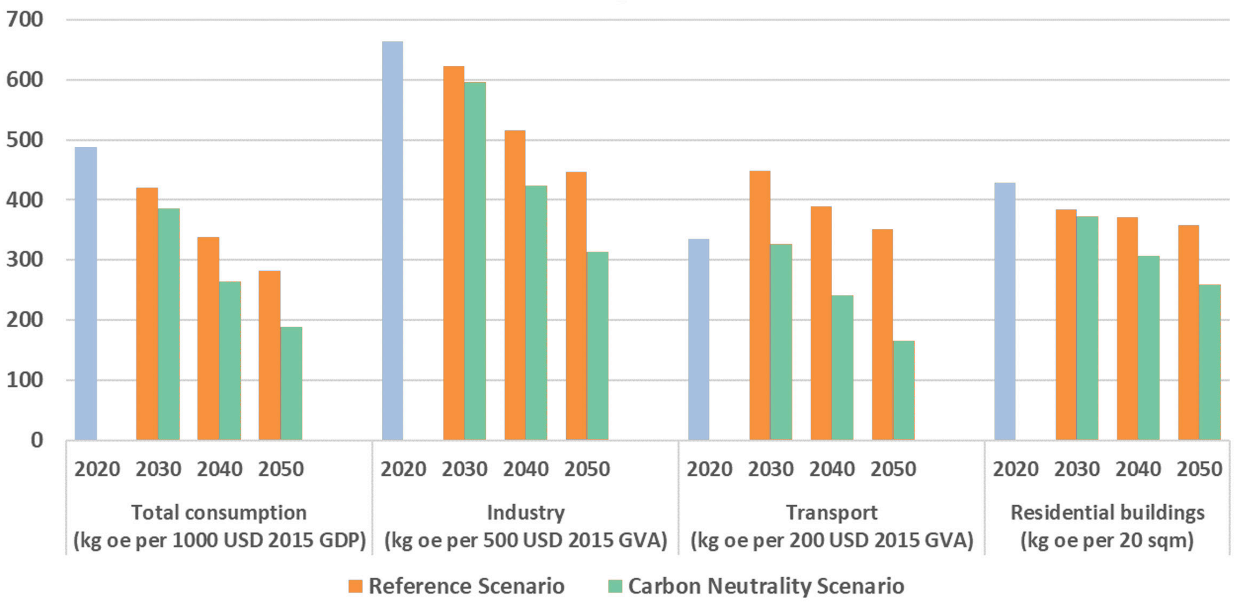
Primary energy import dependence, reference & carbon neutrality scenarios, Ukraine 2020-2050



Furthermore, energy efficiency improvements and electrification drive a decline in energy intensity in end-use sectors, the projected overall decrease would constitute 60% by 2050.

FIGURE 9

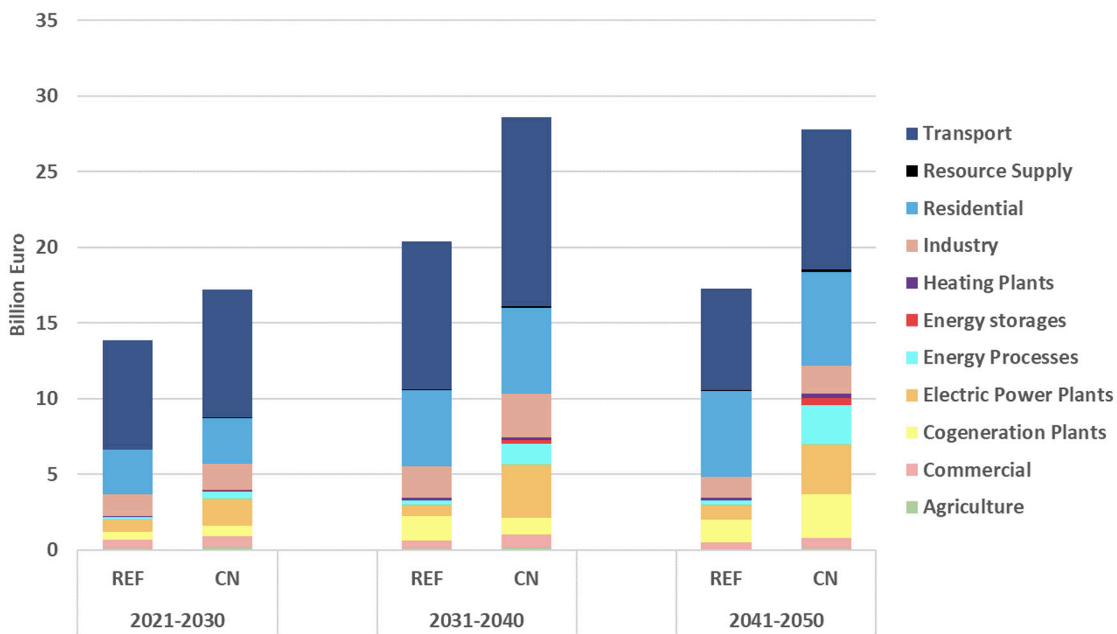
Energy intensity by sector (kilograms of oil equivalent, kgoe), reference & carbon neutrality scenarios, Ukraine 2020-2050



To accomplish carbon neutrality, Ukraine would require increase in annual investments by 30 billion EUR or approximately 15% of GDP by 2050 across various sectors, including transport, residential buildings, industry, power generation, and renewables. The amount needed for energy investments is 9,5 billion EUR annually, and it only partially includes investments in energy infrastructure (e.g. power grids, heat networks, gas pipelines).

FIGURE 10

Average annual investments (billion EUR), reference & carbon neutrality scenarios, Ukraine 2020-2050

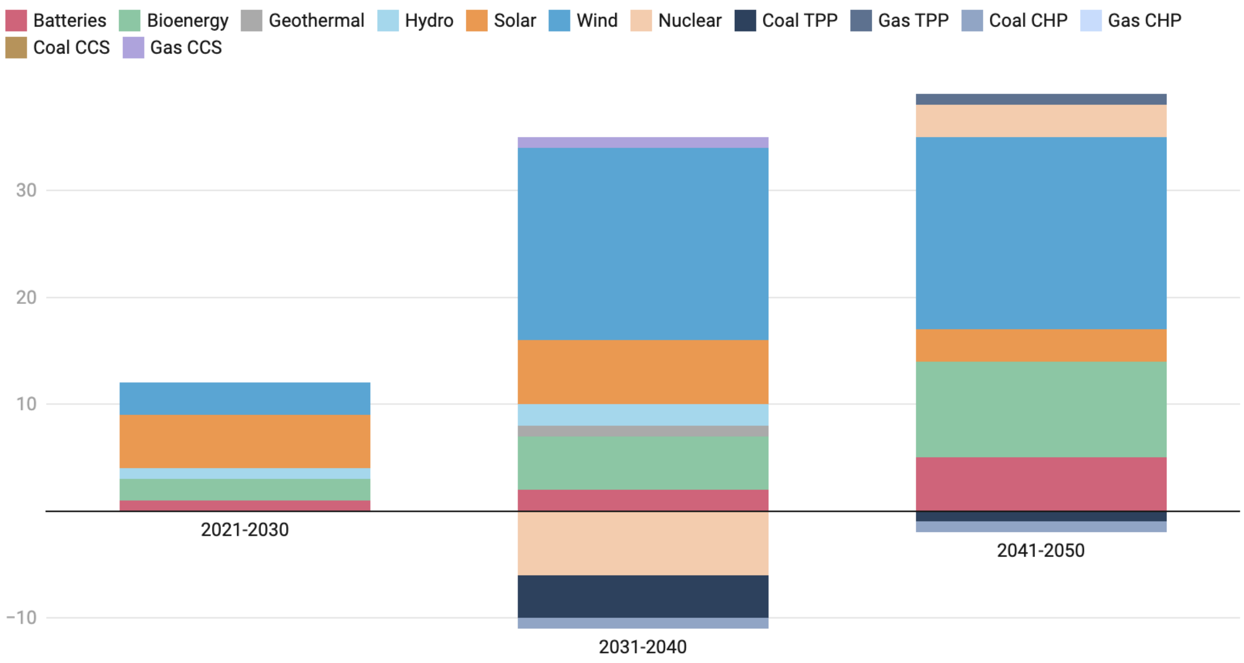


It is crucial to prioritize investments in efficient and clean end-user devices. Over the long term, household spending on energy is expected to decrease below the reference case due to the positive impact of efficiency measures and electrification.

Investments in power generation would need to triple to achieve carbon neutrality. Additionally, a significant restructuring of investment patterns is necessary, with batteries, bioenergy, wind, and solar technologies emerging as key areas for investment.

FIGURE 11

Percentage change of investments in power generation by energy source, carbon neutrality scenario, Ukraine 2020-2050



What do Reference and Carbon Neutrality Scenarios Mean?

Reference scenario is an “exploratory scenario” that considers current policies but does not assume additional policy actions to constrain GHG emission. Its assumptions:

- energy system is developing according to the existing principles, no efforts on energy transition are implied;
- the level of energy efficiency measures implementation corresponds to the present trends;
- new nuclear power generating capacities are not built due to high costs;
- new prominent technologies can’t occupy a significant share in the market due to absence of stimulus and high costs.

Carbon neutrality scenario investigates the least cost pathway to reach total net zero emissions in 2050 and increase negative GHG emissions till 2060. It includes:

- ambitious renovation policies throughout all sectors;
- strict building codes, high rates of thermal modernization and use of energy-efficient equipment such as heat pumps;
- extensive use of waste heat recovery and electrification in end-use sectors;
- deployment of hydrogen and biofuels in transport and other sectors which are difficult to decarbonize;
- high renewables deployment coupled with storage facilities and clean fuel generation;
- mature and coherent institutional environment to ensure strong positive signals for investors.

Common assumptions for both scenarios:

- all occupied territories are restored; captured and damaged production facilities are returned and recovered by 2025;
- there is no import and export of hydrogen, biomethane, or other green fuels/energy.

Key Takeaways

Problem:
Rebuilding Ukraine's energy system sustainably is challenged by the ongoing war and destruction, heavy reliance on fossil fuels, and impacted progress on climate targets. The war in Ukraine has caused immense suffering, and deepened existing vulnerabilities and inequalities in the country's weakened economy.

Mission Possible:
There are achievable pathways for Ukraine to build a resilient carbon neutral energy system.

Radical Transformation of the Energy System:
Rebuilding Ukraine's energy system would require phasing out unabated fossil fuels, harnessing modern bio-energy, and doubling electricity demand through solar and wind generation.

Decarbonization Must Start Now:
Decarbonization efforts would lead to significant reductions in reliance on fossil fuels across sectors. By 2050, transport is projected to reduce fossil fuel dependence by 93%, industry by 97%, and buildings by nearly 100%.

Interconnected Energy System Resilience and Sustainability:
Achieving carbon neutrality would enhance Ukraine's energy system resilience and independence. A shift towards domestic renewables and low-emission technologies could make Ukraine self-sufficient in primary energy, reaching 98% by the mid-century. Energy efficiency improvements and electrification efforts would play a crucial role in reducing energy intensity in end-use sectors, resulting in an overall decline of 60% by 2050.

Investment is Essential:
Reaching carbon neutrality in Ukraine would require doubling of the current level of capital investments, investments in the energy sector only whould reach up to 5% of GDP by 2050. Prioritizing investments in clean and efficient end-user devices, as well as tripling investments in power generation with a focus on batteries, bioenergy, wind, and solar technologies, would be essential.

1. CARBON NEUTRALITY AGENDA FOR UKRAINE

1.1 Country Overview, Energy and Emissions Trends

Ukraine is a resource rich country and is endowed with extremely rich and complementary mineral resources in high concentrations and close proximity to each other. The country has abundant reserves of coal, iron ore, natural gas, manganese, salt, oil, gold, lithium, aluminium, graphite, copper, sulfur, kaolin, peat, titanium, nickel, magnesium, timber, and mercury. Ukraine's conventional and unconventional hydrocarbon resources are located in the Dnipro-Donetsk region in the east, the Carpathian region in the west, and the Black Sea-Sea of Azov region in the south. The Dnipro-Donetsk region accounts for 90% of natural gas production. The remaining 10% of natural gas production originates in the Carpathian and Black Sea-Sea of Azov regions. Coal accounts for over 90% of Ukraine's fossil fuel reserves. In 2020, Ukraine had 34.4 billion tonnes of coal reserves mainly found in eastern part of the country, which ranked eighth in the world for hard coal reserves[1] being close to Germany and Indonesia.

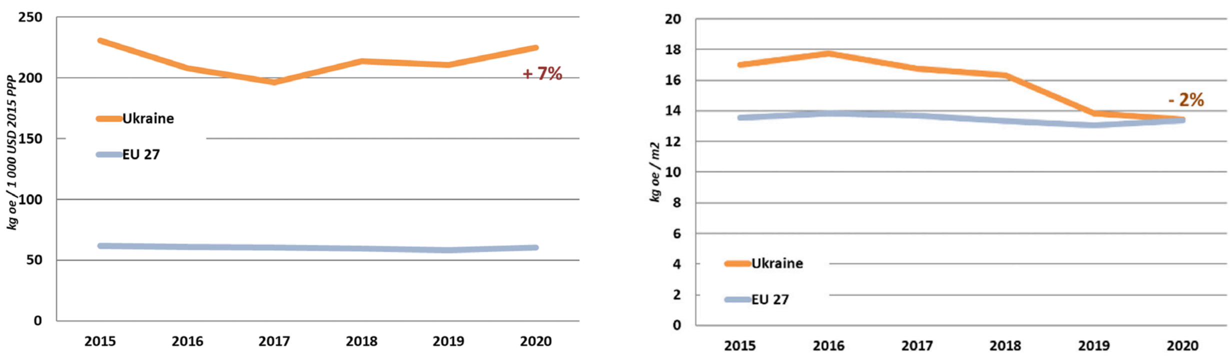
Ukraine has substantial renewable energy (RE) potential which remains largely untapped. In 2020, Ukraine had an extremely low (2–6 times lower) compared to EU countries level of RE sources introduction despite the high levels of insolation and wind potential[2]. The country has significant RE potential which can be deployed to enhance energy security by decreasing energy dependence on natural gas imports from Russia. Between 2018 and 2020, the RE installed capacity excluding hydropower significantly increased from around 2 GW at the end of 2018 to almost 9 GW at the end of 2020. Primary solid biofuels accounted for a major part of the total primary energy supply (TPES) deriving from RE in 2020 (70%). In 2020, Ukraine added 1.4 GW of solar PV capacity, reaching a total of 7.3 GW, an increase of 23.5% compared to 2019 (and 771% since 2015). Total wind capacity at the end of 2020 stood at 1.4 GW with 144 MW added during the year. As of 2021, according to the International Renewable Energy Agency (IRENA) the installed capacity of RE was estimated at 15 GW.[3] Nevertheless, the contribution of renewable energy and waste to the country's primary energy supply remains small up to 6.6%. Nevertheless, Ukraine has adopted a series of laws and regulations to promote the penetration of RE. In 2017, the Energy Strategy of Ukraine was adopted, according to which Ukraine plans to increase the share of renewable energy in its energy balance to 25% by 2035. In 2018, Ukraine became a full member of the IRENA. In that direction, an appropriate regulatory framework with the introduction of green auctions was ratified in order to prevent the formulation of monopolies in the market of renewable energy sources in Ukraine. What is more, since 2008 Ukraine has had a feed-in-tariff scheme in place with fixed prices, called the "green" tariff for electricity which ensures that all generated renewable power is fed into the grid.

Ukraine's economy is among the most energy intensive ones globally. While Ukraine relies mostly on nuclear and coal for electricity generation, it is heavily dependent on gas for heat supply, and residential and industrial uses. The energy intensity of the Ukrainian economy is three to four times higher than the average in the European Union as shown in Figure 1.1. Energy intensity in Ukraine is driven by high demand in residential heating, an industrial structure that is concentrated in capital and energy-intensive activities, and an energy-inefficient industrial, energy, and building infrastructure due to decades of under-investment.

1 https://www.statista.com/statistics/237096/proven-coal-reserves-of-the-top-ten-countries/

FIGURE 1.1

Energy intensity in industry (left) and residential buildings (right)



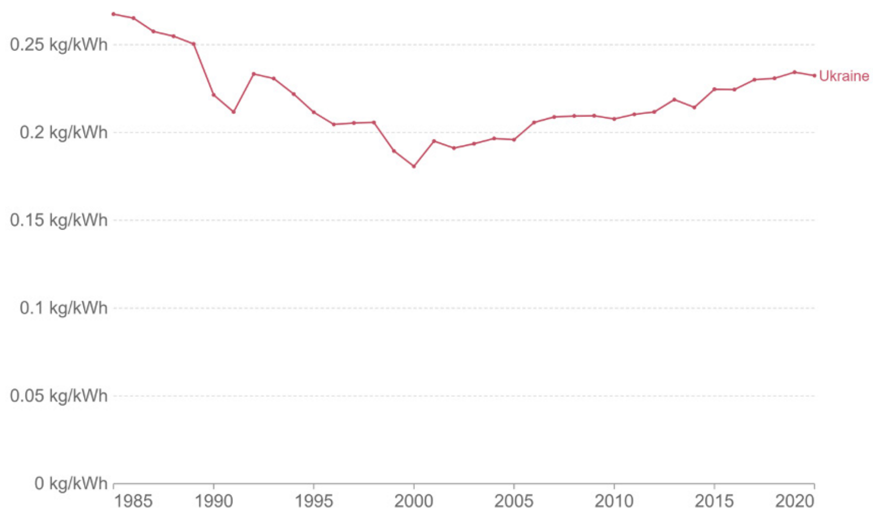
Source: *Estimated by authors based on IEA, Eurostat and State Statistics Committee of Ukraine*

Although the country has made gains in energy efficiency in the industrial sector, it has a long way to go to in order to accelerate this trend, which will require in turn more investments in energy infrastructure modernization, more stable and secure energy supply, and addressing inefficiencies in energy consumption.

Ukraine's economy is carbon intensive. The carbon intensity of GDP in Ukraine is still 4.5 times higher than the global average and more than 8 times higher than the average in OECD Europe while per capita emissions are at the global average[4]. Ukraine makes up 0.5% of global annual carbon emissions, (185 mln t CO_2), and accounted for 1.8% (29 bln t CO_2) of cumulative CO_2 emissions since the industrial revolution. Ukraine's per capita emissions are roughly equivalent to the global average at 4.5 metric t CO_2, and lower than the 6.5 mt CO_2 for the European Union. Despite nuclear power constituting 55% of electricity generation, the carbon intensity of Ukraine's economy is nearly three times that of the European Union. Energy accounts for more than 80% of GHG emissions with electricity and heat production, fugitive emissions, and manufacturing together accounting for about three-quarters of emissions.[5]

FIGURE 1.2

Carbon intensity of the energy production in Ukraine 1985-2020



Source: *Our World in Data based on the Global Carbon Project*

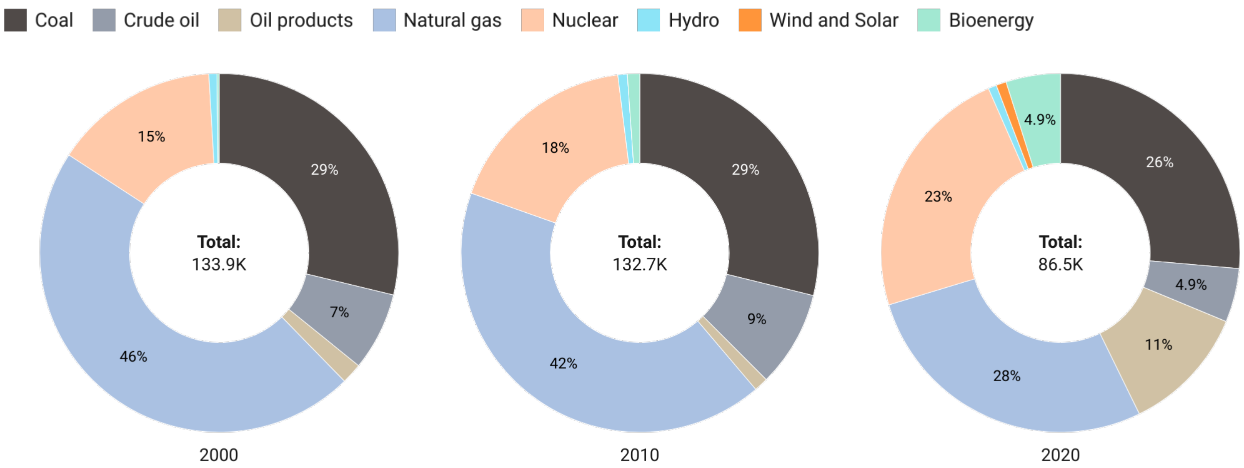
4 The World Bank. CO2 emissions (kg per 2015 US$ of GDP) – Ukraine, World, OECD members. Available from: https://data.worldbank.org/indicator/EN.ATM.CO2E.KD.GD?locations=UA-1W-OE

5 Ukraine's energy policy and prospects for the gas sector. Oxford Institute for Energy Studies. https://www.oxfordenergy.org/publications/ukraines-energy-policy-and-prospects-for-the-gas-sector/

GHG emissions in Ukraine in 2019 amounted to 332.11 Mt CO_2-eq. excluding land use, land-use change and forestry (LULUCF), what is 64.8% lower than in the base 1990 level, and 2.3% than in 2018. With the LULUCF sector, emissions in 2019 amounted to 332.16 Mt CO_2-eq. and decreased in comparison with base year by 62.4%, and by 2.5% in comparison with 2018[6,7].

FIGURE 1.3

Total primary energy supply by energy source, million tonnes of oil equivalent (mtoe), Ukraine 2000-2020



Source: *State Statistics Service of Ukraine*

The energy mix of Ukraine, although being quite diversified, relies predominantly on fossil fuels and imports of energy (see Fig. 1.3). In 2020, fossil fuels accounted for 70% of TPES, while nuclear and renewables (including waste to energy) for 23.1% and 6.5% respectively[8]. In 2018, the share of coal (the country's primary fuel) dropped to 30%, followed closely by natural gas (28%) and nuclear (24%). Ukraine is heavily reliant on fossil fuels and nuclear energy for the generation of electricity. Nuclear energy provides a reliable base load and covers more than half of the electricity production in Ukraine (55.5% in 2021). There are four nuclear power plants (NPPs) in Ukraine with a total installed capacity of 13.8 GW (15 reactors in total, incl. 13 reactors with a capacity of 1,000 MW and two reactors with a capacity of 415 MW and 420 MW, respectively)[9]. in June 2020, the Cabinet of Ministers adopted an order prioritising coal use in Ukraine's power sector, aiming to strengthen the domestic coal industry. Despite producing significant volumes of natural gas, Ukraine is still dependent on gas (and oil) imports and is a major transit route for Russian gas exports towards Europe. As of 2020, the country depended on imports for around 84.5% of its oil consumption, 31% of its natural gas and 48% of its coal.

Industry is the largest final energy consumer, and the residential sector is second, with households being the major users of natural gas. The residential and industrial sectors account for 28% and 33% respectively and rely predominantly on natural gas. All sectors need to enable structural shifts to promote energy efficiency, which remains largely untapped due to limited investments. Despite the fact that the Government has adopted a number of strategies (National Energy Efficiency Action Plan (NEEAP) by 2030, Energy Efficiency Law (2021)) for the promotion of energy efficiency measures across the various sectors, it needs to intensify its efforts towards this direction in order to quickly realise substantial energy savings.

6 Ukraine Energy Profile. International Energy Agency. https://iea.blob.core.windows.net/assets/ac51678f-5069-4495-9551-87040cb0c99d/UkraineEnergyProfile.pdf

7 National Inventory Report for Ukraine. UNFCCC. https://iea.blob.core.windows.net/assets/ac51678f-5069-4495-9551-87040cb0c99d/UkraineEnergyProfile.pdf

8 Energy balance of Ukraine. State Statistics Service of Ukraine. https://ukrstat.gov.ua/operativ/operativ2012/energ/en_bal/arh_2012_e.htm

9 Ukrainian Energy Sector Damage Assessment Report. Energy Charter Secretariat. https://euneighbourseast.eu/wp-content/uploads/2022/08/20220831_ua_sectoral_evaluation_and_damage_assessment_final.pdf

The power sector relies on fossil fuels and nuclear energy for more than 85%, with the share of renewable energy in 2020 accounting for about 8% (excluding hydro). Coal plays a huge role in the power sector, despite aspirations for coal phase out by 2035. On a positive note, the Ukrainian electricity market was opened on 1 July 2020 shifting from a regulated single-buyer model to a competitive liberalised model in line with EU Directives and completed the ENTSO-E synchronization in 2022. Although at an early stage of synchronization, it is a decisive step for the country to enjoy the benefits of full market integration in the future. What is more, the electricity sector is vulnerable to many electricity transmission and distribution losses exceeding 10% annually and recurring outages in urban and rural areas.

In Ukraine, the transport sector is difficult to decarbonize due to lock-in effects and a fragmented governance. The share of renewables in the transport sector was at the level of 3.1%. The current taxation system does not properly incentivize the uptake of efficient cars, while the Ukrainian legislation has favoured car ownership. Taxes on vehicle registration and emission of cars were abolished in the beginning of 2015 and the newly introduced tax on car ownership has no real environmental component. While expensive cars are taxed, old and inefficient cars remain untaxed. On the other hand, stimulating measures have helped to increase sales of electric vehicles. In 2016, custom duties on electric vehicles were abolished, and as of 2018, excise tax and VAT for the import of electric vehicles have been dropped as well.

The residential sector accounts for a large part of the energy related emissions in Ukraine. In 2018, the buildings sector accounted for approximately 8% of Ukraine’s total GHG emissions and the residential buildings sector alone was responsible for 30% of Ukraine’s total final electricity consumption. The building stock dates from the Soviet Union era and is in need of modernization as energy consumption per square meter of most buildings consume three times more energy than class B energy-efficient buildings. Although several programs such as the Energy Efficiency Fund or the Warm Loans Program has been established to drive financing towards more efficient buildings envelop and buildings technical systems, they did not deliver the expected results. Ukraine has also adopted laws to implement the Energy Performance of Buildings Directive and align them with the Energy Efficiency Directive, promoting nationwide modernisation of buildings, replacement of low-efficiency boilers, substitution of fossil-fired heating systems and nationwide reconstruction of residential buildings.

There is still room for improvement in the energy efficiency performance of the industrial sector in Ukraine. Industry is responsible for 18% of Ukraine’s total GHG emissions excluding LULUCF. The industrial sector is among the hardest to decarbonize due to the difficulties of reducing industrial emissions in cement, lime and other industries. In January 2018, Ukraine’s environment ministry published a draft law that will require large emitters to audit their emissions as an initial step towards Ukraine developing a functioning Emission Trading System (ETS). Nevertheless, the carbon tax applied is quite low compared to world average, which makes it highly unlikely to reduce emissions in the sector. Ukraine has also supported the development and implementation of several industry-led initiatives to broaden and deepen demand restraint in the industry sector, including implementation of ISO 50001 energy management system standard.

Ukraine is highly vulnerable to the impacts of climate change. The country is expected to suffer from an increase in intensity and frequency of droughts, high temperatures, heat waves, variable precipitation patterns and floods[10]. Climate change is also expected to shift boundaries of spring frosts, with adverse impacts on the agriculture sector, the backbone of the Ukrainian economy accounting for almost 11% of GDP as of 2021[11]. What is more, water resources will be affected by changing temperatures and precipitation regimes, which will have long-term implications on the amount and quality of water available, which would in turn undermine the quantity of available water used in the energy sector too.

10 https://climateknowledgeportal.worldbank.org/country/ukraine

11 https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?locations=UA

1.2 Energy and Environmental Policy Landscape, Governement Decarbonization Efforts

1.2.1 Updated NDC of Ukraine

On July 30, 2021, the Government of Ukraine approved the second (updated) Nationally Determined Contribution of Ukraine to the Paris Agreement (NDC2), which calls for the need to reduce GHG emissions to the level of 35% compared to 1990 by 2030[12].

The analytic basis for the NDC2 has been elaborated during 2018-2021 by the group of experts led by the Institute for Economics and Forecasting, National Academy of Sciences of Ukraine, within the framework of the EBRD project “Support to the Government of Ukraine on Updating its Nationally Determined Contribution” with financial support provided by the Swedish International Development Agency (SIDA).

According to the project reports, as of 2018, GHG emissions in industry already decreased by 34% comparing to 1990. Although to meet updated target, this sector requires further the largest GHG reductions by 2050 and the largest amount of investment – 114 Mt CO_2 and 11,1 bln EUR by 2050. GHG emissions in agriculture decreased by 51% as of 2018 from 1990. By 2050, it is necessary to reduce another 36 Mt CO_2, which will require 3.6 bln EUR. Instead, the growth of GHG emissions in 2018 compared to 1990 occurred in the LULUCF sector (+104%, although in 1990 they were negative) and in the waste sector (+2%). By 2050, the forestry and land use sectors will require 2.6 bln EUR, and the waste sector will require 14.2 bln EUR.

1.2.2 Waste Management

On June 20, 2022, Ukrainian Parliament adopted the framework Law of Ukraine "On Waste Management". Since only 6% of household waste is processed in Ukraine, and the rest is buried in landfills, methane emissions from landfills in Ukraine increased annually during 2016-2021, calling into question the government's declared commitment to the goals of the Paris Agreement. According to official data on GHG emissions, which Ukraine submits to the UN, landfills accounted for 15.4% of national methane emissions in 2019 – more than from agriculture (13.7%). Decaying household waste in landfills is the third largest source of methane emissions into the atmosphere – GHG that is 86 times more potent than CO_2 in a 20-year perspective.

During COP26, Ukraine joined the "Global Methane Pledge" initiative founded by the EU and the USA, which aims to reduce global methane emissions by 30% or more by 2030 from the 2020 level in order to reduce the level of global warming by at least by 0.2°C by 2050. In mid-September 2022, the Government of Ukraine released the draft Action plan on the implementation of Ukraine's climate policy in the scope of participation in the global initiative to reduce methane emissions "Global Methane Pledge".

The Framework Law on Waste Management provides the update of dozens of legal acts that will introduce a hierarchy of waste management, create a foundation for waste management, allow local communities to attract investors to establish processing facilities, and introduce new approaches to the certification of landfills and the licensing of companies that provide services in the field of waste management.

1.2.3 Monitoring Reporting and Verification. Emissions Trading System (ETS)

The Ukraine-EU Association Agreement, signed in 2014, lays down the basic principles for greening of the Ukraine's economy by expansion of the EU legislation to Ukraine. The EU Directive 2003/87/EC establishes a financing scheme to facilitate the reduction of GHG emissions in a cost-effective and economically feasible way. Upon the Order No. 371-r from April 15, 2015, Ukrainian Government has approved the implementation plan for this Directive, that involves development of a national plan for the allocation of emission quotas; introduction of the GHG emission permit system and GHG emission permit units to be sold at the national level; establishing of the national system of monitoring, reporting and verification (MRV), as well as procedures for public consultations.

12 https://www.kmu.gov.ua/en/news/uryad-rozpochinaye-proces-formuvannya-dorozhnoyi-karti-zahodiv-u-sferi-zmini-klimatu

According to the Law of Ukraine “On Principles of Monitoring, Reporting and Verification of GHG Emissions”[13], a new system for regulation of GHG emissions was introduced from January 1, 2021.

The establishment of the ETS in Ukraine is still ongoing. As part of international technical assistance, various projects were implemented in Ukraine, including those supported by the World Bank and GIZ is planned that the GHG MRV system, as well as the ETS architecture, will be fully operational starting from 2025.

1.2.4 Carbon Tax

On November 30, 2021, Ukrainian Parliament supported the draft law No. 5600 that provided for an increase in the tax rate for carbon dioxide emissions from 10 UAH/t CO_2 to 30 UAH/ t CO_2 (about 1 EUR per ton) from January 1, 2022. Even after such increase, the tax rate remains one of the lowest in Europe. For example, Sweden has the highest rate of about 130 euro/t CO_2. At least 70% of the tax revenue should be directed to reduce CO_2 emissions in manufacturing and energy sectors. As expected, additional revenues from this rate increase will be about 2.1 bln UAH, that could be directed at the technological modernization of industrial and energy enterprises.

1.2.5 Carbon Border Adjustment Mechanism

In the middle of 2021, the European Commission presented the concept of CBAM – Carbon Border Adjustment Mechanism, the protective measure as part of the EU policy to combat climate change[14]. CBAM provides for the introduction of a tax on imported products in the EU depending on their carbon footprint. The protective measure will come into effect in 2023 as part of a transitional three-year implementation phase. It covers imports of steel, iron, aluminium, cement and electricity generation. Full implementation of CBAM is expected from 2026. The draft regulation on CBAM takes into account the special legal regime of countries, including Ukraine, which are parties to association agreements with the EU.

It is not clear so far how the CBAM will be imposed on Ukraine and how it will affect the foreign trade. GMK Center, Ukrainian think tank, estimates that a one third of the Ukrainian exports to the EU could be subject to CBAM. According to the estimates of Kyiv School of Economics, the carbon tax will reduce the EBITDA of industrial companies to 248 mln euro in 2030 and may lead to a 9% decrease in exports of Ukrainian industrial products to the EU[15]. Experts from the "Society and Environment" center believe that losses of the Ukrainian iron and steel exporters after the introduction of CBAM could amount from 300 to 900 mln Euro per year[16].

Given the fact that before the full-scale Russian invasion, Ukrainian industry had the lowest technical and economic indicators and the highest energy intensity in Europe, implementation of CBAM can indeed have a significant impact on the Ukrainian economy. Implementation of the Directive 2010/75/EU in Ukraine will increase the energy efficiency of the sector and significantly reduce the impact on the environment and human health. In the context of post-war reconstruction, this is an important reform that corresponds to the principle of build back better.

1.2.6 Green Finance

Green finance reforms open up opportunities for the long-term decarbonization measures. Ministry of Energy and the Ministry of Environment have already proposed a set of instruments for financing environmental protection measures and decarbonization. The Ministry of Energy envisages establishing a Fund[17] that will be filled with a carbon tax revenue, and will support projects that lead to a reduction in CO_2 emissions and have energy saving, environmental and social effects. It should have a format of the "article in the budget", similar to the State Regional Development Fund or the State Road Fund. Under such option, the administration process will not require additional costs from the state budget and will be carried out by existing state institutions. It is proposed that the State Energy

13 https://zakon.rada.gov.ua/laws/show/377-20
14 https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3541
15 https://interfax.com.ua/news/greendeal/785289.html
16 https://www.eurointegration.com.ua/articles/2021/12/1/7130830/
17 https://www.kmu.gov.ua/news/minenergo-iniciyuye-stvorennya-fondu-dekarbonizaciyi

Efficiency Agency, which is in the process of reform and will receive all the necessary competencies, will manage this Fund. The Government also approved the Concept for the introduction and development of the green bond market in Ukraine.[18] According to expert estimates, the potential of the green financing market in Ukraine is 73 bln USD by 2030. Almost half of them – 36 bln USD – is the potential of the green bond market. It is expected that the issue of green bonds can become a promising tool for attracting funds during the post-war recovery period.[19]

The Ministry of Environment proposed to establish a special fund to finance environmental protection and decarbonization measures similar to the Polish experience. It was assumed that the fund would act as an independent legal entity that would allow to attract additional funds within the framework of the European Green Deal and other international initiatives, to form priorities of financial support and relevant programs with equal rules for participants, to introduce different levels of support and more complex financial products (from covering the body of the loan, co-financing programs to grants), as well as to solve the problems of delaying financing decisions in the public decision-making process.

1.3 Economic and Energy Consequences of the Russian Aggression

The unprecedented military aggression of the Russian Federation against Ukraine started on February 24, 2022, has led to significant consequences both in the energy sector and the national economy. A considerable part of Ukraine's energy facilities has been occupied, damaged, or destroyed. This has primarily impaired the security of supply and power system resilience while various sectors of the economy experienced continuous scheduled and emergency disruptions in the energy supply, particularly electricity, gas, and petroleum fuels, which also harmfully impacted the heating and water supply.

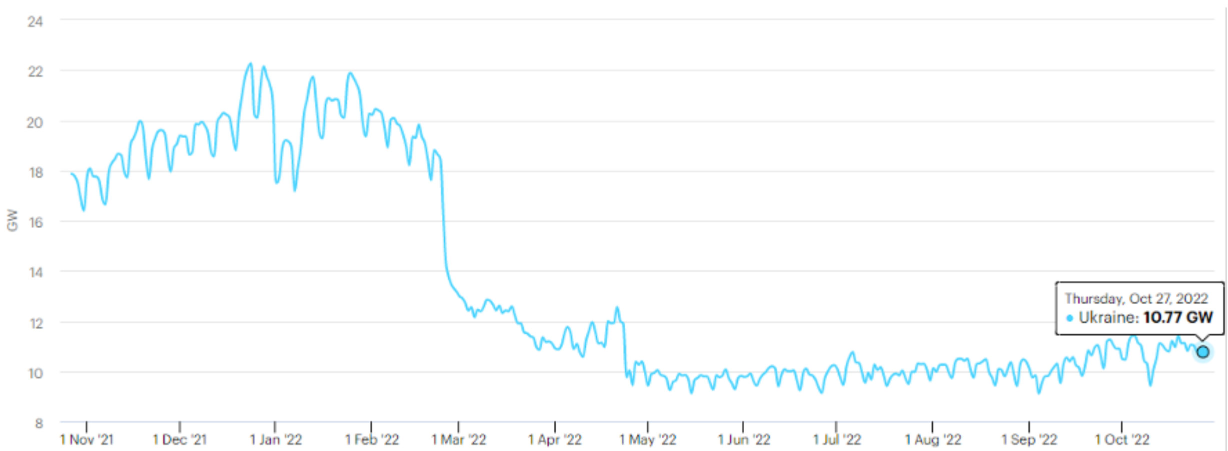
1.3.1 Impacts on the Energy Sector

1.3.1.1 Electricity Consumption

The war in Ukraine caused a drastic impact on electricity demand as, according to the transmission system operator (TSO), it has dropped on average by 30-35% compared to 2021. Overall, electricity consumption by industry fell by 63% and households by 24%.[20] The snapshot of the date-to-date comparison of average daily demand for October 27, 2021 (17.86 GW) and 2022 (10.77 GW) demonstrates a 39.7% decline (Figure 1.4).

FIGURE 1.4

Average daily electricity demand in Ukraine (from October 27, 2021, to October 2, 2022)



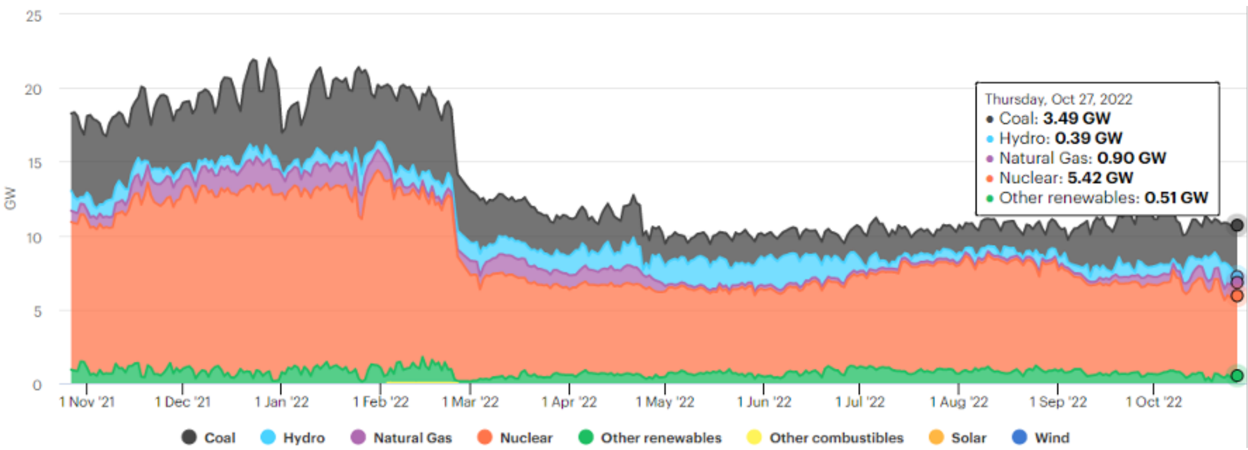
Source: IEA

18 https://www.kmu.gov.ua/news/uryad-shvaliv-koncepciyu-zaprovadzhennya-ta-rozvitku-rinku-zelenih-obligacij-v-ukrayini
19 https://www.ukrinform.ua/rubric-economy/3625639-zeleni-obligacii-mozut-dopomogti-u-vidnovlenni-mist-pisla-vijni-op.html
20 https://www.epravda.com.ua/columns/2022/09/22/691749/

The fall in electricity demand influenced the respective decline in the generation, predominantly by nuclear and thermal power plants (TPPs) (Figure 1.5). Electricity generation by renewables was also impacted in the early days of the full-scale Russian invasion due to forced curtailments applied by the TSO to keep the power system balanced and further because of occupation and damage of large part of solar and wind installations.

FIGURE 1.5

Daily electricity mix in Ukraine (from October 27, 2021, to October 27, 2022)



Source: IEA[21]

Following massive deliberate missile and drone attacks on Ukraine's critical energy infrastructure since October 10, 2022, and henceforward, the emergency disruptions of electricity supply across all regions of Ukraine were broadly applied by the TSO and distribution system operators (DSOs) to keep the power system balanced.[22]

1.3.1.2 Nuclear Generation

The critical importance of nuclear generation in Ukraine's electricity mix, ensuring the security of electricity supply and reliability of the grid, makes nuclear power plants (NPPs) vulnerable targets for attacks, occupation, or other kinds of damage disrupting their stable operation. The Russian forces regularly shelled the Zaporizhzhya NPP (ZNPP) site, causing multiple damages to the plant's ancillary facilities and four high-voltage transmission lines connecting ZNPP to the grid. The plant has been under occupation since March 4, 2022. The occupation of ZNPP breached its regular supply with spare parts and materials necessary for the plant operation and maintenance. Besides, ZNPP may experience a lack of qualified personnel required for its stable operation. Given the above factors, all six ZNPP units were shut down in September 2022, which considerably impaired the power system operation. The IAEA concluded that the ZNPP occupation by the Russian military violated most of the seven indispensable IAEA pillars necessary for the secure operation of nuclear facilities.[23]

1.3.1.3 Thermal Power and Co-generation

After February 24, 2022, the Russian forces occupied three TPPs – Zaporizhzhia, Luhansk, and Vuhlehirsk – with a total capacity of 8.7 GW. Thus, about 44% of the total thermal power capacities are occupied.[24] Four TPPs with an

21 https://www.iea.org/data-and-statistics/data-tools/ukraine-real-time-electricity-data-explorer

22 https://ua.energy/zagalni-novyny/20-zhovtnya-po-vsij-ukrayini-mozhut-buty-zastosovani-zahody-obmezhennya-spozhyvannya-z-7-00-do-22-00/

23 https://www.iaea.org/sites/default/files/22/09/ukraine-2ndsummaryreport_sept2022.pdf

24 https://euneighbourseast.eu/news/publications/ukrainian-energy-sector-damage-assessment-report/

installed capacity of 5.6 GW are located close to the areas of active hostilities. Since October 10, 2022, the Burshtyn, Ladyzhyn, Prydniprovsk, Kurakhiv, Zaporizhzhya, and other TPPs suffered multiple attacks, which caused severe damage to the plants and adjacent switchgear power systems and distribution equipment, disrupting electricity supply from the TPPs to the grid.

The supplementary issue would be ensuring a proper fuel supply of TPPs. A considerable part of the coal mines is under occupation or damaged. About 92.4% of total coal reserves are located in the Donetsk coal basin. As of September 2022, about 63% of the country's coal deposits were temporarily occupied. There were 151 coal mines in operation in 2013 and only 47 in 2021. As of September 2022, 95 mines were temporarily occupied, while several coal mines were flooded. To avoid fuel shortage, the Government introduced a temporary embargo on exporting steam coal, natural gas, and oil fuel on June 14, 2022.[25] Since September 7, 2022, the embargo was extended to include coking coal, as it could be also used by TPPs, CHPs, and boiler houses as a part of their fuel mix.

Around 10% of the total combined heat and power plants (CHPs) installed capacity is under occupation. Four CHPs in Severodonetsk, Kremenchuk, Chernihiv, and Okhtyrka with an installed capacity of app. 700 MW, or about 11% of the total CHPs capacity, were destroyed by deliberate shellings. Besides that, the missile attack damaged Kharkiv CHP (540 MW). CHPs in Kyiv were attacked several times with severe damages causing forced outages of electricity supply in Kyiv and adjacent settlements. The supplementary issue would be ensuring the fuel supply of CHPs, primarily with natural gas. This situation imposes a considerable risk for the sustainable fuel supply of CHPs and other gas-fired generation. Additionally, in the heating sector, 322 local boiler houses were damaged and 13 were destroyed.[26]

1.3.1.4 Hydro

The Russian forces occupied Kakhovska hydropower plant (HPP) (343.2 MW) from February 24, 2022, until mid-November 2022. Two plant units were damaged, and only three out of six are currently operating, which is about 30-40% of the installed capacity of Kakhovska HPP. Given a considerable amount of TPPs being captured or damaged, Ukraine's power system has become even less flexible compared to its pre-war status, which imposes an additional risk for system resilience and its due balancing.

1.3.1.5 Other Renewables

According to ENTSO-E, as of the beginning of 2022, the total installed capacity of RES in Ukraine reached 6.9 GW (12.2% of total installed capacity), with the dominant part of solar installations (app. 5.4 GW). However, as of June 2022, 90% of wind and 30% of solar power capacity in Ukraine was out of operation.[27] As of August 2022, according to information by the Ukrainian Association of Renewable Energy (UARE), Ukrainian Wind Energy Association (UWEA), European-Ukrainian Energy Agency (EUEA), and Ukrainian Association of Solar Energy (UASA), over 75% of wind farms and 15 solar installations were occupied, damaged, or destroyed. Thus, associations expect a fall in electricity generation from RE by 45% compared to 2021, to 7.6 bln kWh.[28]

1.3.1.6 Electricity Networks

The electricity network infrastructure appeared vulnerable as its elements – high voltage power lines, transformer substations, etc. – have become the permanent targets for multiple missile and drone attacks and other shellings by the Russian forces. As of September 2022, over 30 overhead transmission lines and ten 220-750 kV substations were either damaged or disconnected due to continuous shellings.[29] Repeatedly attacked were open switchgear, transformers, etc., to disrupt power plants' electricity supply to the grid. The key targets appeared to be high-voltage transformer substations of the TSO and switchgear and distribution systems at TPPs.

25 https://biz.ligazakon.net/news/211871_uryad-zaboroniv-eksport-mazutu-vugllya-ta-prirodnogo-gazu
26 https://www.minregion.gov.ua/press/news/oleksij-chernyshov-zyma-spytaye-z-kozhnogo/
27 https://www.bloomberg.com/news/articles/2022-09-14/russia-s-invasion-knocked-out-almost-all-of-ukraine-s-wind-power
28 https://e-b.com.ua/asociaciyi-vde-zaklikali-vladu-ne-dopustiti-bankrutstva-galuzi-ta-usunuti-pereskodi-dlya-yiyi-rozvitku-4672
29 https://euneighbourseast.eu/news/publications/ukrainian-energy-sector-damage-assessment-report/

However, on March 16, 2022, the Ukrainian power system was synchronized with the Continental European grid. On June 30, 2022, Ukraine started commercial electricity exports to the ENTSO-E countries – Romania and Slovakia with a total export capacity of 300 MW. The equivalent amount could also be imported from those countries. Additionally, Ukraine and the ENTSO-E countries could provide mutual emergency system support through the available interconnectors contributing to the security of electricity supply and power system resilience. Currently, the maximum capacity of cross-border interconnectors with the ENTSO-E countries is about 2,000 MW, with a potential of extending to over 4,000 MW. Although, following massive systemic attacks on energy infrastructure, Ukraine has refused electricity exports since October 11, 2022, to redirect generating capacity to cover internal demand.[30]

1.3.2 Economic Impacts

Ukraine's economy has suffered due to the war and occupation of certain territories, where metallurgical and other large enterprises are located, the destruction of logistics and energy infrastructure, the outflow of labor and capital, and many other factors. In addition, supply chains are seriously disrupted. Thus, the war, directly and indirectly, impacted the national economy. These impacts include damages and destruction of production, energy, and other facilities and indirect economic losses from suspending the regular activity of production facilities, various business entities, services and commercial sectors, etc.

1.3.2.1 Direct Impact

The preliminary evaluation of direct economic losses of the State Enterprise National Nuclear Energy Generating Company Energoatom due to damages to its facilities, particularly ZNPP, amounted to over 770 mln USD.[31] According to the Ministry of Energy of Ukraine assessment, as of the end of September 2022, the overall direct losses of the energy sector from damages and destruction of energy facilities amounted to 3.6 bln USD.[32] However, following the systemic attacks on critical energy infrastructure after October 10, 2022, the losses are expected to grow substantially. Additionally, the Ministry of Environmental Protection and Natural Resources made a preliminary evaluation of the environmental losses due to the war, which amounted to about 37.3 bln Euro.[33]

The overall direct losses of Ukraine's economy due to damages and destruction of facilities are being assessed by the Kyiv School of Economics (KSE) in compliance with the World Bank methodology.[34] As of September 1, 2022, the total documented losses amounted to 127 bln USD, including 50.5 bln USD (39.7%) in the housing sector, 35.3 bln USD (27.7%) in transport infrastructure, 9.9 bln USD (7.8%) in industry, 7 bln USD (5.5%) in education, 6.6 bln USD (5.2%) in agriculture, 3.6 bln USD (2.8%) in energy, and 14.2 bln USD (11.2%) in other sectors.[35]

1.3.2.2 Indirect Impact

According to assessment of the Ministry of Economy of Ukraine, the reduction of Ukraine's GDP over three quarters of 2022 amounted to -30%.[36] At the same time, the International Monetary Fund forecasts a fall in annual GDP of -35% in 2022.[37] However, the systemic missile and drone attacks on critical energy infrastructure since October

30 https://transparency.entsoe.eu/transmission-domain/r2/scheduledCommercialExchangesDayAhead/show?name=&defaultValue=false&viewType=TABLE&areaType=BORDER_CTY&atch=false&dateTime.dateTime=11.10.2022+00:00|CET|DAY&border.values=CTY|10Y1001C--00003F!CTY_CTY|10Y1001C--00003F_CTY_CTY|10YSK-SEPS-----K&direction.values=Export&direction.values=Import&dateTime.timezone=CET_CEST&dateTime.timezone_input=CET+(UTC+1)+/+CEST+(UTC+2)

31 https://t.me/energoatom_ua/10475

32 https://uhe.gov.ua/media_tsentr/novyny/yak-pidpriemstvam-energetiki-kompensuvati-zbitki-vid-agresii-eksperti

33 https://t.me/mindovkillia/559

34 https://damaged.in.ua/damage-assessment

35 https://kse.ua/wp-content/uploads/2022/10/Sep22_FINAL_Sep1_Damages-Report.docx.pdf

36 https://www.me.gov.ua/News/Detail?lang=uk-UA&id=4725f89d-00a3-4d63-941e-4dac3018ab07&title=PadinniaVvpUkrainiZa9-Misiatsiv2022-RokuOtsiniutsiaNaRivni30-

37 https://www.imf.org/en/Publications/WEO/Issues/2022/10/11/world-economic-outlook-october-2022#Gdp

10, 2022, led to continuous electricity outages across Ukraine and disrupted production processes in various industries of the national economy.

By the estimation of the Ministry of Economy, the continuation of periodic electricity outages in Ukraine due to continuous shellings may lead to a more significant decrease in Ukraine's annual GDP than was previously expected – up to -39%.[38] To mitigate this problem, it is crucial to improve the physical protection of energy facilities, ensure rapid restoration of damaged infrastructure, stimulate energy efficiency and transition to alternative energy sources to the extent possible.

38 https://www.ukrinform.ua/rubric-economy/3611087-zataguvanna-blekautiv-v-ukraini-zagrozue-znizennam-vvp-do-minus-39-minekonomiki.html

2. MODELLING AND SCENARIO ANALYSIS APPROACH

2.1 Modelling Approach

The energy system model for Ukraine which is used in this study has been established in the Institute for Economics and Forecasting, National Academy of Sciences of Ukraine, yet in 2007 and thereafter was systematically updated, substantially extended and improved. It was created using TIMES[39] energy systems model generator (partial equilibrium model); the TIMES family[40] of models is widely used as they provide a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. The concept of TIMES approach is to supply energy services at the minimum global cost (minimum loss of total surplus) by simultaneously making decisions on technology investments, level of operation of various energy technologies, primary and final energy mix, and international energy trade. The choice made by the model is based on the iteration of alternative technological options on supply and demand sides, on the economics of the energy supply and consumption, and on energy/environmental policy criteria. Thus, TIMES approach is vertically integrated and concentrated on optimization of the entire energy system unlike the single-project based approach. The TIMES framework is normally applied to the analysis of the entire energy sector, but may also be applied to the detailed study of single sector (e.g. the electricity and district heating sector) on the national or regional scale. The framework can also be used to simulate the mitigation of GHGs, including methane (CH_4) and nitrous oxide (N_2O), as well as non-GHG gases and other pollutions.

Calculation of the trajectory of the energy system development and the corresponding GHG emissions in TIMES is normally made upon criteria of minimization of total energy system costs[41], which includes:

- capital investments (costs) both for the construction of new energy assets (that should be considered exactly as an investment in accordance with accepted macroeconomic statistics terminology), and for the purchase of final energy consumption appliances, some of which could be considered as not investment, but intermediate production or final consumer costs (for energy management, installation of modern control systems, thermal modernization of buildings, purchase of household appliances or vehicles, etc.);
- fixed and variable operating and maintenance costs for energy production, transportation and consumption technologies;
- energy and fuel costs (expenditures) assessed on the basis of the marginal cost of each type of fuel, taking into account the cost of imported resources;
- concessions, rental or other payments (target allowances, emission tax, etc.);
- residual value of technologies at the end of the modelling horizon.

This approach allows developing energy/environmental projections from the standpoint of minimization of social costs, and at the same time maximization of surplus of energy producers and consumers. Thus capital investments, considered in TIMES models, are not just investments in the energy sector, but more precisely are «energy related investments», accounting for about 60-70% of total investments in the economy. At this point, through the explicit representation of the technologies, it is possible to investigate the impacts of taxes, subsidies, as well as technical standards or other policy constraints for single and multiple technologies, for specific sectors or for the entire system, and therefore to provide quantitative indications of the energy efficiency improvements, technology shift or expected effectiveness of the specific policies.

39 Documentation and various applications of Markal/TIMES models could be found at https://iea-etsap.org/

40 The Energy Technology Systems Analysis Program (ETSAP) Community. Available from: https://iea-etsap.org/index.php/community

41 This methodological approach is generally accepted; for example, see Impact Assessment. Energy Roadmap 2050 https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part1.pdf, or Impact Assessment of the Energy Efficiency Directive (2012/27/EU) for the Energy Community http://manu.edu.mk/wp-content/uploads/2016/12/Final-Report-for-Assessment-of-the-impact-of-the-Energy-Efficiency-Directive.pdf

The topology of TIMES-Ukraine is harmonized with international statistical classifiers, it is fully charged with the latest available economic and energy statistics to reflect reported national energy balances and GHG inventory, and its database contains over 2,000 new technologies that helps to investigate decarbonization pathways throughout all economic sectors. The energy system is represented in the TIMES-Ukraine model by a single region, and consists of seven sectors: energy supply; generation of electricity and heat; industry; households; services; transport and agriculture.

While some energy processes are presented in the model explicitly, such as big power plants or transport vehicles, and this makes possible to consider scrupulously their technical and cost (investment) parameters, other energy process could not be presented with such level of details because of variety of technological processes in specific sector, lack of correspondent data or other reasons. The latter set of processes is then presented in a dummy “aggregated” way based on sector-level data and assumptions on possible improvements, related investments etc. For example, Ukraine’s energy-intensive industries are presented in terms of actual technological chains for manufacture of the main types of their products, i.e. iron and steel, ferroalloy and aluminum, ammonia, fertilizers and other chemical production, cement, lime, glass, pulp and paper. For other branches of industry, the structure of energy flows is split by the four types of general processes: electric engines, electrochemical processes, thermal processes and other processes. The transport sector in TIMES-Ukraine is represented by the types of transportation: road, railway, pipelines, aviation and navigation, with explicit specification of technical and cost parameters of each technology (vehicle type). Respectively, energy services, which are provided by technologies of road and rail transport, are transportation of passengers and freights. Energy consumption in residential and commercial sectors is determined by the most energy intensive categories of consumer needs, such as space heating and cooling, water heating, lighting, cooking, refrigerating, clothes washing and drying (ironing), dishwashing etc. The upstream sector is presented in detail by the type of extraction and split by the group of mining companies; the biggest power plants are presented separately and by generation units, while small CHPs and boiler houses are grouped by fuel used. Energy generation and consumption are not localized in the model, thus energy transportation and distribution are presented in a simplified way, that may result in some underestimation of investments needed for perspective development of energy (electricity, heat, gas) networks and other sectoral infrastructure.

During 2022 TIMES-Ukraine was permanently updated to consider war damages; it was also improved and its technology database was extended to better represent technological options for production, transportation and consumption of hydrogen and other synthetic fuels.

2.2 General Framework Conditions for Scenario Analisys

The war in Ukraine has put a major toll on country’s economy, displacing population, damaging physical infrastructure, pushing businesses to shut down and thus – stipulates high uncertainty regarding the post-war recovery path. The current state of business is also unclear as most of statistical data is unavailable. In general, the energy demand is driven by the macro drivers such as aggregate gross domestic product (GDP), sectoral output or value added, population growth and other. Meanwhile, owing to a lack of current information and high level of uncertainty, energy demand drivers discussed below cannot be properly assessed upon traditional approach but should largely rely on assumptions and indirect information from open sources.

2.2.1 Demographic Development

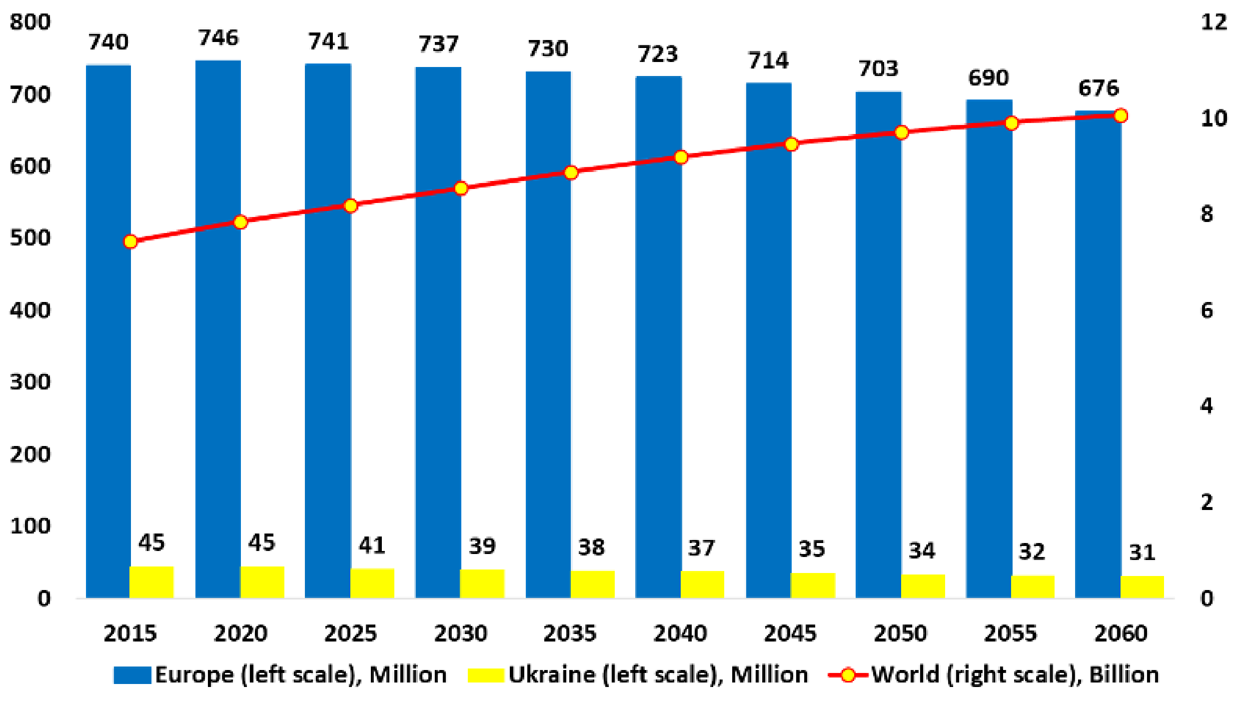
Prolonged hostilities normally cause an increase in the mortality rate, decrease in the birth rate, and deterioration in the state of health, in particular due to stress, untimely treatment and the unavailability of quality medical care, limited access to energy and drinking water. The population near the front line, as well as internal migrants, are particularly acutely aware of such welfare issues. Losses of the civilian population directly from military actions, in particular from missile strikes or other war crimes, are tangible, especially in the occupied territories. At the same time, despite the tragic nature of these losses, external migration is much more critical for Ukraine's economy, as it will be measured in millions of citizens. Having arranged family life abroad, some share of Ukrainian families will prefer to stay at their new place of residence, especially if their original place of residence or workplace in Ukraine are destroyed. Among the people who will remain in Ukraine in the post-war period, it is currently difficult to expect for a rapid increase in the birth rate (baby boom) because of the preservation of security risks and the uncertainty of the economic situation.

Due to the lack of reliable and complete information on current demographic characteristics of households, we did not take into account war victims in our study, as well as the probable increase in natural mortality and decrease in birth rates. As reported by the UN Refugee Agency[42], as of September 7, 2022, 7.2 mln refugees fled Ukraine and were recorded across Europe. Although this number did not change a lot since the spring 2022, it is likely to increase during the winter of 2022/2023 given the high risks of electricity and heat cutoffs due to ongoing destruction of energy infrastructure.[43] According to surveys conducted at the end of August 2022[44], 6.8% of Ukrainian refugees in the EU countries have already decided not to return to Ukraine, and another 17% hesitated to answer. In general, the share of refugees of about 20%, who are unlikely to return to Ukraine after the war, has remained stable since the beginning of the Russian invasion.[45]

Demographic projection prepared for the purpose of this study considers the population losses via external migration in 2022, and is aligned in a long run after 2023 with the "medium" scenario (medium fertility, medium life expectancy, medium net migration) prepared by the Institute of Demography and Social Studies, NASU, in 2020. [46]Respectively, this projection covers the total population of Ukraine (occupied territories are included) and is based on pre-war assumptions on demographic parameters such as mortality rate, TFR (children per woman), number of survivors, probability of death, born alive, migration and others. Resulting estimates of population's dynamics are shown in Figure 2.1.

FIGURE 2.1

Demographic development in the world, Europe and Ukraine



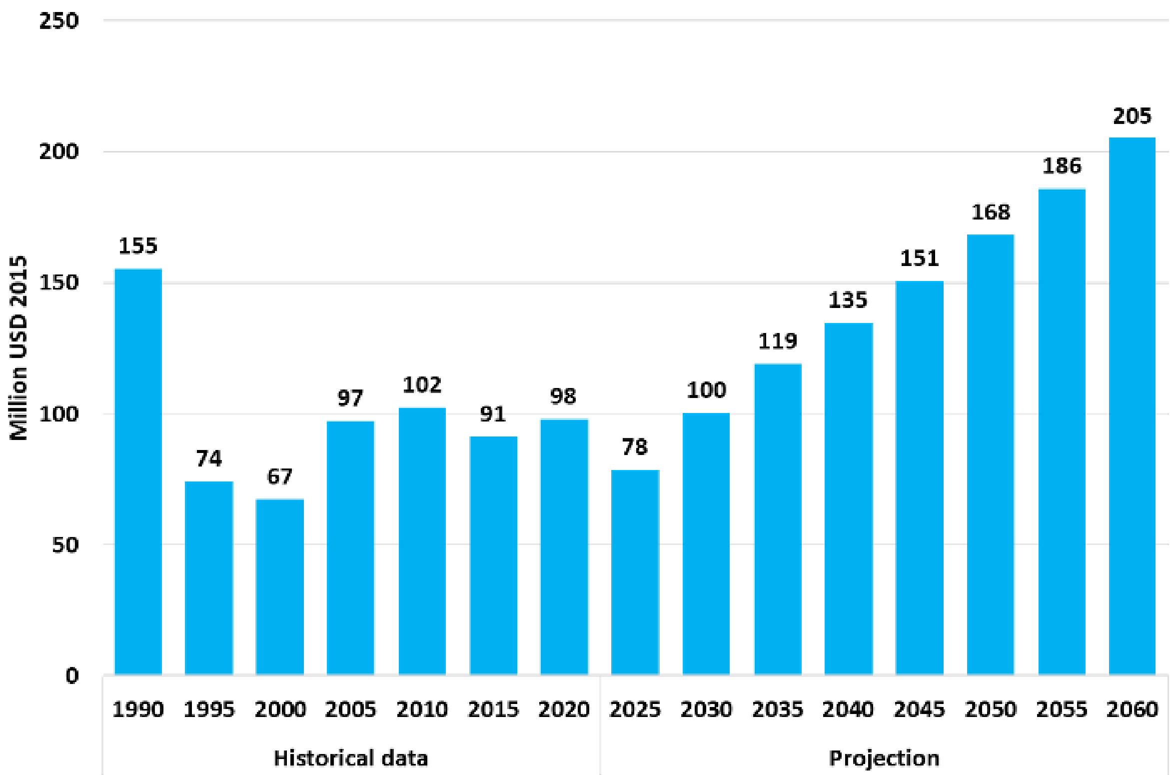
42 https://data.unhcr.org/en/situations/ukraine
43 https://www.polskieradio.pl/395/9766/Artykul/3059703,Polish-official-warns-of-new-wave-of-Ukraine-refugees-in-winter
44 https://razumkov.org.ua/napriamky/sotsiologichni-doslidzhennia/nastroi-ta-otsinky-ukrainskykh-bizhentsiv-lypen-serpen-2022p
45 https://razumkov.org.ua/napriamky/sotsiologichni-doslidzhennia/ukrainski-bizhentsi-nastroi-ta-otsinky
46 https://idss.org.ua/forecasts/nation_pop_proj

2.2.2 GDP Projection

The war has severely impacted Ukraine's economy, destroyed country's infrastructural objects, as well as resulted in damages to the energy system. Early estimates suggested that in 2022 Ukraine's GDP could decline in a range of 45%[47][48] and 30%[49] with a significant uncertainty regarding the dynamics of economic recovery in the coming years. The most recent estimate of the National Bank of Ukraine[50] provides 33.4% drop in 2022, followed by 5% annual growth within next two years. This will make very partial rebound of the GDP drop, as in 2025 it would still be 23% lower than in 2021.

FIGURE 2.2

GDP projection



As suggested by the World Bank, during 2025-2030 the economy would keep rebuilding with around 5% per year. In the post-2030 period, the assumed growth rate of economy would be gradually reducing from 3.5% during 2030-2035 to 2.0% at the end of the modelled period (2051-2060) (Figure 2.2). Such recovery rates will let Ukraine reach back the pre-war level by 2031, and by 2060 the GDP will double.

To estimate changes in production by sector in 2022, a "territorial withdrawal" approach was applied and supported by the information on expectations of enterprises regarding development of their business activity[51] and assessment of damages caused to Ukraine's physical infrastructure by the Russian invasion.[52] For example, in industry the biggest drop in 2022 is expected in metallurgy and oil refinery caused by destruction of plant assets

47 https://www.worldbank.org/en/news/press-release/2022/04/10/russian-invasion-to-shrink-ukraine-economy-by-45-percent-this-year
48 http://ief.org.ua/?p=12018
49 https://www.ebrd.com/what-we-do/economic-research-and-data/rep.html
50 https://bank.gov.ua/en/news/all/inflyatsiyniy-zvit-lipen-2022-roku
51 https://ukrstat.gov.ua/operativ/menu/menu_e/tda.htm
52 https://kse.ua/russia-will-pay/

and suspension of production. While refinery plants are supposed to get back into operation after repairing, almost half of the steel production capacities are assumed as totally destroyed. Food and textiles manufactures were less affected by the war, as these enterprises being widely distributed throughout the country managed to reallocate their facilities and quickly adapt to the new operational environment. Modelling assumption on non-recovery losses were made on the basis of various open sources (Table 2.1)

TABLE 2.1

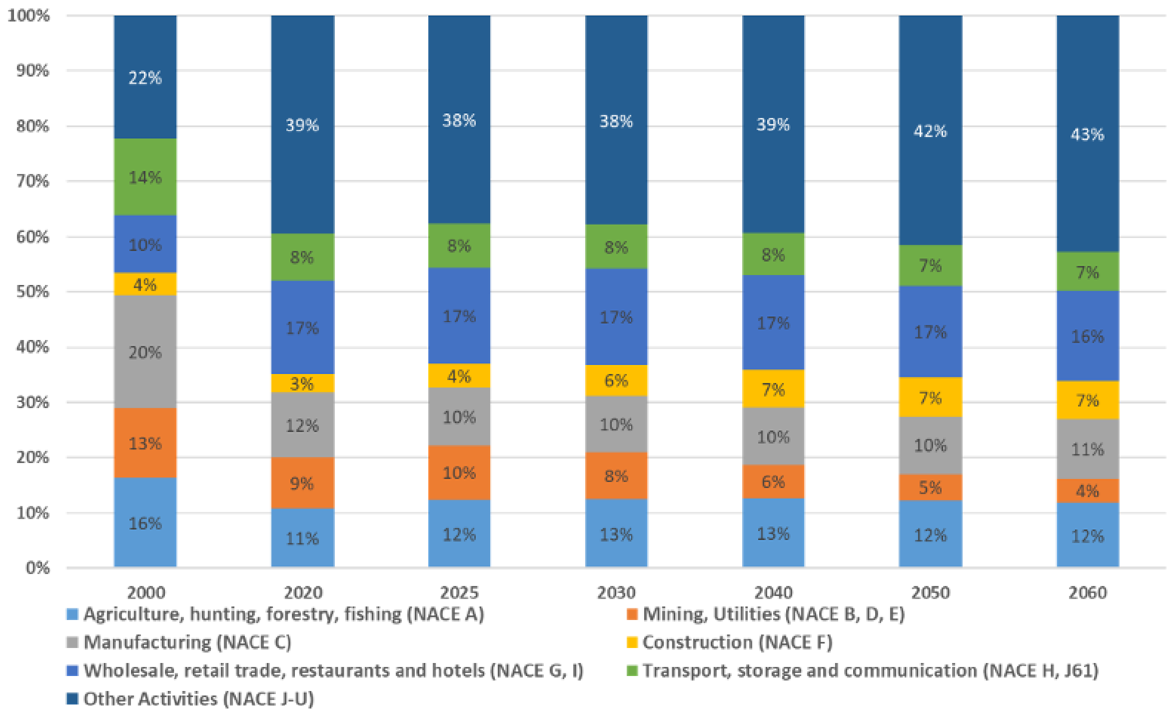
Production drop and loss of assets in industry in 2022

INDUSTRY	PRODUCTION DROP IN 2022	NON-RECOV. LOSSES IN 2022
Food, beverages and tobacco products	-16%	-30%
Textiles, wearing apparel, leather and related products	-0.3%	-30%
Wood, paper, printing and reproduction	-23%	-30%
Coke	-48%	-30%
Refined petroleum products	-90%	
Chemicals and chemical products	-32%	-30%
Rubber, plastic, other non-metallic mineral products	-34%	-30%
Metallurgy	-76%	-40%
Machinery	-32%	-30%
Other industries	-45%	-30%

In terms of gross value added (GVA), in 2022 its production will drop by 30% (w.r.t. 2021) in agriculture, in mining by 47%, in manufacturing by 35% and in services by 34%. In the long run no pre-defined radical structural transformations in the economy were assumed. Although different rates of recovery among sectors will still provide some structural changes. It was estimated that by 2030 GVA of the manufacturing activity would reach 87% of the pre-war level (that of 2021), transport and services – 96%, agriculture – 103% and construction – 161%. The more rapid growth of the construction sector and non-metallic minerals (NMM) production (construction materials) would be driven by the economic recovery and rebuilding activities, giving a place to services and machinery in a long run. By 2060, services and transport would constitute 66% of GVA, construction – 7%, manufacturing – 11%, mining and utilities – 4% and agriculture – 12%.

FIGURE 2.3

Gross value added by sector



2.2.3 Manufacturing

Metallurgy and chemical industry are vastly export-oriented, thus production facilities that were not destructed during the war will still be able to cover domestic demand on traditional steel and chemical products. For this reason, we assume that no new facilities will be phased in, while existing plants could be improved and upgraded by the model decision. This is in contrast to cement, glass and other NMM products, where rapidly growing demand will overstep the pre-war level already by 2030, thus new factories have to be constructed. Cement production will be driven by the growth in construction sector, ammonia – by agriculture needs (manufacturing of synthetic fuel from ammonia was not considered), advanced growth of paper and glass production was assumed to displace imports from domestic market. (Table 2.2)

TABLE 2.2

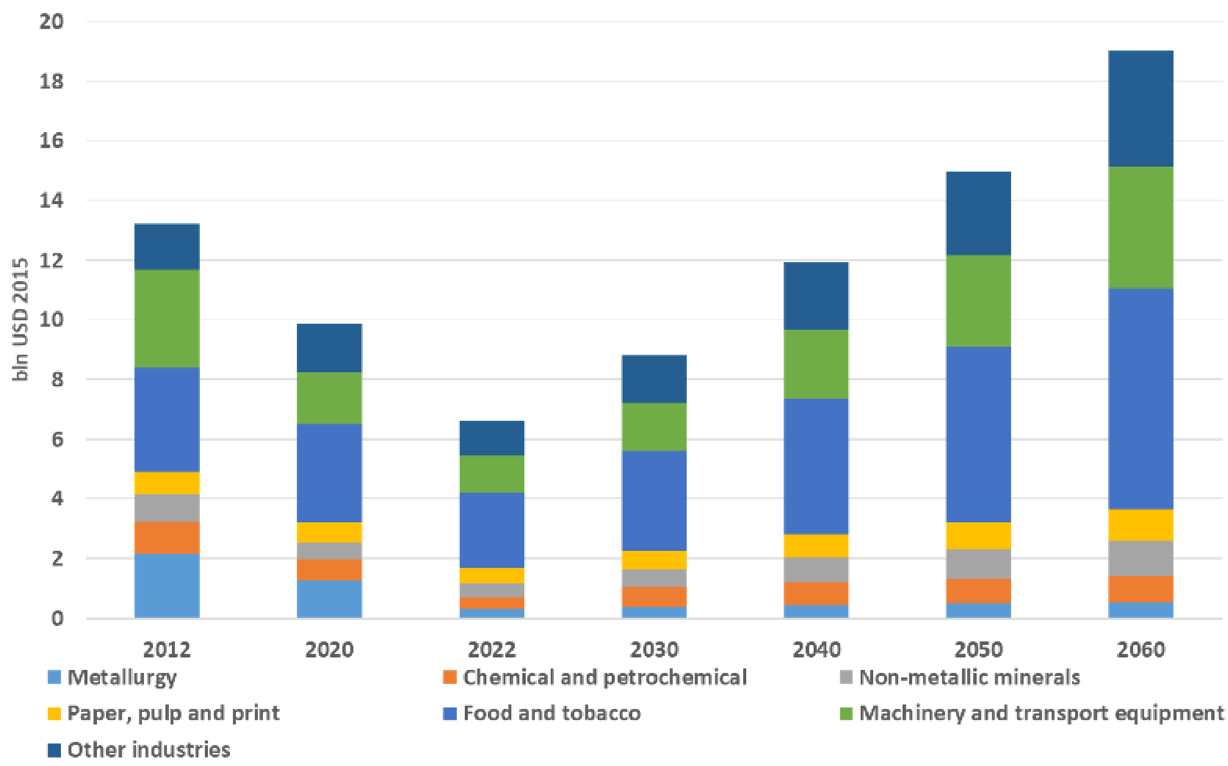
Selected demand drivers in manufacturing

PRODUCTS	2010	2020	2022	2030	2040	2050	2060
Crude steel , mt	17.5	10.3	2.6	3.2	3.6	4.0	4.4
Aluminium, unwrought, kt	53.5	7.9	2.0	2.4	2.8	3.1	3.4
Ammonia, mt	4.2	2.8	2.3	2.6	3.0	3.2	3.3
Portland cement, mt	9.5	9.7	9.3	13.5	16.6	18.6	20.2
Lime, mt	4.2	2.5	1.5	2.0	2.4	2.7	2.9
Paper, kt	411	387	300	363	448	525	610
Glass, mt	0.95	0.87	0.63	0.84	1.10	1.25	1.37

Despite statements in press regarding rehabilitation of totally destroyed metallurgical plants and infrastructure[53], most of the projects currently discussed by experts and the Government of Ukraine are focused on domestic demand prevail – it is expected that sheet steel, rails, beams and coated steel will be needed to rebuild damaged infrastructure in Ukraine. Other projects[54] also support the intention to join the value-added chain of "green" steel production: to increase the production of DR-class coils, the production of direct reduction iron and hot briquetted iron, including with the use of hydrogen, production of "green" steel in electric arc furnaces. However, we assume that metallurgy will be able to recover no more than 50% of its gross value added.

FIGURE 2.4

Gross value added in manufacturing



Instead, the restorative nature of economic growth will ensure advanced growth in the food, textile, and pharmaceutical industries. The growing focus on the processing of agricultural raw materials within the country will result in 2.4 times increase of food production till 2060. After investments will be directed not only to the modernization of infrastructure, but also to the production of technological equipment, household appliances, equipment for the development of information technologies and other types of mechanical engineering, the share of mechanical engineering will increase almost 3 times by 2060. (Figure 2.4)

2.2.4 Services

Moderate but gradual increase in household income will ensure the harmonization of household spending and lead to an increase in the share of the services in GDP up to 52% from 49% as of today. The largest growth among services during 2023-2050 will be observed in computer programming, consultancy and related activities: production of services there will grow in average 4% annually resulting in threefold increase over the period and almost its double share in GDP (Figure 2.5). Instead, destruction of production facilities in industry enhanced by the

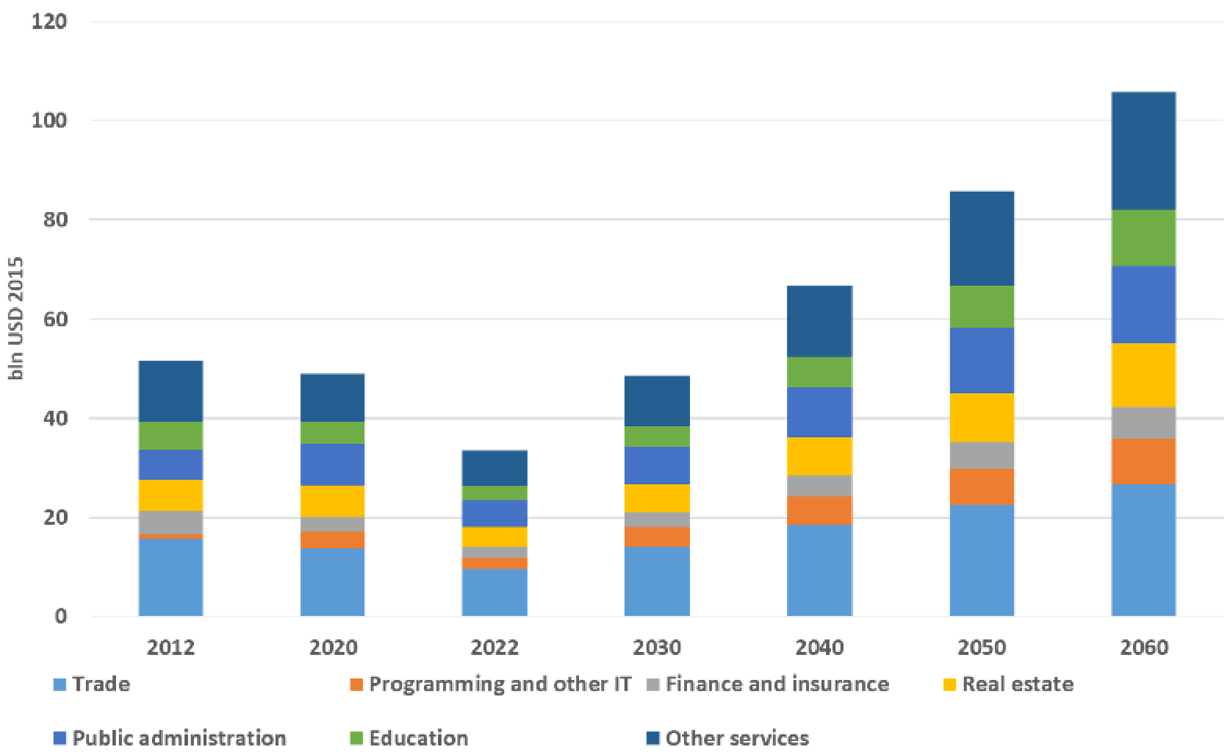
53 https://www.elespanol.com/eventos/7-aniversario/20221103/natalia-yemchenko-scm-haemos-rusia-millones provocados/715428862_0.html

54 https://www.kmu.gov.ua/storage/app/sites/1/recoveryrada/eng/economic-recovery-and-development-eng.pdf

shift towards new technologies and newly created materials will result in reduction of the share of manufacture of the main chemicals and metallurgy to 0.5% of GDP from 2% as of before 2022.

FIGURE 2.5

Gross value added in services



2.2.5 Residential Sector

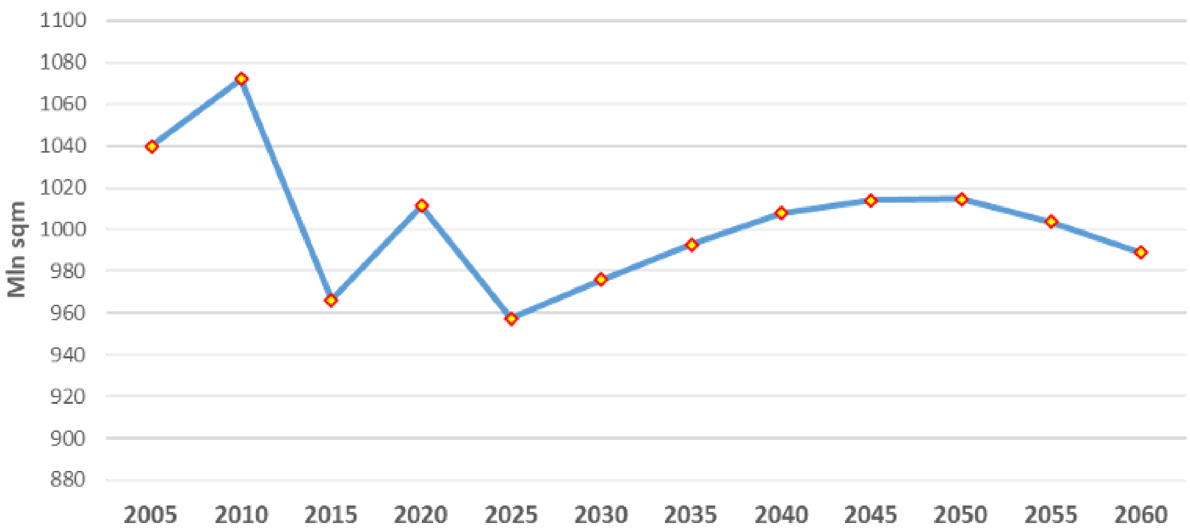
Population and floor area are the main energy demand drivers in the residential sector, further decomposed for analysis. For example, space heating demand is assessed as floor area (but not in energy units) using the number and category of residential dwellings in urban and rural areas, taking into account the dynamics of population at the place of residence and composition of households, growth rate of the specific dwelling area per resident, as well as construction of new buildings with centralized and individual heating systems. As it was reported in September, 2022,[55] 6.4% of residential and commercial buildings were destroyed by that time.

We assume that rebuilding of dwellings will be made with an average pre-war rate, i.e. about 10 mln sqm annually. Assuming reaching 1.5 room per person in 2060 (132 sqm per household in urban private buildings, 119 sqm in rural private buildings and 65 sqm in multi-apartment buildings), total floor area of (inhabited) housing stock is supposed to decrease after 2050 (Figure 2.6).

55 https://kse.ua/wp-content/uploads/2022/10/ENG_Sep22_FINAL_Sep1_Damages_Report-1.pdf

FIGURE 2.6

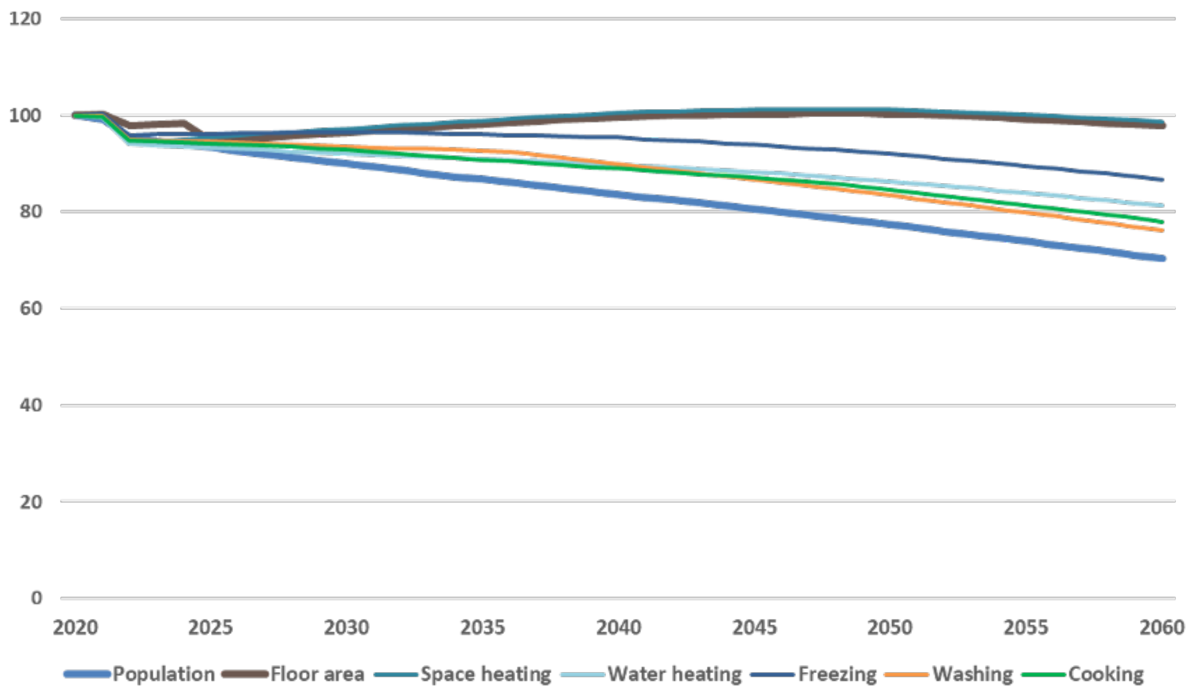
Total floor area of residential buildings



New buildings that meet high standards of energy performance and constructed after 2023 will constitute 27% of total housing stock by 2050, while all other buildings are supposed to be properly insulated. This will require to keep 2.8% annual rate of thermal insulation of existing building stock throughout modelling horizon. Gradual reduction in population and floor area predetermines that most of the demand drivers will be cut back (space and water heating, cooking, lightning etc.); actual energy consumption may reduce even faster owing to the use of energy efficient appliances and renewable energy (Figure 2.7). The only drivers that are assumed to increase are the use of dish washing machines (increase 2.3 times in 2060 comparing to 2020) and air conditioners (increase 2 times).

FIGURE 2.7

Selected energy demand drivers in the residential sector



2.2.6 Transport Sector

The consequences of war for the transport sector are extremely painful. In addition to the obvious reduction in demand for transport services due to the drop in business activity and the blockade of transport highways and ports due to hostilities, the transport infrastructure and fleet of vehicles suffered significant damage. Civilian transport infrastructure remains a priority target for Russian attacks. As of the end of summer 2022, 25,000 km of highways and 500 km of railways, 315 bridges, 111 railway stations were destroyed as a result of hostilities. Losses due to destroyed public transport reached 657 mln USD, private vehicles – 1.7 bln USD or about 200,000 cars.[56] For the modelling purpose we assume that 10% of urban public transport (except metro), 5% of intercity buses and rail locos, and 2% of private cars were destroyed in 2022.

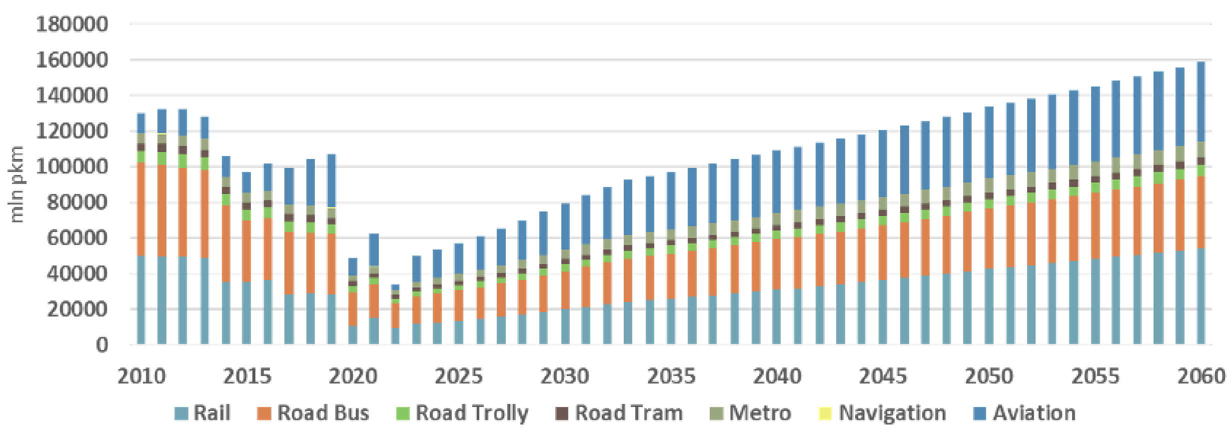
Energy demand drivers in the Transport sector are expressed as passenger*km or ton*km and estimated by regression considering:

- population (urbanization), real personal income (RPI);
- GVA (output) of transport sector by mode; GVA (output) of sectors that provide the main groups of goods transported by mode.

In this study, we did not analyze any specific sectoral policies such as modal shift in passenger transportation, for example switching from private to public transport that is normally assumed as an efficient mitigation measure but is not provided so far by the Ukrainian legislation. Thus, model calculations provide insight of optimal fuel and technology mix to meet pre-defined demand expressed as passenger turnover by transport mode. (Figure 2.8)

FIGURE 2.8

Passenger turnover

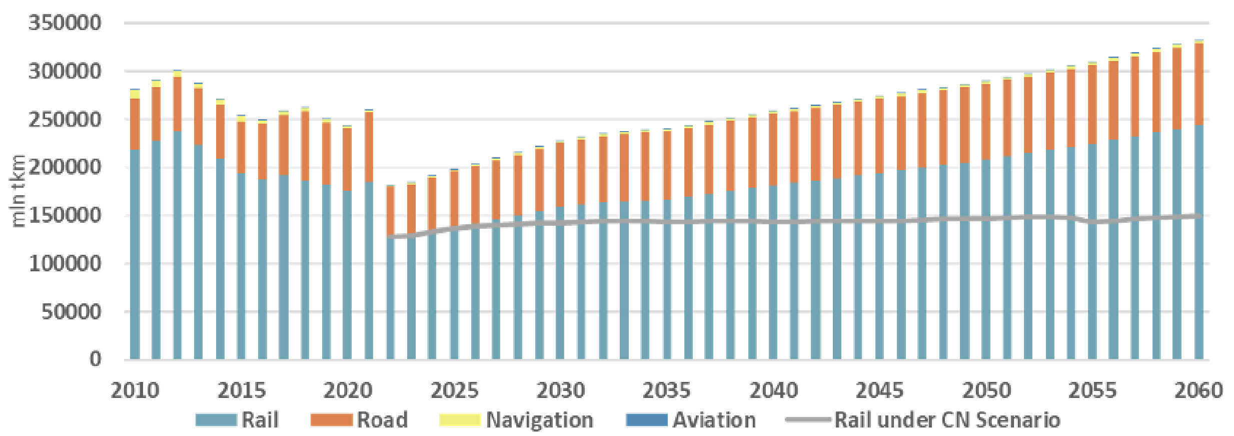


Considering that about 40% of rail freight consists of fossil energy resources (incl. coke and oil products) and iron ore, the driver for the rail freight transportation for the Carbon Neutrality scenario slightly differs from the one in the Reference scenario. (Figure 2.9)

56 https://kse.ua/wp-content/uploads/2022/10/ENG_Sep22_FINAL_Sep1_Damages_Report-1.pdf

FIGURE 2.9

Freight turnover



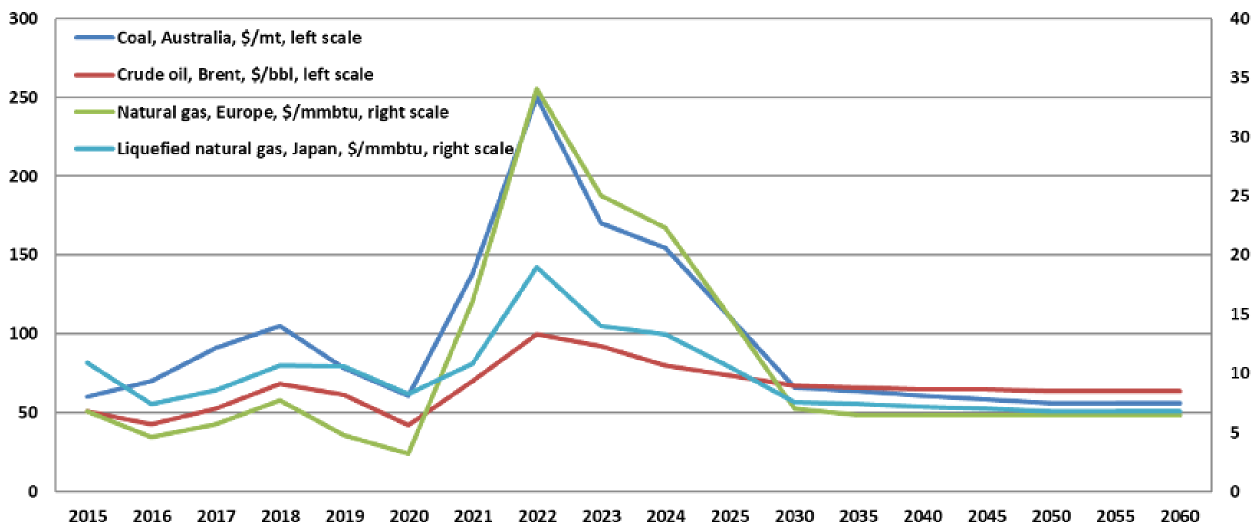
2.2.7 International energy prices

Comprehensive energy prices projection is as important as macroeconomic drivers or energy policy targets, as different price dynamics for different energy resources determine the price parity between energy resources and thus may affect economic viability of technologies or policy options in the future.

For the purposes of this analysis we used the World Bank Commodities Price Forecast (April 2022)[57] extended by 2060 with an IEA projection (World Energy Outlook 2021, Announced Pledges Scenario)[58] and supported by assumption that prices are stabilized for the last decade. (Figure 2.10)

FIGURE 2.10

Commodity prices forecast



57 https://openknowledge.worldbank.org/bitstream/handle/10986/37223/CMO-April-2022.pdf
58 https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf

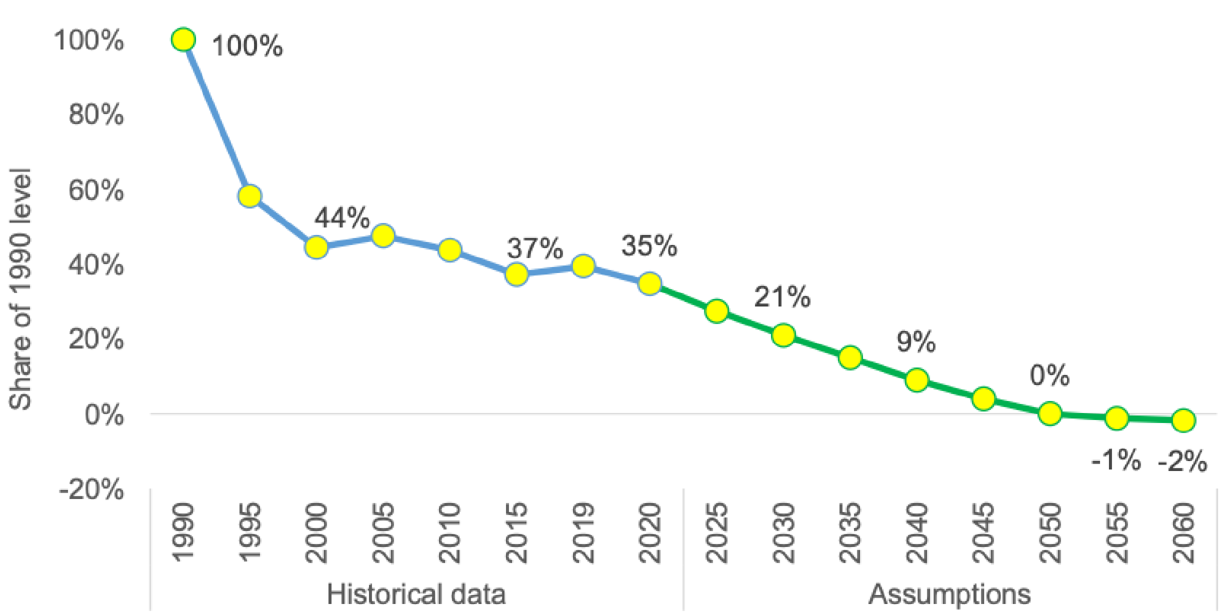
2.3 Scenarios Description

The Paris Agreement (Art. 2), in seeking to strengthen the global response to climate change, reaffirms the goal of limiting global temperature increase to well below 2°C, while pursuing efforts to limit the increase to 1.5°C. To achieve this temperature goal (PA, Art. 4), Parties aim to reach global peaking of GHGs as soon as possible, recognizing peaking will take longer for developing country Parties, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of the century.

GHG emissions in Ukraine in 2020 amounted to 317.7 Mt CO_2e excluding LULUCF, that is 66.3% lower than in 1990, and 4.8% than in 2019. Together with the LULUCF sector, emissions amounted to 315.94 Mt CO_2e and decreased by 65.1% in comparison with 1990 level and by 11.7% in comparison with 2019[59]. Since Ukraine became a candidate for joining the EU, Ukraine's climate targets should be the same as in the EU – climate neutrality (net zero emissions) by 2050 with the subsequent increase in negative GHG's emissions. In this study, based on historical data and the EU goals, we've assumed the dynamics of GHG emissions as shown on Figure 2.11, and that was further imposed as a constraint for modelling exercise upon Carbon Neutrality scenario.

FIGURE 2.11

Assumed dynamics of GHG emissions



The energy sector is the largest emitter of GHGs in Ukraine. In 2020 its share was around 65% without the LULUCF. Together with "Industrial processes and product use", the share of these two sectors was 84%. In 2020 CO_2 remained the largest emitted gas – 64.8% of all emissions, with 22.6% of CH_4 and 12.0% of N2O.

In order to achieve climate neutrality, decarbonization processes in the "Energy" sector and the closely related sector "Industrial processes and product use" (in terms of the IPCC) will play a crucial role. Using the TIMES-Ukraine model, the pathway to reduce GHG emissions to net-zero in these two IPCC sectors is proposed and modelled. The Reference scenario (REF) was developed as the basis to calculate the differences between scenarios without climate policies (REF scenario, business-as-usual approach) and active mitigation policies (Carbon Neutrality scenario), and identify economically feasible measures to reduce GHG emissions to net-zero.

59 Ukraine. 2022 National Inventory Report, May 2022. – https://unfccc.int/ghg-inventories-annex-i-parties/2022

2.3.1 Reference Scenario

The development of a Reference (business as usual) projection is a crucial step in understanding the GHG emission reduction potential in "Energy" and "Industrial processes and product use" (IPPU) sectors in the current (base) year throughout modelling horizon. Based on the comparison with the Reference scenario, it is possible to estimate the feasibility of implementation of additional or alternative (low-emission) policies and measures by comparing investment needs, economic and environmental impacts etc.

The REF scenario is set as an "exploratory scenario", assuming that no fundamental changes take place and particularly no additional emission reduction measures are implemented during the projected period. This scenario is also developed to model conditions when implementation of energy efficiency improvements, development of renewable energy sources, penetration of new technologies, environmental and climate commitments are implemented with rates that have been observed over the past 5-7 years, clearly insufficient to meet ambitious climate targets. Existing policies are still considered in REF, such as feed-in tariff for RE or replacement of incandescent lamps with energy-efficient ones, although various policy statements or targets (indicators) of sectoral programs, for example as for total electricity generation or capacity mix, were neglected. Instead the model estimates energy demand internally and identify the optimal technology mix to meet this demand. The main purpose of the REF scenario is to create a basis for comparison with scenario of GHG emissions reduction to net-zero in Energy and IPPU sectors.

2.3.2 Carbon Neutrality Scenario

The Carbon Neutrality Scenario (CN) is a decarbonization scenario for "Energy" and "Industrial processes and product use" sectors, representing the least cost pathway to achieve total net zero emissions in 2050 and increase negative GHG emissions till 2060.

Carbon Neutrality Scenario provides ambitious renovation policies and strict building codes, high rates of thermal modernization, penetration of high energy-efficient equipment such as heat pumps, extensive use of waste heat recovery and high rate of electrification in industry and other sectors, deployment of hydrogen and biofuels in transport, high renewables deployment coupled with storage facilities and clean fuel generation, enabling conditions for successful transition, such as higher market acceptance, learning-by-doing, etc.

The CN scenario assumes favorable conditions for nuclear (large and small reactors), hydrogen and carbon capture, utilization and storage (CCUS) (including direct air capture) development not only in power sector, but also in industry, synthetic electric fuels production etc.

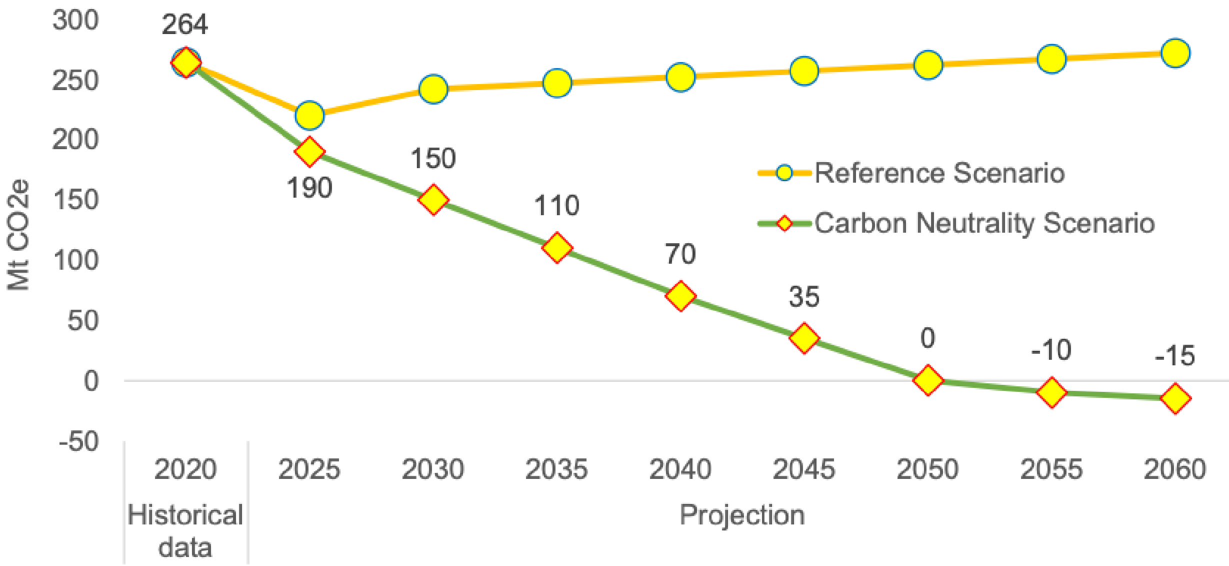
In the REF and the CN scenarios, import and export of hydrogen or biomethane, or other green fuels/energy are not provided.

One of the key assumptions of a long-term modelling of the Energy and IPPU sectors' decarbonization pathway is the inclusion of all temporary occupied by Russian Federation territories of Ukraine in macro-economic, energy and climate drivers.

It is assumed that GHG emissions in the Reference scenario may not decrease till 2060, except for 2022-2023 due to the invasion of Russia, when the Carbon Neutrality scenario have a cap and assumes faster rates of GHG emissions reduction in the first decades and slower rates at the end of the modelling horizon. As an example, it was set target to achieve negative emissions at the level of 10-15 Mt CO_2e in 2055-2060, which is approximately 1-2% of the 1990 level. The Carbon Neutrality scenario envisages that the post-war recovery and further economic development of Ukraine would be based on green and clean technologies (Figure 2.12).

FIGURE 2.12

GHG emissions cap by scenario



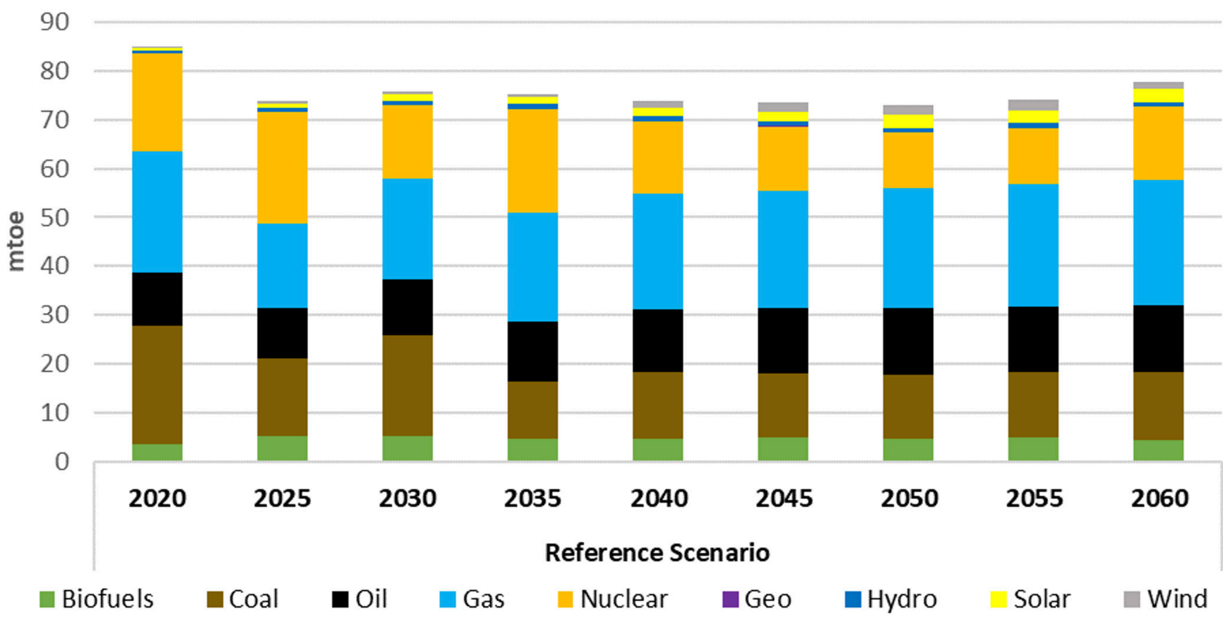
3. PERSPECTIVE ENERGY SYSTEM OF UKRAINE: MODELLING RESULTS

3.1 Primary Energy

According to the results, the Total primary energy supply (TPES) in the Reference scenario (Figure 3.1) would remain stable in the post-war period and the fuel structure would not be significantly changed. In this case, Ukraine would remain dependent on the import of fossil fuels, though the level of dependence decreases after the end of the war from 40% to 28%. Oil is the only resource, which import is higher than mining and higher substantially, 3 to 4 times. This difference would increase by the end of horizon with growing import volumes and phase out of own extraction. Despite the significant potential of RE, it is utilized to no more than 13% of the TPES with half of it being the biofuels share.

FIGURE 3.1

Total primary energy supply in the reference scenario

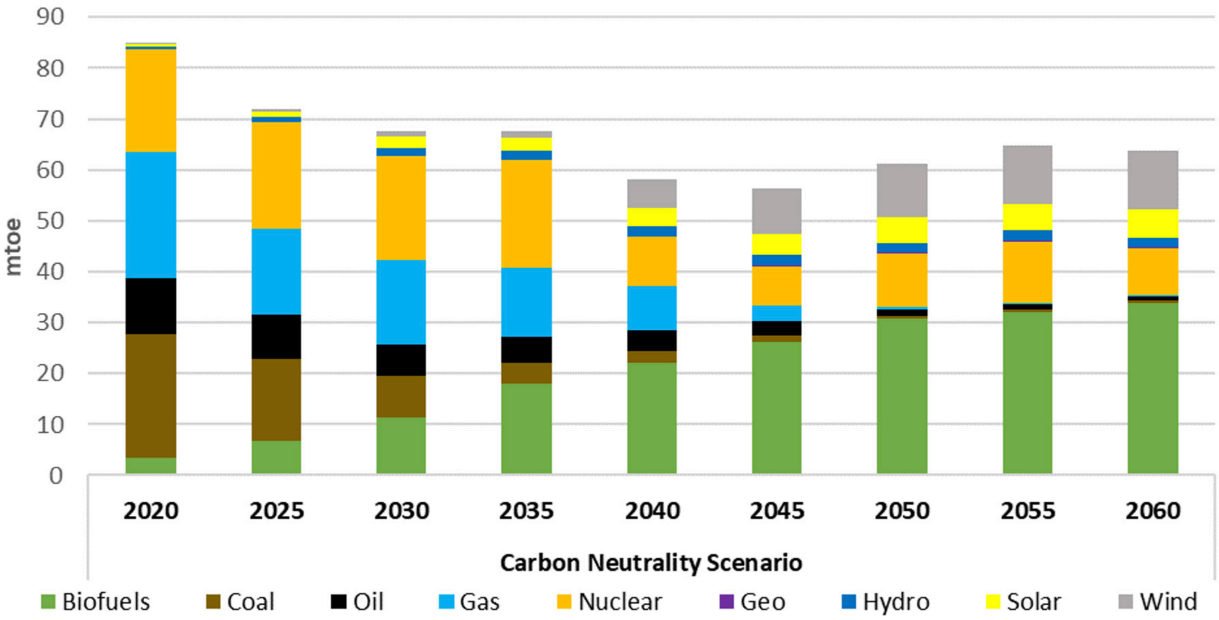


In the Carbon Neutrality Scenario (Figure 3.2), significant changes of the TPES are required to reach the carbon neutral economy, which include the almost complete replacement of fossil fuels with RE by the middle of the century, as well as the implementation of energy-efficient measures (in particular, deep retrofit of buildings). The role of nuclear energy in the decarbonisation process may be significant, but much lower compared to renewables, which share reaches 76% in 2050 and 80% in 2060. The bioenergy share alone might comprise the half of TPES, hence this resource potential is very special and of great importance.

Moreover, 99% of all biomass is mined inside Ukraine, which in addition to wide utilization of solar, wind, hydro and geothermal energy, and owing to phase out of fossil fuels could make Ukraine by the middle of the century for 98% independent of energy imports.

FIGURE 3.2

Total primary energy supply in the carbon neutrality scenario

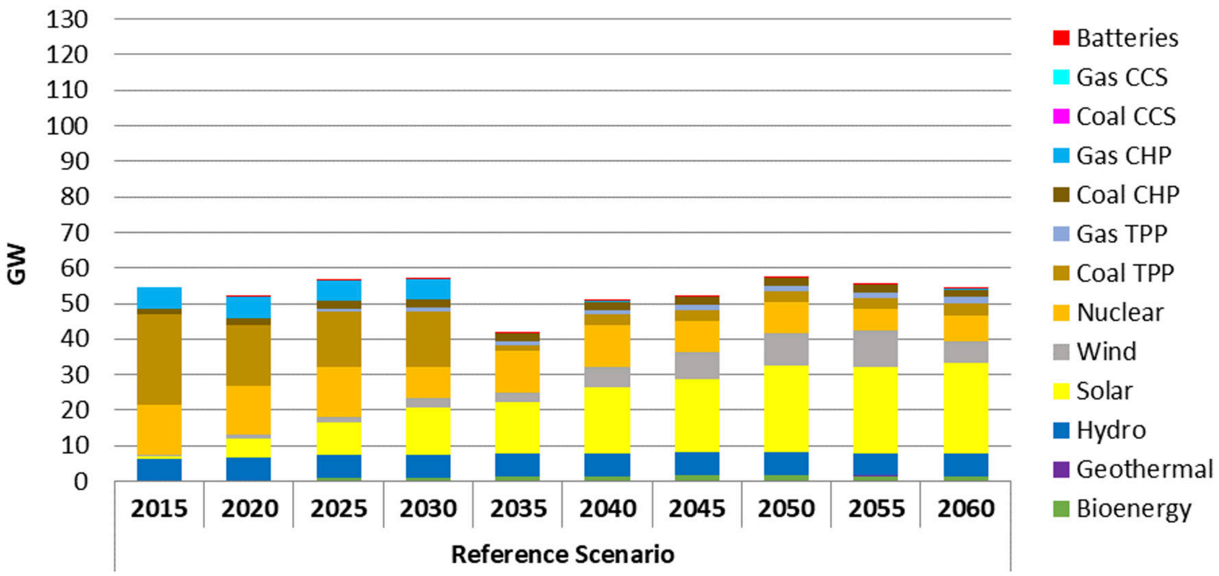


3.1.1 Transformation

Total installed capacities might reach 57.3 GW in 2050 (Figure 3.3). Investments in the RE capacities continue the recent growing trend even under the Reference scenario, reaching 72% in 2060 with solar PP being the largest contributor reaching 26 GW. Nuclear power capacities decrease twice having at disposal 7.4 GW of new big reactors by the end of the horizon. Coal TPP almost phase out by 2035 in compliance with European standards (Directive 2010/75/EU) of pollutant emissions, marking Ukraine's continuous efforts of regulatory approximation towards key elements of the EU acquis.

FIGURE 3.3

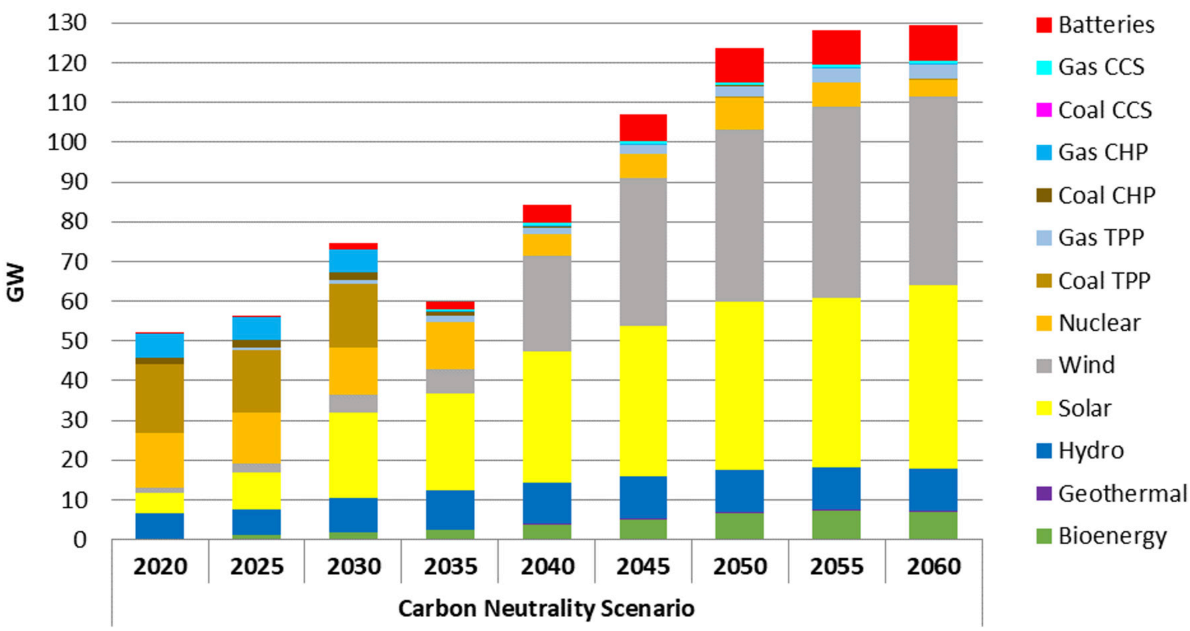
Power generation installed capacity in the reference scenario



Under the Carbon Neutrality scenario, the need in total installed capacity would reach 129 GW – 2.4 times higher (Figure 3.4). Solar and wind capacities would be almost 78% of the total and equal in size, RE at a whole constitute 96%. One new big nuclear unit and 3 GW of small modular reactors would appear by the end of the modelling period. The energy storage capacities are planned at 9 GW and along with 7 GW of bioenergy, 10.6 GW of hydro and 4.5 GW of clean gas (biomethane, synthetic methane) power plants they would have crucial role in balancing intermittent wind and solar sources.

FIGURE 3.4

Power generation installed capacity in the carbon neutrality scenario

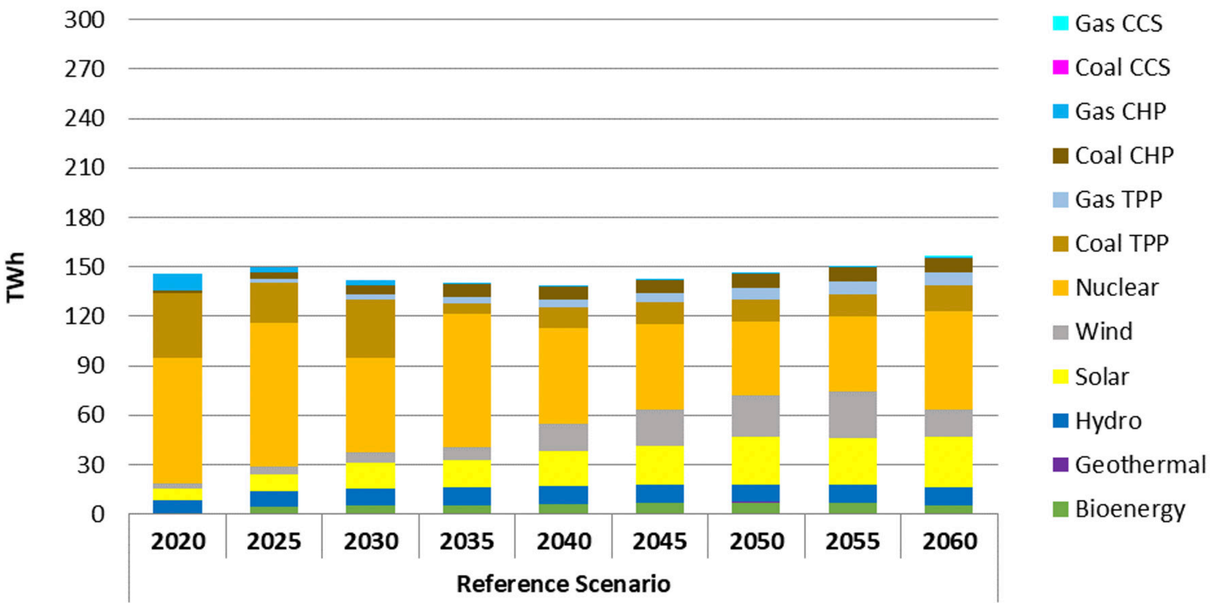


Due to early decarbonisation in 2050, we could observe high capacity growth from 2035 to 2050 (+64 GW). Coal TPP and, peculiarly Gas CHP, would be phased out by 2035, given that the latter could have switched to carbon-neutral types of methane.

The power mix in the Reference scenario (Figure 3.5) is quite stable in total amount and dominated by nuclear energy till 2040. The share of RE in the structure of electricity production outmatches nuclear and may reach 49% in 2050 but then drop to 40% by 2060. Coal and Gas plants still have important place as they would continue to provide balancing and auxiliary services together with bioenergy TPPs, hence we do not see the development of energy storages.

FIGURE 3.5

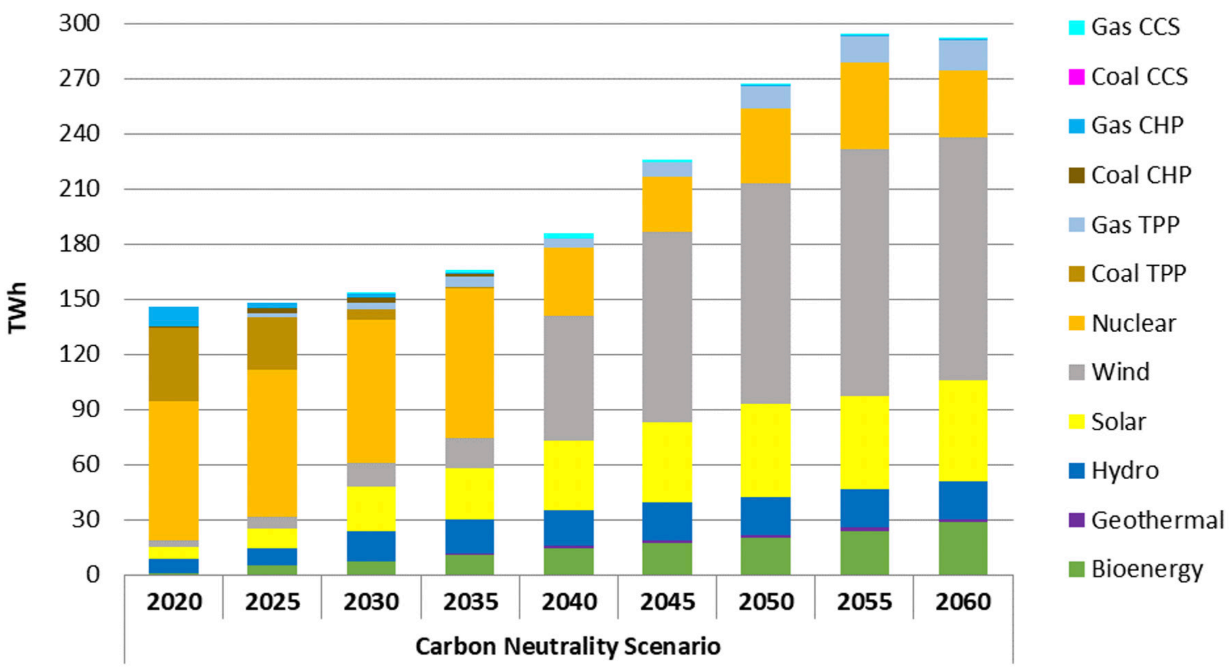
Electricity generation by fuel in the reference scenario



Reaching net-zero in 2050 (Figure 3.6) would need 267 TWh of electricity and by 2060 its production would grow to almost 300 TWh. The share of RE would reach 87% in 2060 – 255 TWh, solar and wind - 64% or 188 TWh. By 2035 all gas power plants might switch from natural gas to bio and synthetic methane which are carbon neutral. The average annual growth of electricity production would be 4.8% in the period 2025-2050.

FIGURE 3.6

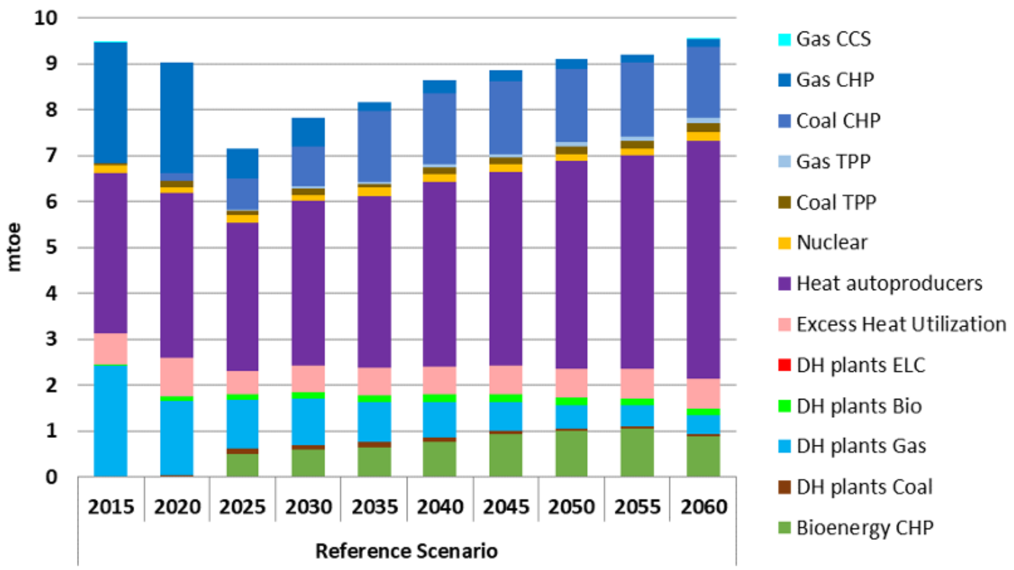
Electricity generation by fuel in the carbon neutrality scenario



Total heat generation in the Reference scenario (Figure 3.7) is characterized by a stable increase after the end of war. This tendency caused by two factors: autoproducers (i.e. entities generating heat wholly or partially for their own use as an activity supporting their primary activity) in commerce and industry, which corresponds with post-war reconstruction and GDP growth and with gradual superseding of natural gas district heating plants with new biomass CHPs.

FIGURE 3.7

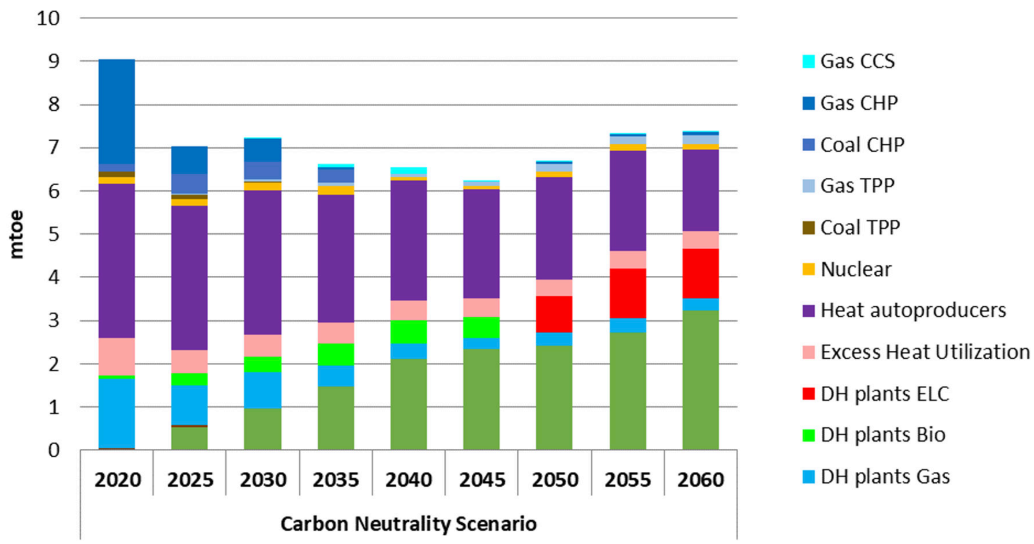
Heat generation by fuel in the reference scenario



In the Carbon Neutrality scenario (Figure 3.8) overall heat demand dynamics alternates depending on the exact period, but generally it would be 30%-40% lower than in Reference owing to buildings retrofit, wide energy efficiency measures implementation and electrification. Heat generation by autoproducers would reducs most significantly, which is explained mostly by decrease in industrial, commercial and transport heat demand. On the contrary to the Coal CHPs development in the Reference scenario, in Carbon Neutrality Scenario we see the expanse of biomass CHPs and air-source heat pump district heating plants.

FIGURE 3.8

Heat generation by fuel in the carbon neutrality scenario

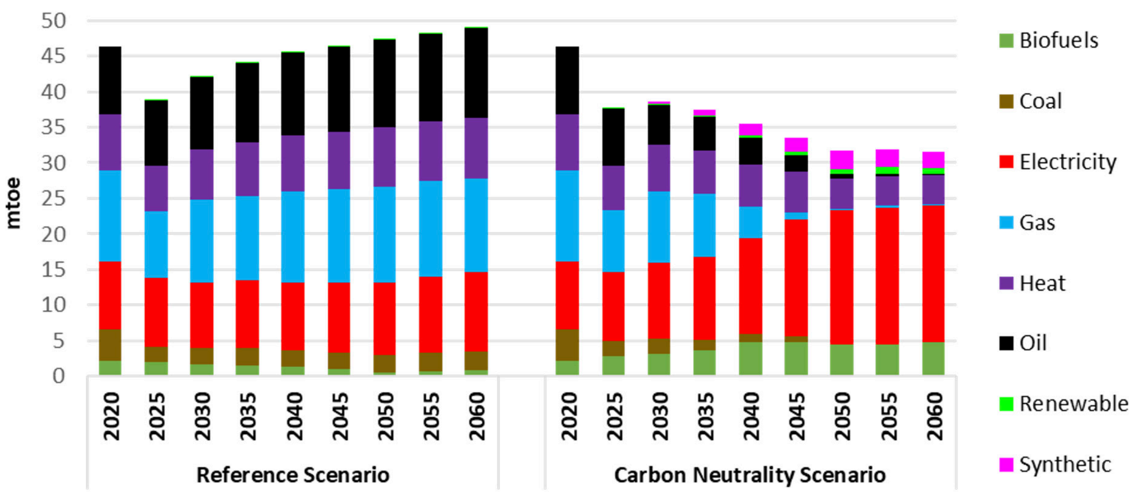


3.1.2 Final Energy

Total final energy consumption in the Reference scenario (Figure 3.9) would grow after the war, but the structure of fuel consumption remains the same.

FIGURE 3.9

Energy demand by fuel

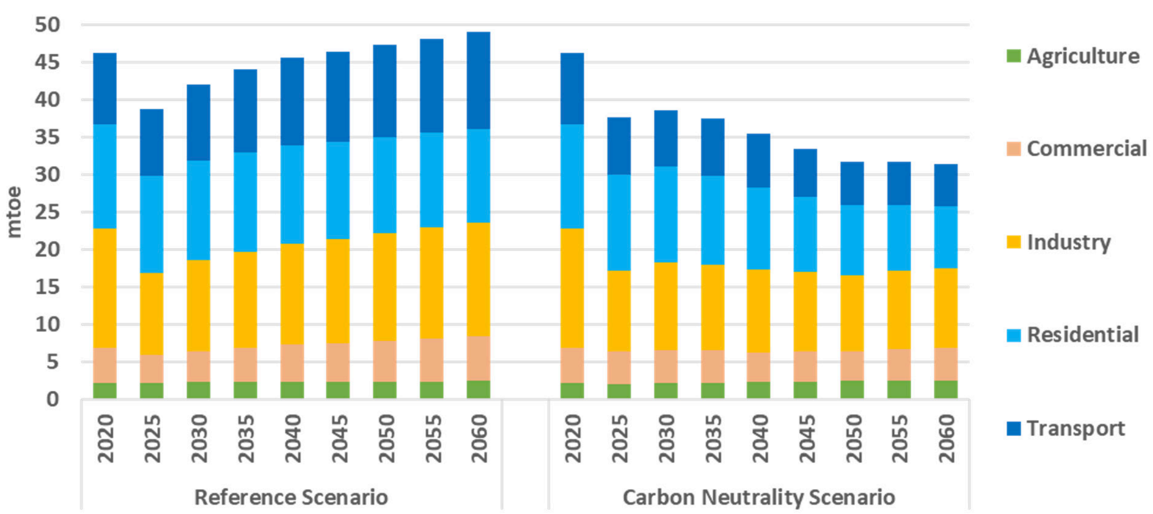


In the Carbon Neutrality scenario, there is seen a significant increase in the level of electrification, including expanse of rooftop solar panels, as well as the direct use of synthetic and new biofuels (biomethane, hydrogen, synthetic methane) which supersede natural gas. After 2030 energy demand would be steadily reducing first of all owing to deep retrofitting of buildings, new building codes and electric vehicles which are substantially more efficient than ICE vehicles.

The greatest potential for reducing final consumption is in the residential sector due to buildings thermal modernization and new building codes, in industry due to the replacement of obsolete or war-destroyed technologies with new modern ones, and transport due to electrification (Figure 3.10).

FIGURE 3.10

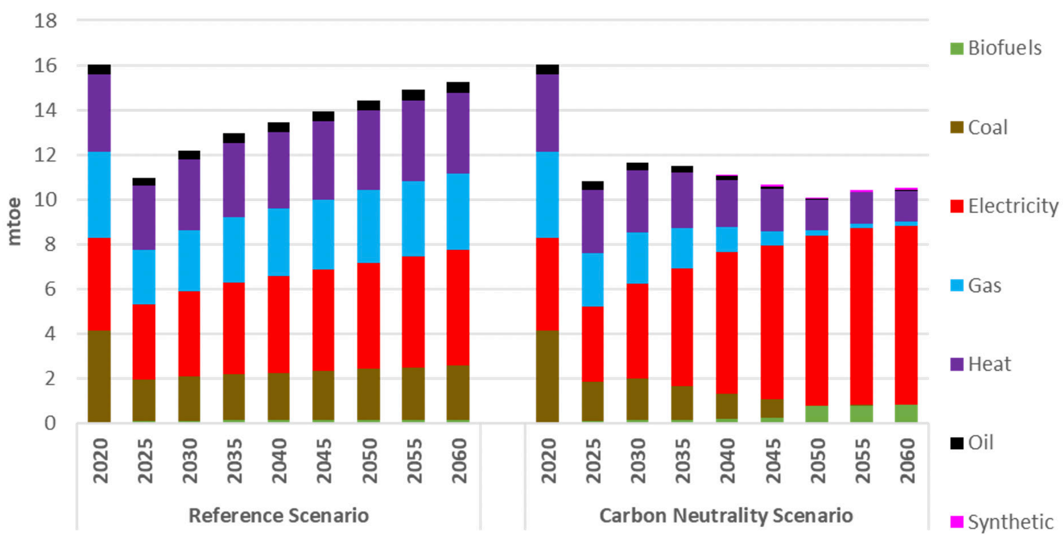
Energy demand by sector



Due to the war, the largest reduction in final consumption in 2022-2025 could occur in industry (Figure 3.11) due to large-scale destruction of industrial facilities, including energy-intensive enterprises such as metallurgy factories in Mariupol city. The implementation of the carbon neutrality scenario would require the industry to switch from fossil fuels to clean green energy. First of all, electricity produced by carbon-free technologies. In addition, those processes in industry that currently require natural gas can replace it with bio and synthetic gases (bio-, synthetic methane, etc.).

FIGURE 3.11

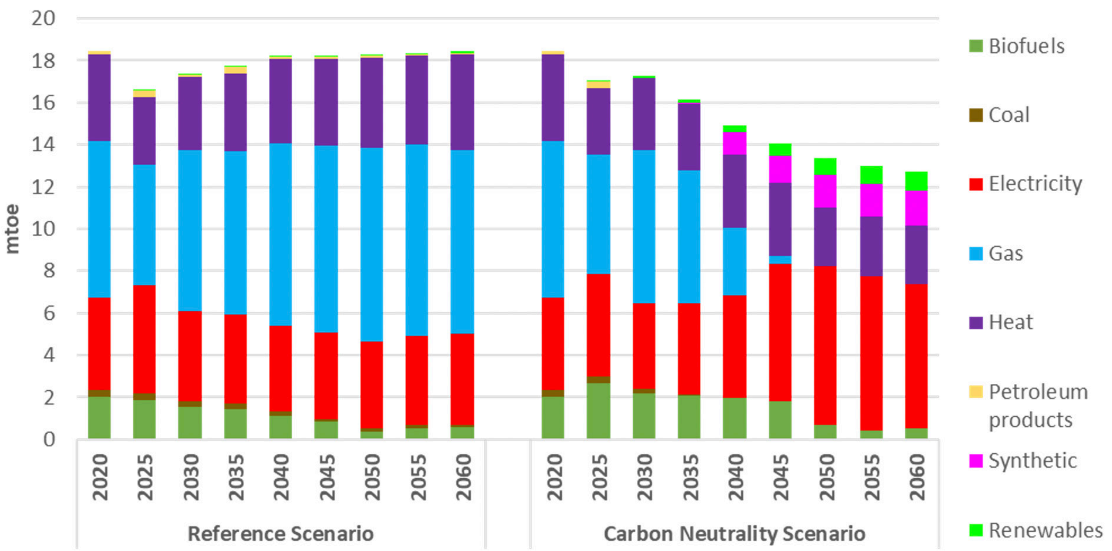
Energy demand in industry by fuel



Due to the war, the energy demand decreased in all sectors of the economy, including the buildings sector due to the destruction of a significant number of houses, internal and external migration of Ukrainians. Demand may increase slightly until 2030 due to the recovery and reconstruction of the housing stock. In the buildings sector, demand for electricity, bio- and synthetic gases would grow the most, replacing natural gas by 2050 or earlier. At the same time in 2060, the share of district heat (24%) would remain approximately the same as in 2020 (Figure 3.12).

FIGURE 3.12

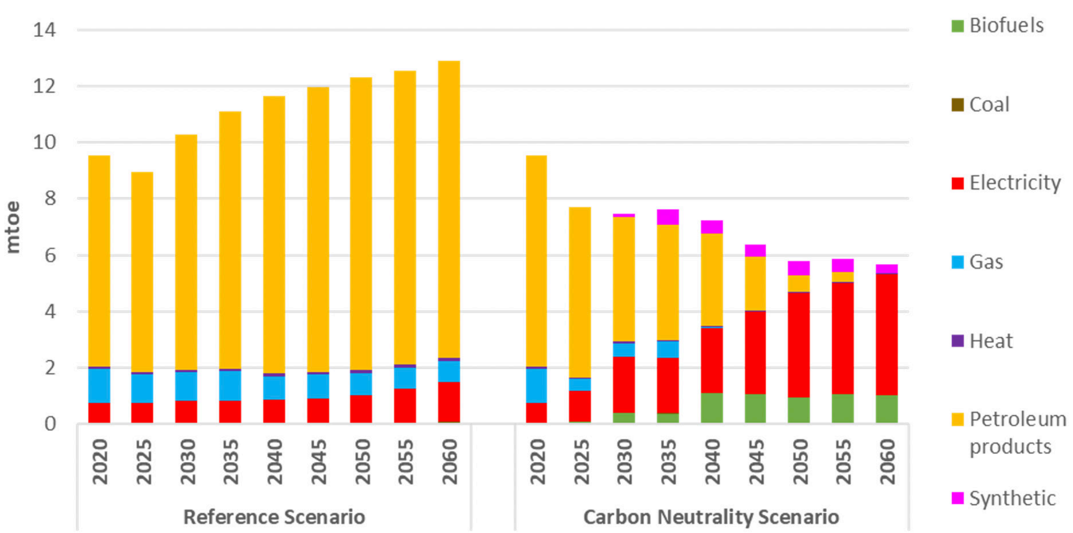
Energy demand in buildings sector by fuel



Under the conditions of the Reference scenario, energy consumption by the transport sector (Figure 3.13) would grow at a significant rate, as permanent increase in population mobility and freight transportation in Ukraine is expected, especially in the post-war period, but modern transportation technologies like EVs are not popular.

FIGURE 3.13

Energy demand in transport sector by fuel



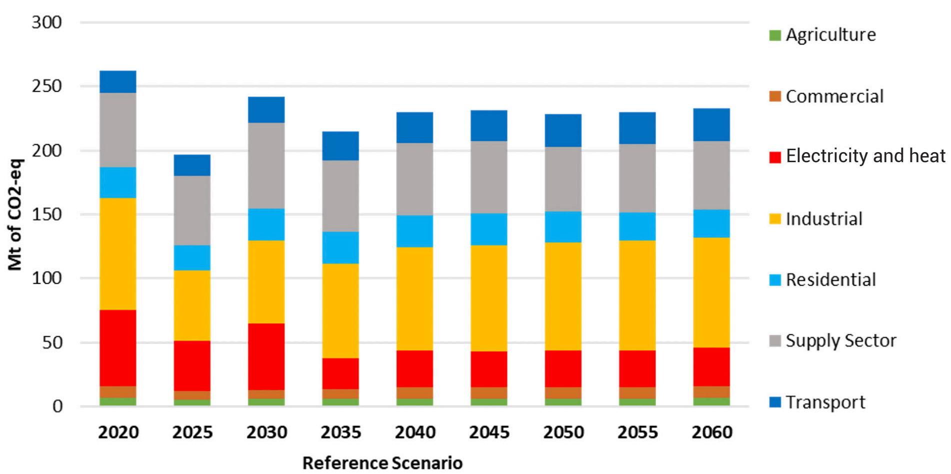
In the Carbon Neutrality scenario, significant electrification is expected, primarily of road transport, which would essentially increase the efficiency of energy use and supersede petroleum products by 2060. For the decarbonisation of aviation and navigation, it is considered as appropriate to use bio- and synthetic types of fuel.

3.1.3 GHG Emissions

The Reference scenario (Figure 3.14) has no constraints on emissions, however, we can observe to some extent the decoupling of GHG emissions and GDP growth, since after 2040 GDP continue to increase, but emissions would be very stable at 230 Mt CO_2e. The moderate penetration of new more efficient energy technologies, as long as existing technologies are phased out, would provoke a "natural" gradual increase in energy efficiency of economy and development of RE. This primarily stabilizes TPES even under growing GDP (see Figure 3.1), and thus – the level of GHG emissions.

FIGURE 3.14

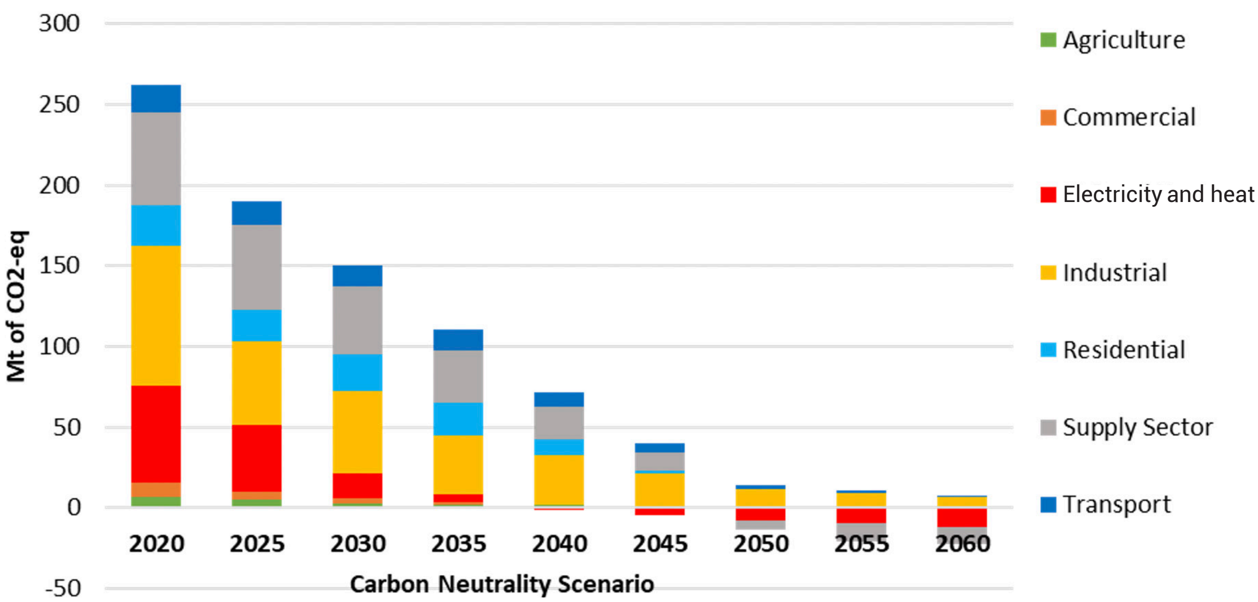
GHG emissions in the reference scenario



In Carbon Neutrality scenario (Figure 3.15) emissions trajectory is pre-defined for reaching net zero emissions in 2050 and mentioned above in Section 2.3. Among all sectors, Industry remains the hardest to decarbonize until 2060 because of hard-to-abate processes like cement and lime production or other chemical where CCS can be applied to curtail 5 to 12 Mt CO_2e of emissions but they can't be reduced to zero. The power and heat, commercial and agricultural sectors may be the first throughout the economy to reach near zero GHG emissions in 2040, while transport and residential sectors can achieve net zero emissions in 2050. The electricity and heat sector might then produce negative emissions after 2040 using bioenergy PPs with CCS installed starting from 2.3 Mt CO_2e and reaching 11.5 Mt CO_2e in 2060. Direct Air Capture facilities in supply sector would appear in 2050 providing 14 to 18 Mt CO_2e of negative emissions and climate neutral carbon for synthetic fuels production.

FIGURE 3.15

GHG emissions in the carbon neutrality scenario

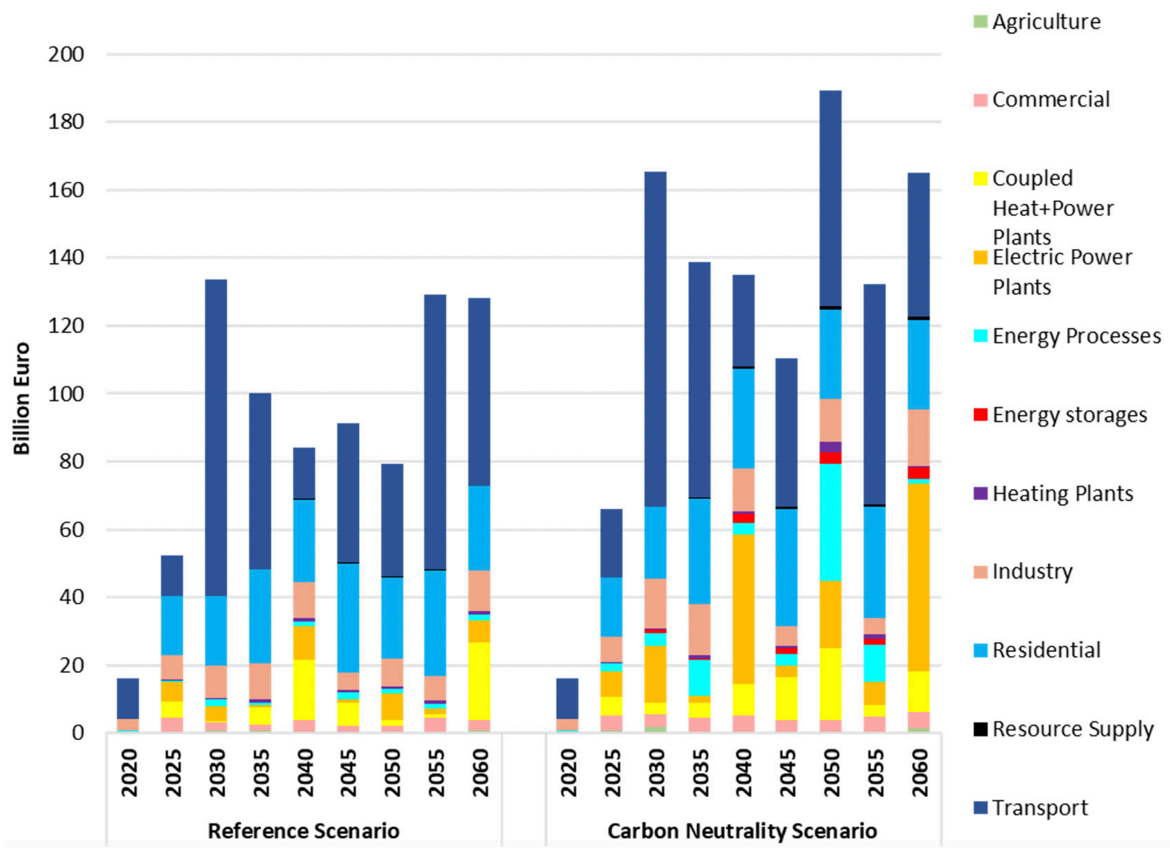


3.1.4 Investment Needs

It is obvious that achieving net-zero GHG emissions in the energy sector would require more investment efforts compared to the Reference scenario. The largest investments should be attracted in transport, building sector and power plants (including, power capacities for e-fuels production). Presented investment needs on the Figure 3.16 include consumer spending, such as the purchase of household appliances (individual heat and heat water boilers, air conditioners, washing machines and dishwashers, refrigerators, gadgets, etc.) and private vehicles, which account for 20% to 30% of total investment needs depending on the scenario.

FIGURE 3.16

Total investment needs by scenario



*Investments in mining of energy resources, incl. processing of biomass, together with cross-border energy infrastructure (LNG, GTL, regasification plants) are included in **Resource Supply**. Investments in other energy facilities except for power and heat generation, such as refineries, coke oven and briquetting plants, synthetic gas production, together with energy grids are summarized in **Energy Processes**.

Looking at the Figure 3.17 one can observe that consumer expenses comprise 377 bln Euro (46%) for the Reference and 414 bln Euro (37%) for the Carbon Neutrality scenarios which is a significant amount to be paid by the citizens, but not by the state government or investors.

In the structure of investment needs in demand sectors (Figure 3.18) in both scenarios, transport and households would occupy the largest shares. In transport the largest investments should be involved in road transport (cars, trucks and buses). In Carbon Neutrality Scenario comparing to Reference scenario, the amount of investments would increase the most for the renewal of trucks and slightly decrease for the renewal of cars and trains. In households, more than 50% would be the cost of purchasing new household appliances, which must be replaced regardless of the scenarios due to the end of their relatively short lifetime.

FIGURE 3.17

Investment needs without consumer expenses

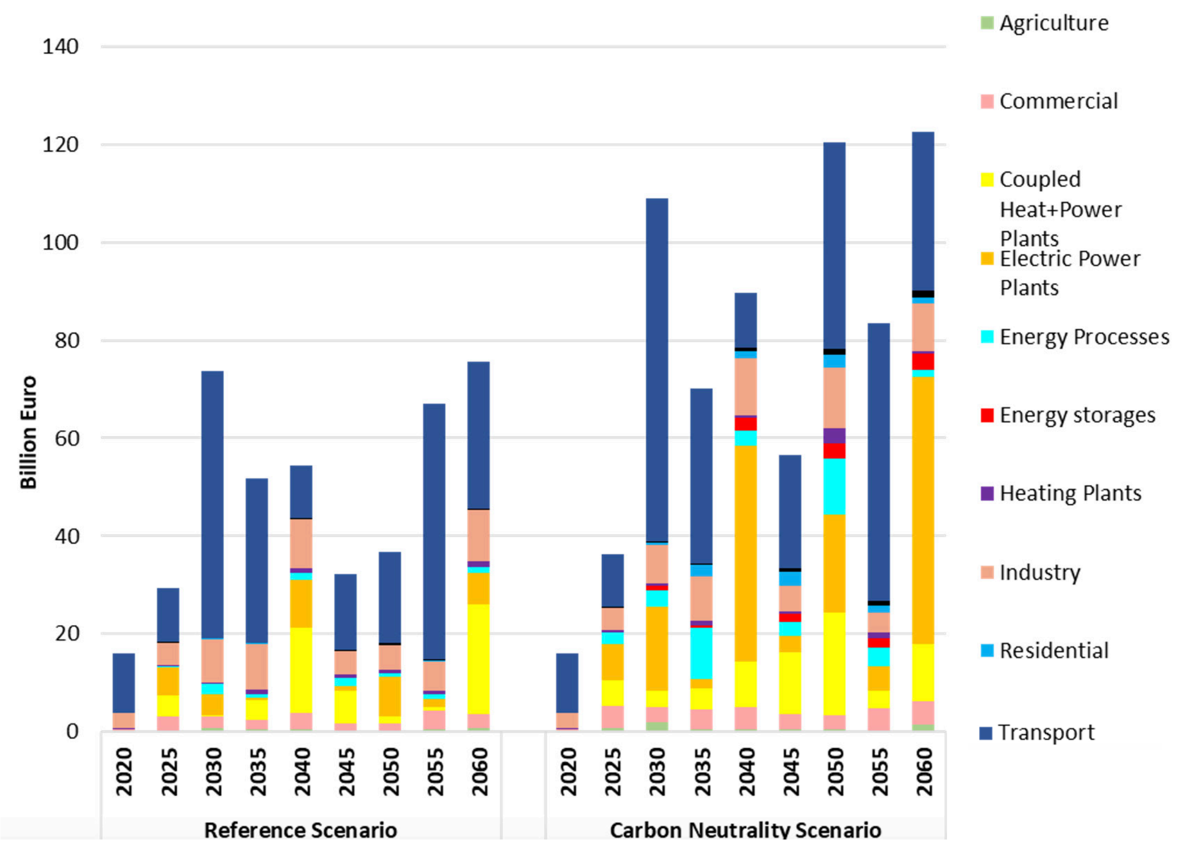
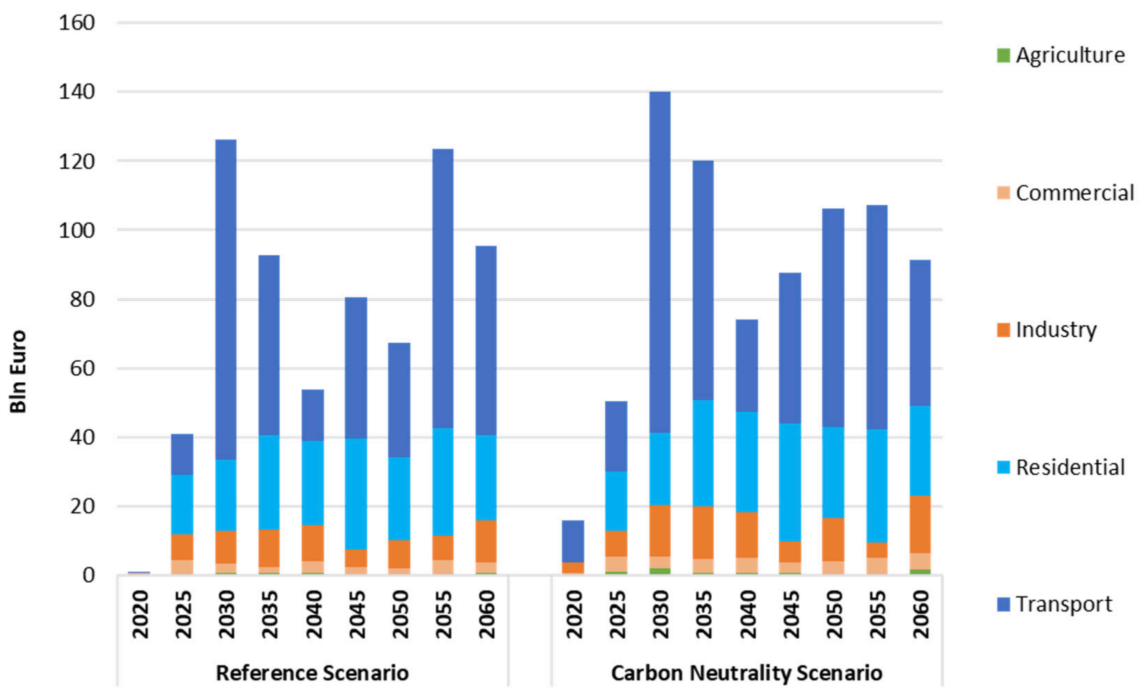


FIGURE 3.18

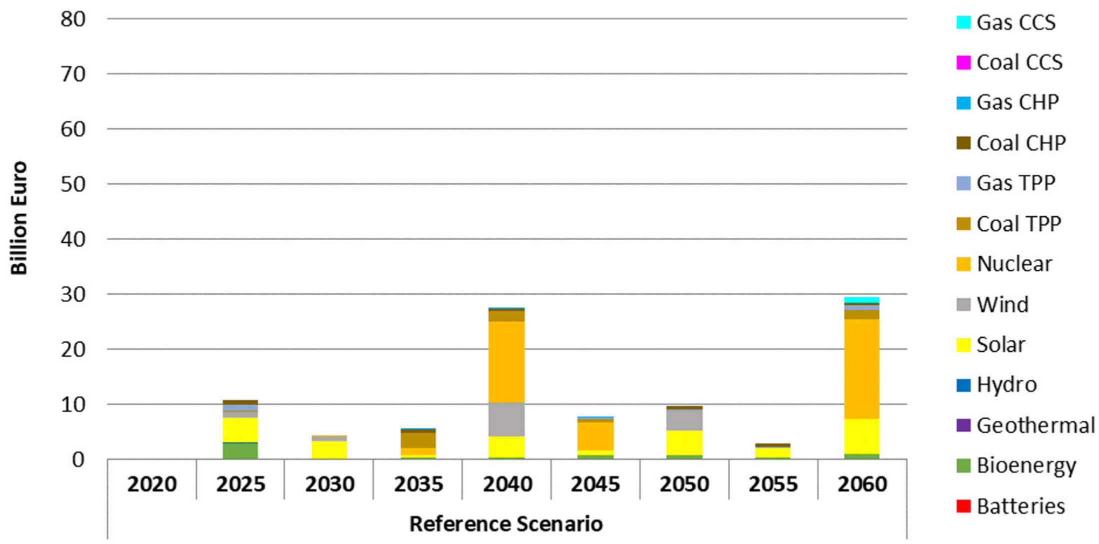
Investment needs in demand sectors



In the Reference Scenario (Figure 3.19) investment needs in power generation sector would be small, because existing power plants (based on fossil fuel) have enough reserves to cover electricity demand in the economy, which would not increase significantly.

FIGURE 3.19

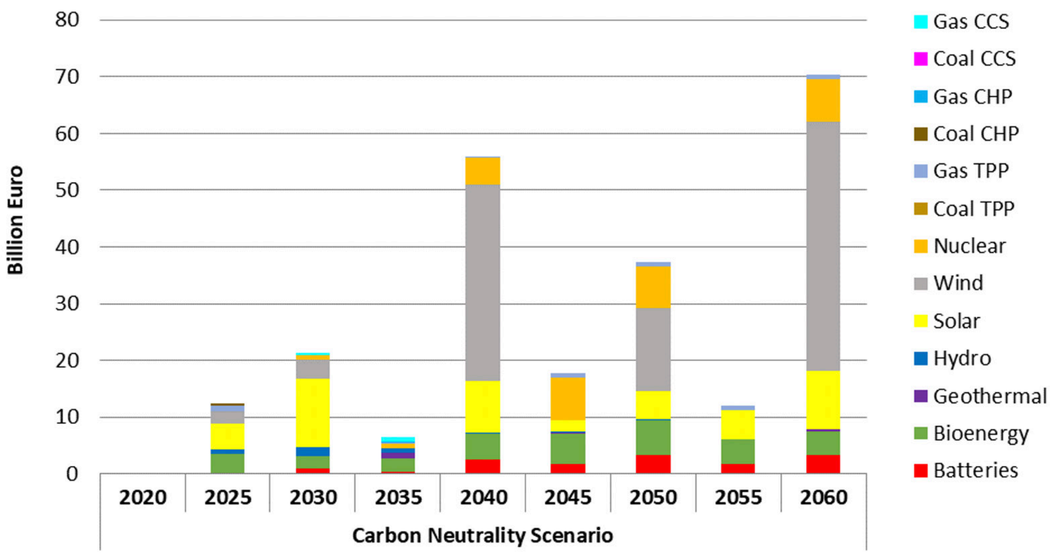
Investment needs in power generation sector in the reference scenario



In case of the Carbon Neutrality Scenario (Figure 3.20) much more investment would be needed in the clean power capacity, first of all in wind (around 100 bln Euro) and about the same amount of investments in total for solar, bioenergy and nuclear power plants. In addition, investments in energy infrastructure (power grids, heat networks, gas pipelines, etc.) would be required, which were not directly assessed in this project, but are partially presented in Figures 3.16-3.17 (as Energy Processes).

FIGURE 3.20

Investment needs in power generation sector in the carbon neutrality scenario



Significant investment needs of about 46 bln EUR in bioenergy and batteries would be necessary to ensure the flexibility and reliability of the power system. Another 6 bln EUR might be invested in clean gas power plants and 4 bln EUR in new hydro capacities.

4. POWER AND HEAT SECTOR

4.1 Reaching Carbon Neutrality in Power and Heat Generation

4.1.1 Power System

Power generation is the largest source of GHG emissions, primarily of CO_2. Before the Russia-Ukraine war, Ukraine utilized some of the most environmentally polluting coal-fired power plants in Europe and globally. Besides, subpar energy efficiency caused additional emissions and made Ukraine more vulnerable to energy crises or other turbulences. **Enlargement of renewable energy development and substantial improvement of energy efficiency are the primary pathways to reduce GHG emission and enhance air quality, along with improving the sustainability and resilience of Ukraine's energy system.** Simultaneously, wider RE deployment requires the eradicative transition of the power system to ensure its greater flexibility for more efficient balancing.

Simulation results presented in previous section indicate that under the Reference scenario, energy from RE would reach only 12% of the TPES in 2060.[60] The largest share of energy would belong to biomass (5.6%), followed by solar (3.5%) and wind (1.8%). Conversely, under the Carbon Neutrality Scenario, the share of RE in TPES would grow drastically and reach 83%, with the largest contribution from biomass (53%), followed by wind (18%) and solar (9%). As described in section 3, scaling up of energy production from RE together with notable technological shift within end-use sectors (primarily – electrification) under CN scenario could result in considerably lower TPES and FEC comparing to the REF scenario.

To achieve net-zero GHG emissions in Ukraine, the primary trend assumes a significant fall in energy consumption accompanied by the extensive electrification of the economy. While the final energy consumption (FEC) reduces in CN Scenario by 36% in 2060 compared to the REF scenario, inversely, the share of electricity in FEC grows more than twofold – from 22.9% to 61%. Such a transition would require consistent investments in new generating capacity and storage technologies, as well as other sectors of energy consumption. Under the REF scenario until 2060, the total lump sum of investments in CHPs, power plants, energy storage, and the residential sector amounts to 300 bln EUR, with the most significant investments needed in the residential sector (202 bln Euro). However, **to implement the CN scenario, the total lump investments for the power sector transition by 2060 – CHPs, power plants, and energy storage – should substantially increase**, amounting to 241 bln EUR, almost 2.5 times exceeding investments under the REF scenario (98 bln Euro). At the same time, the residential sector would only need slightly higher investments of 218 bln EUR.[61]

The primary tool and driver of the development of electricity generation from renewable energy in Ukraine was the feed-in tariff, introduced in 2009 and valid until the end of 2029. In 2019, the transition to the bilateral contracts market began in Ukraine, but no effective model was developed for financing electricity generation from renewable sources. Thus, the costs of renewable electricity imposed a significant financial burden on consumers and other market participants, along with the accumulation of substantial debts to electricity producers from renewables.[62] At the same time, renewable generation technologies, especially solar photovoltaics, are rapidly becoming cheaper and more affordable globally, which made it possible to move away from the feed-in tariff system in favor of other market-based support schemes.

The Ukrainian Government made a policy decision to switch to the auction system to distribute state support quotas on a competitive basis and at the lowest price (that is, at the auction price). Auction winners sign a power

60 Reference scenario is set as an "exploratory scenario" and models "business as usual" development. REF considers existing trends and policies, such as feed-in tariff for RE generation, although does not account policy statements or targets, including effective national commitments on RE.

61 New investments in power grids and other sectoral infrastructure are not explicitly presented in the model, and thus could be underestimated.

62 https://www.gpee.com.ua/news_item/342

purchase agreement (PPA), which guarantees a fixed price for the sale of electricity or energy produced during a stipulated long-term period of up to twenty years.[63] Technology-specific quotas of state support for future periods (for five years) were selected but yet to be introduced.[64] Therefore, the main recommendations for promoting electricity production from RE in Ukraine include the following:

- establish a sustainable and viable model of payments for "green" electricity.
- conduct a pilot auction to distribute the state support quotas.
- establish a long-term auction pipeline to ensure predictable industry development.

As of today, RE installations of households also have a feed-in tariff. However, the transition toward the net billing system was announced, and the respective draft law was developed.[65] The net billing system is designed to stimulate self-consumption while mitigating the financial burden on the electricity market from the growing number of prosumers.

To mitigate the significant current burden of RE costs for consumers and the market and ensure sustainable financing of renewables, additional cost-reflective and market-based support schemes are vital. One of the possible options should be an introduction of the feed-in premiums in the form of contracts for differences. The electricity producer from RE signs a contract for electricity supply at a fixed price (contract price) and sells electricity on the market at the market price. The difference between those prices should be directed to the RE producer when it is positive and to a special entity appointed by the government when it is negative. The scheme should incentivize investments in renewable energy by providing developers of RE projects with high upfront costs and long lifetimes with direct protection from volatile wholesale electricity prices, as well as protecting consumers from paying increased support costs, which is the strong case in Ukraine.

Another perspective option to be implemented is a fully market-based operation of RE electricity producers, which allows them freely trade electricity in the market at non-regulated prices while taking entire financial responsibility for imbalances. The recent legislative developments set out this voluntary opportunity for RE producers, as well as the possibility to come back to the balancing group of SOE Guaranteed Buyer.[66] Moreover, RE producers are eligible to enter any other balancing groups to manage their imbalances efficiently. Overall, **it is essential to ensure a shift from not cost-reflective to market-based support schemes providing RE producers with several alternative options to chose.**

Additional measures required to foster RE deployment include:

- implementation of the energy guarantees of origin, which is critical for enabling trading electricity from renewables by bilateral contracts, including exporting;
- ensuring access to long-term finance at affordable rates;
- further R&D for demonstration, commercialization, and diffusion of new technologies based on RE (e.g., offshore wind energy deployment, green hydrogen output and its internal use, and export to the EU with the existing natural gas infrastructure);
- implementation of new business forms in the energy market – aggregators[67] and energy cooperatives (communities or clusters) – to foster the development of distributed energy and local energy systems, contributing to sustainability and resilience of the power system.

To ensure the technical viability of the power system with a considerable part of intermittent and inflexible renewables in the capacity mix, particularly wind and solar – about 72% under the CN Scenario in 2060 (94 GW out of 129 GW of total installed capacity) – system flexibility is essential. As nuclear power plants cannot provide a

63 https://zakon.rada.gov.ua/laws/show/555-15#Text
64 https://www.gpee.com.ua/news_item/496
65 https://itd.rada.gov.ua/billInfo/Bills/Card/41360
66 Art. 71 of the Law on electricity market, https://zakon.rada.gov.ua/laws/show/2019-19#Text
67 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Aggregators_2019.PDF

balancing capacity, their share in the capacity mix is expected to decline gradually. Simultaneously, **large nuclear power units are supposed to be progressively replaced by new technologies – small modular reactors (SMRs), which are more flexible**. The installed capacity of SMRs in Ukraine's power system under the CN Scenario in 2060 would amount to 3.3 GW out of 4.3 GW of installed nuclear capacity. **The installed capacity of coal-fired TPPs would also decline with an almost complete phase-out after 2030 to diminish their harmful environmental and climate impact.**

To provide sufficient balancing capacity and improve power system resilience, coal-fired TPPs should be replaced by highly-flexible gas-fired TPPs. Their generating capacity is expected to reach 4.3 GW in 2060, including 0.6 GW of the cutting-edge gas-fired TPPs with CCS. **Additionally, to enhance the dispatchable generation, the deployment of biogenerating facilities is also crucial.** Under the CN Scenario, their installed capacity is expected to develop moderately and reach over 7 GW in 2060. Those technologies would contribute to the development and sustainability of distributed energy as they focus on local energy sources – biomass – abundant in Ukraine.

Together with dispatchable generation capacity, **the progressive deployment of energy storage technologies is crucial to provide critically needed balancing services in the market and facilitate significant integration of renewables into Ukraine's power system and energy market**. However, innovative energy storage technologies require establishing an appropriate legislative environment to provide an economically viable model of their operation in the electricity market. The recent developments provided a legislative framework for energy storage systems; however, it requires further elaboration in the secondary legislation.[68]

To improve system balancing, along with the commissioning of flexible generating capacity, demand-side management (DSM) is essential, particularly by the application of real-time pricing for electricity and enhancing the respective responsiveness of consumers' demand. The practical implementation of DSM would also require the deployment of smart metering and the development of smart grids.[69] Additionally, the introduction and proliferation of a new business model in the energy market – aggregators (virtual power plants) – would facilitate DSM and improve the power system balancing while enabling household consumers and prosumers to become more active market players and benefit from their participation in the market.

4.1.2 Heating Sector

Comparing the REF and CN scenarios, the heat consumption in the latter is projected to be approximately 23% lower in 2060, primarily due to extensive energy efficiency measures. As for heat production, under the REF scenario, the role of biomass is projected to be insignificant, reaching only 8.8% throughout 2015-2060, with the peak heat output from biomass in 2040-2050. Under the CN scenario, the contribution of biomass for heat production is expected to be more significant, reaching 36% throughout 2015-2060. The bio-CHPs would produce the vast majority of the heat. Moreover, bio-CHP technology would contribute to the sustainability of local energy systems as they usually rely on local sources, which are redundant given the extensively developed agricultural sector in Ukraine.

Despite the significant role that renewables may play in heat generation, the shortfalls in industry regulation impede market development. Given the entirely monopolized heat market in Ukraine with the heavily limited or restricted entry of new participants, **establishing a competitive heat market is the first and foremost measure critically required to attract investments in the sector and improve the efficiency of heating systems**.

Currently, natural gas prices for the residential and public sectors are heavily subsidized. The existing legislation presumes the tariff for heat from renewables at 90% of the tariff for heat from natural gas. In the presence of subsidies, the projects of heat production from renewables are unfeasible. Therefore, the subsidies for natural gas are to be gradually cancelled and should remain only for the most vulnerable and energy-poor consumers. Additionally, the law provision regarding the size of the tariff for heat from renewables at the 90% tariff for heat from natural gas should be abolished.

68 Chapter 4 of the Law on electricity market, https://zakon.rada.gov.ua/laws/show/2019-19#Text

69 New investments in power grids and other sectoral infrastructure are not explicitly presented in the model, and thus could be underestimated.

As for biomass use for heat output, biomass-fired heat-producing facilities should be exempt from CO_2 tax, as the necessity to pay such a tax adversely affects the feasibility of the projects. Additionally, the biomass market needs to become better organized by establishing an online biomass exchange platform, which would facilitate meeting the suppliers and heat-producing facilities, ensure their better access and competitive market prices, as well as guarantee the decent quality of the feedstock.

To enhance the output of biomass as a feedstock, support measures are needed for the dedicated energy crops, such as investment grants to start the plantations, tax exemptions for the imported machinery and equipment, temporary land rent waivers, and extension of the land rent agreements to at least twenty years.

Additionally, municipal solid waste should be considered a significant energy source to cover heat-ing demand. The best European practice proves that the combustion of refuse-derived fuel (RDF) could cover up to 80% of the heating demand of municipalities. Therefore, waste processing facilities should be deployed across Ukraine to provide raw stuff. Proper waste management could also allow the production of biogas for bio-CHPs. To effectively utilize the potential of municipal waste, dedicated policy and legislation regarding the development of district heating and RDF combustion in co-generation plants should be implemented. However, as district heating could be more vulnerable compared to the individual heating given the ongoing deliberate attacks on the critical energy infrastructure of Ukraine, a balanced approach should be elaborated for the development of heating systems taking into consideration regional and local specificity – availability of biomass, logistics, technical and economic status quo of existing district heating systems, etc.

Enabling measures for biomethane production include capital grants aimed at the decreased up-front costs of equipment for biogas production and its further purification to the level of bio-methane and a special tariff for heat produced from biomethane.

4.2 Building a Resilient Power System in Ukraine

The power system of Ukraine, which is mostly the inheritance of the Soviet era, appeared vulnerable to systemic physical (e.g., missile and drone) attacks targeting the energy fleet. They repeatedly damaged or destroyed large generation and network facilities, harmed the security of the electricity supply, and led to massive and continuous outages across the country. Consequently, it became evident that Ukraine's power system should improve its resilience, which would be one of the crucial tasks during further recovery and long-term power system development while taking advantage of building a decarbonized and distributed energy.

Given large-scale energy facilities already in place, one of the ways to build a resilient and decarbonized power system will need to find ways to efficiently combine the advantages of large-scale and small-scale power systems, with the latter mainly relying on available local energy resources and logistical advantages. Small power systems should be designed around local energy needs and resource capabilities to ensure better energy sustainability for individual communities and the whole country.

4.2.1 Priority Areas for Investments in the Electricity Sector

Given the steady European aspirations of Ukraine and adherence to a decarbonized energy pathway, it is supposed that Ukraine's electricity sector will develop in compliance with the provisions of the Clean energy for all Europeans package[70] and the Green Deal initiative.[71] Thus, most of investments should be made in a decarbonized generation fleet and electricity networks, along with improving the flexibility and resilience of Ukraine's power system.

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70 Clean energy for all Europeans package. https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en

71 European Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

4.2.1.1 Electricity Generation

Under the CN scenario, the share of RE in the generation capacity mix, including big hydropower plants (HPP), would grow drastically and reach over 83% in 2050, with the most significant contribution from wind (43,100 MW or 35%) and solar (42,400 MW or 34%). By modelling assessments, the overall investments needed for wind and solar energy development till 2050 amount to 54.7 bln EUR and 32.6 bln EUR, respectively. This accounts for 55% of overall investments expected in all other types of generation and storage capacities until 2050.

Notably, 60% of solar installations are expected to be roof ones. As of the beginning of 2022, almost 45,000 households installed solar panels with a total capacity of 1,205 MW,[72] while there is massive potential for further deployment of roof solar panels by households and public buildings (e.g., hospitals, educational facilities, public administration buildings, etc.). However, the recent wartime experience in Ukraine proved that most residential solar installations appeared vulnerable as they were not able to operate under electricity outages. Thus, the drawback revealed should be rectified in the further rollout of solar installations by households. The option would be the application of hybrid inverters that combine the work of a grid-tied and battery inverter and increase energy resilience by providing backup power in case of a grid outage while maximizing energy independence through self-consumption.

It is worth noting that in the early stage, since 2009, the originally opted feed-in tariff support scheme was effective for extensive RE deployment and ensured one of the highest paces in Europe. However, in the long term, this scheme proved unviable in Ukraine, leading to the accumulation of considerable debts[73] and market distortions. Consequently, it became one of the key hindrances to further extensive RE deployment and is not compliant with best European practices of supporting renewables and ensuring their better integration into the market. Thus, despite recent legislative developments enabling RE producers to leave the balancing group of Guaranteed Buyer (GB) and directly act in the competitive market, they remain reluctant to take advantage of deeper integration into the electricity market. Another critical bottleneck of full-fledged renewables deployment remains the connection of RE installations to the networks. Therefore, additional policy, legislative, and regulatory adjustments should be made to facilitate and ease the process of their connection to the grid.

Given the strong adherence of Ukraine's government to nuclear generation, the long-term energy policy will likely rely on existing nuclear generation capacity and further application of cutting-edge nuclear technologies. Particularly, in June 2022, Westinghouse and Energoatom expanded agreements for Westinghouse to build nine AP1000 nuclear units across the country.[74] The AP1000 unit is a proven Gen III+ reactor featuring unique fully passive safety systems, modularized standard design, and industry-leading operability performance and load-following capability. At the same time, given the long-term consequences of war in Ukraine, such a decision should be comprehensively scrutinized and economically and technically reevaluated and justified, focusing on improving the power system's flexibility, resilience, and affordability. In contrast, by modelling assessment within the CN scenario, over 28 bln EUR should be invested in new nuclear generation units (3,200 MW), primarily small modular reactors (SMR) (2,200 MW), as well as extending the lifetime of the existing nuclear fleet. The investments into SMRs are expected to start after 2040.

To ensure a smooth and diversified nuclear fuel supply for the existing fleet, it is vital to establish domestic fuel fabrication to cover at least half of the plants' demand, while another part could be imported from several external sources. Ukraine never had fabrication technology and, according to international agreements, is not eligible for uranium enrichment. However, relying on the domestic uranium mining industry and imports of enriched uranium, the nuclear power plants' (NPP) operator, Energoatom, plans to apply Westinghouse's technology for launching

72 Explanatory note to the Draft Law of Ukraine "On supporting the production of electricity from alternative energy sources by generating plants owned by consumers" https://itd.rada.gov.ua/billInfo/Bills/pubFile/1674547

73 State enterprise Guaranteed Buyer. https://www.gpee.com.ua/news_item/342

74 Energoatom and Westinghouse Begin AP1000® Plant License Process in Ukraine. https://info.westinghousenuclear.com/news/energoatom-and-westinghouse-begin-plant-license-process

domestic nuclear fuel production in the mid-term, presumably after 2025.[75] This project would improve Ukraine's energy security and provide some contribution to foreign trade and new jobs in the sector.

At the same time, although deemed decarbonized, wind, solar, and nuclear energy is not easily dispatchable, which significantly complicates the power system balancing and resilience. Thus, ensuring appropriate system flexibility will, in parallel, require deploying highly-flexible generation and storage capacity. Building new balancing capacity – gas-fired power plants (3,100 MW), including those with carbon capture and storage technology, and hydropower units (4,300 MW) – would require a total investment of over 7 billion EUR by 2050. Thus, the share of flexible generation in the capacity mix is projected to increase from 12% in 2020 to 18% in 2050.

Within the Ten-year transmission system development plan for 2022-2031,[76] NPC Ukrenergo, the Ukrainian transmission system operator (TSO), defined the most appropriate sites for building new highly-flexible generation and storage facilities to optimize power system operation and maximize the rollout of such energy capacity. According to TSO, those capacities should be distributed geographically and connected to existing electricity facilities – primarily TPPs and high-voltage substations (220 kV, 330 kV, and 750 kV), along with individual CHPs and NPPs. The minimum installed capacity of new generation plants/units is recommended over 20 MW, while the maximum capacity should not exceed 250 MW.

4.2.1.2 Battery Energy Storage Facilities

Additionally to extending flexible generation, to improve system flexibility and resilience and mitigating balancing issues related to heavy penetration of variable RE and other non-dispatchable fleet, energy storage technologies should be deemed an inevitable investment option. Particularly, the extensive rollout of battery energy storage systems (BESS) is projected throughout 2025-2050 to reach app. 8,500 MW in 2050, with the corresponding total investments of over 9 bln EUR. The recently adopted 2035 Ukraine's smart-grid development concept envisages the implementation of pilot energy storage projects yet in 2022-2023 with their further extensive utilization over 2024-2035.[77] By the concept, such projects should be included in development plans and investment programs of electricity producers, transmission system operator and distribution system operators (DSOs), etc.

To enable BESS development, the dedicated primary legislation was set up in February 2022 by amending Laws on Electricity Market (LEM) and the National Energy and Utilities Regulatory Com-mission (NEURC).[78] Particularly, BESS operators were authorized to participate in all segments of the wholesale electricity market for trading electricity and providing ancillary services. The TSOs and DSOs were also enabled to run BESS, although with stringent limitations in electricity trading, providing balancing and ancillary services, etc. Notably, dedicated legislation does not provide investors in BESS with special incentives or preferences; hence, they may only rely on their competitive advantages in the electricity market.

4.2.1.3 Enhancing Networks

Most of the electricity network infrastructure in Ukraine is significantly outworn and obsoleted. According to the TSO, almost 21 thousand km of transmission lines (88%) have been utilized for over 30 years, while over 16 thousand km (almost 70%) have been utilized for over 40 years. Modernization of 220 kV power lines is a priority, as most have been utilized for over 50 years. Besides, 64.5% of relay protection and emergency automation devices have completed their normal operation lifetime.

Given the current status quo, the development of networks, including their extensive digitalization, is essential to build a decarbonized, distributed, and resilient power system. The investment priorities for the modernization

75 Cooperation between Energoatom and Westinghouse will help oust russia from global nuclear fuel market: German Galushchenko. https://www.kmu.gov.ua/en/news/spivpratsia-fakhivtsiv-enerhoatomu-i-westinghouse-dopomozhe-vytisnyty-rosiiu-zi-svitovoho-rynku-iadernoho-palyva-herman-halushchenko

76 The plan is currently unavailable due to martial law (the document was downloaded in 2021).

77 Concepts of implementation of "smart networks" in Ukraine until 2035. https://www.kmu.gov.ua/npas/pro-skhvalennia-kontseptsii-vprovadzhennia-rozumnykh-merezh-v-ukraini-do-2035-roku-908-141022

78 Law of Ukraine on the development of energy storage facilities. https://zakon.rada.gov.ua/laws/show/2046-IX#Text and development of Ukraine's electricity network infrastructure, both internal and external (cross-border interconnections), stem from two key documents – the Ten-year transmission system development plan and the 2035 Ukraine's smart-grid development concept. Both documents, among other things, are focused on improving the security of electricity supply and resilience, ensuring better integration of renewables into the grid, and unlocking demand-side management (DSM) potential. Total investments for the network development envisaged in the Ten-year transmission system development plan for 2022-2031 amounted to over 2.1 bln EUR.[79] Additionally, all DSOs in electricity produce five-year distribution system development plans with supplementing annual investment programs subject to Regulator's approval and further progress reporting.

To significantly improve Ukraine's power system resilience, its digitalization is vital. Given that only 10% of households and most of other consumers are not equipped with smart meters, the initial step in building a smart grid in Ukraine would be an extensive implementation of smart-metering systems needed for effective DSM and greater penetration of renewables, particularly small-scale RE installations by prosumers. Additionally, the rollout of smart-grid technologies would improve system flexibility by enabling the application of new business models for active participation in the electricity market, e.g., aggregators, virtual power plants, energy communities, etc.

To unlock a large-scale external potential for improving power system resilience, Ukraine should substantially enhance interconnectivity with neighboring power systems within ENTSO-E. According to Regulation (EU) 2018/1999, cross-border electricity interconnectivity should reach at least 15% in 2030, considering the 2020 interconnection target of 10%.[80] Currently, the interconnectivity of Ukraine with ENTSO-E countries is under 5%.[81] Developing cross-border interconnectors will enable deeper integration of Ukraine and EU power systems and markets, particularly emergency support and effective market coupling with Eastern European countries. One of the short-term priorities is the restoration and commissioning of the Khmelnytskyi NPP – Rzeszów (Poland) transmission line with a cross-border capacity of 1,000 MW.[82] Another major medium-term project would be the reconstruction of the 750 kV Pivdennoukrainsk NPP – Issacea (Romania) transmission line from the new 750 kV Prymorska substation to 750 kV Isaccea PS by the construction of a double-circuit 400 kV line, increasing Ukraine's cross-border capacity for 1,000 MW.[83] By the Ministry of Energy assess-ment, the potential total cross-border capacity of Ukraine's power system with ENTSO-E countries could reach 6,000 MW, which would exceed 10% interconnectivity threshold.

4.2.2 Promising Policies and Investment Attraction Mechanisms

4.2.2.1 Mature and Coherent Institutional Environment

Building a resilient and decarbonized power system in Ukraine would require a combination of short-term and long-term actions. The first and foremost precondition should be establishing a consistent institutional and policy environment, ensuring strong positive signals for potential investors. In this regard, finalizing and adopting key policy documents – the 2050 Energy Strategy, integrated National Energy and Climate Plan (NECP), the 2030 National Renewable Energy Action Plan (NREAP), etc. – is essential. The process of their design and implementation should be transparent.

4.2.2.2 Introduction of Sustainable and Viable Market-Based Support Schemes for RE

Renewable generation technologies are rapidly becoming cheaper and more affordable globally, enabling a shift from the feed-in tariff to market-based support schemes. Thus, the government decided to switch to the auction

79 This assessment does not come from our modelling, but was made by the TSO before the war; thus, evidently, the total investments required will increase, including those for restoring damaged and destroyed network infrastructure.

80 Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.328.01.0001.01.ENG

81 The capacity of electricity export of Ukrainian can increase to 6 GW, - Herman Galushchenko. https://www.kmu.gov.ua/news/propuskna-spromozhnist-eksportu-ukrainskoi-elektroenerhii-mozhe-zrosty-do-6hvt-herman-halushchenko

82 NPC Ukrenergo works on increasing electricity export to Poland. https://ukraineinvest.gov.ua/news/17-08-22-2/

83 750 kV Pivdennoukrainska (Ukraine) – Isaccea (Romania) OHL rehabilitation and modernization. https://www.energy-community.org/regionalinitiatives/infrastructure/PLIMA/EL09.html

system to distribute state support quotas on a competitive basis at the lowest price. Auction winners should sign a power purchase agreement (PPA), which guarantees a fixed selling price for electricity for up to twenty years.[84] Technology-specific quotas of state support for future periods (for five years) were selected but have yet to be introduced.[85] The main recommendations for promoting further RE deployment include conducting a pilot auction to distribute the state support quotas and establishing a long-term auction pipeline to ensure predictable industry development.

Besides, additional cost-reflective and market-based support schemes are vital to mitigate the significant burden of RE costs for consumers and the market and ensure sustainable renewables financing. Among the options should be considered feed-in premiums and contracts for differences. The former should incentivize investments by providing developers with extra profitability, while the latter would guarantee producers with high upfront costs and long lifetimes with protection from volatile wholesale prices and protect consumers from paying extra costs.

Another perspective option is a fully market-based operation of RE electricity producers, which allows them freely trade electricity in the market at non-regulated prices while taking financial responsibility for imbalances. The recent legislative developments set out this voluntary opportunity for RE producers and the possibility of returning to the balancing group of Guaranteed Buyer.[86] Moreover, RE producers are eligible to enter any other balancing groups to manage imbalances efficiently. Additional measures to foster RE deployment include the implementation of the guarantees of origin, which is critical for enabling the trading of electricity from renewables by bilateral contracts, including exporting. Overall, it is essential to ensure a shift from non cost-reflective to market-based support schemes providing RE producers with alternative options to choose.

4.2.2.3 Improving Electricity Market Functioning

To attract investments, Ukraine's electricity market should be liberalized and competitive and provide proper signals for market players and potential investors, especially on prices. Currently, the electricity market is immature and heavily distorted by a lack of competition and overwhelming and frequently changing regulation, making it difficult for potential investors to provide feasibility studies relying on market signals and decide on entering the market. Thus, mitigating regulation and improving its rationale and transparency are critical for improving the business climate and attracting new technologies and players in the sector.

One of the most significant distortions derives from price caps applied by the Regulator (NEURC) in the wholesale electricity market, heavily limiting competitive price formation. This distortive practice not only defers the entry of new market participants but also prevents demand-response business models. It is strongly recommended to gradually eliminate price caps and replace this price control mechanism with effective market monitoring and surveillance by dedicated public authorities – NEURC and Anti-monopoly Committee. Additionally, to provide greater transparency of the market operation and the capability to conduct monitoring, the implementation of Regulation (EU) No 1227/2011 on wholesale energy market integrity and transparency (REMIT)[87] is crucial.

Another considerable market distortion preventing investments in the sector is the Public service obligation (PSO) scheme aimed at keeping non market-based, low electricity prices for households. The current PSO scheme heavily impacts the profitability of Energoatom and, to less extent, Ukrhydroenergo. By estimation, the total cost of PSO in 2022 for both companies was app. 3.7 bln EUR. Thus, Energoatom annually transfers to Guaranteed Buyer nearly half of its total revenue from selling electricity and suffers losses or has severely limited profitability. Such a scheme does not allow for investments required for modernization and building new nuclear facilities. To unlock investments into nuclear generation and other capacities, it is reasonable to gradually introduce market-based electricity prices for households, along with lifting PSO and enhancing targeted monetary support for vulnerable and energy-poor consumers.

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84 Law of Ukraine on Alternative Energy Sources. https://zakon.rada.gov.ua/laws/show/555-15#Text

85 "Green" auctions for the distribution of support quotas are expected in 2021. https://www.gpee.com.ua/news_item/496

86 Art. 71 of the Law on electricity market, https://zakon.rada.gov.ua/laws/show/2019-19#Text

87 REGULATION (EU) 1227/2011 on wholesale energy market integrity and transparency. https://www.energy-community.org/dam/jcr:011d891f-6cef-4555-9e9a-53d88e54d4b1/Regulation_1227_2011_REMIT.pdf

Deeper integration into the EU energy market would also improve the business climate in the sector and promote investments. Remarkably, the market coupling of Ukraine's day-ahead and intraday electricity markets with Eastern European markets will boost cross-border trade, competition, wholesale market liquidity, and more fair and market-based prices, which are essential indicators for potential investors.

4.2.2.4 Development of Distributed Energy and Small Energy Systems

Ukraine has massive potential for the deployment of renewables in local communities and make local energy systems more sustainable and resilient. Several pilot projects and good practices in energy efficiency and RE had significant economic and energy effects;[88,89] however, they needed to be more systemic.[90] Building an effective institutional environment is essential to ensure consistent implementation of energy efficiency and renewable energy projects in local communities.

One of the best practices is designing the Sustainable energy and climate action plans (SECAPs) for 5-10 years in the framework of the EU Covenant of Mayors. Some cities and municipalities demonstrate that introduction of such practice leads to better outcomes in establishing more resilient local energy systems. Several communities in Ukraine developed energy plans, which appeared to be of different scopes, time horizons, and content, complicating their integration into the national planning system and dedicated umbrella policy documents and organizing progress monitoring and reporting.

To ensure an appropriate institutional and business environment for improving energy sustainability and resilience across Ukraine, it is vital to introduce the practice of designing sustainable energy development plans for medium-term and long-term perspectives in local communities. Those plans should have specific targets and be coherent with key national energy-related targets and policy documents, e.g., the Energy Strategy, NECP, NREAP, NEEAP, etc.

Conducting comprehensive energy audits in local communities should precede the designing of the plans. To ensure a consistent approach to planning, the guidelines and templates are to be developed by the government, particularly by the dedicated Ministry for Communities and Territories Development of Ukraine. Additionally, effective and transparent reporting procedures regarding the plans' implementation should be established. To foster the establishment of sustainable and resilient local energy systems, it is worth implementing this practice through pilot projects in several local communities.

4.2.2.5 Fostering New Business Models of Participation in the Electricity Market

Increased digitalization and smart metering have created new business models. Aggregators are new market players that can optimize the use of distributed energy resources and contribute to system flexibility and resilience. An aggregator can help better integrate renewable energy resources by providing both demand- and supply-side flexibility services to the grid. Demand-side flexibility is provided by aggregating demand-response resources or energy storage units to meet grid requirements. Supply-side flexibility is provided by optimizing power generation from flexible resources such as combined heat and power (CHP) plants, biogas plants, etc., and the use of energy storage units.[91] To unlock and foster the potential of aggregators, it is essential to raise public awareness by educating stakeholders and the wide public about these possibilities, as well as to streamline legislative procedures required for establishing and authorizing new business models and their operation in the electricity market.

Implementing the above policies and measures would require due transparency, accountability, and coordination between government agencies, private sector actors, and civil society.

88 Eight ideas for green cities in Ukraine (2020). https://decentralization.gov.ua/uploads/library/file/595/Посібник_8_ідей_для_зелених_міст_України__2_.pdf

89 https://www.epravda.com.ua/publications/2017/12/6/631860/

90 https://interfax.com.ua/news/press-conference/902666.html

91 IRENA (2019), Innovation landscape brief: Aggregators, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Aggregators_2019.PDF

4.2.3 Best Practices and Case Studies

4.2.3.1 Energy Resilient and Decarbonized Communities

In the recent years, Ukraine has made significant progress in increasing of the use of renewable energy sources, including solar, wind, and biomass. Ukrainian government has set a target of generating 25% of electricity from renewable sources by 2035[92]. Moreover, some local communities have successfully applied the best European practices of building sustainable and resilient local energy systems. E.g., the city of Zhytomyr, following a comprehensive energy audit, has developed a 100% renewables transition plan for the city in 2021. Currently, Zhytomyr has several initiatives and projects underway to promote the development of renewables. Zhytomyr would require coherent, collaborative efforts from the government, businesses, and the community to implement this plan. It would also require a long-term commitment of various stakeholder groups to sustainable energy practices.

The city has multiple solar panels installed on public buildings, such as schools and hospitals, reducing the city's reliance on fossil fuels. The city also explores construction of several wind farms, which could potentially supply the city and the region. Additionally, Zhytomyr promotes the use of biomass for heating and electricity generation. Notably, wood chips and agricultural and other local waste (RDF) will be burned to generate heat or electricity, reducing the need for fossil fuels. The best European practices prove that some large cities could cover up to 80-90% of their heating demand by combustion of RDF (e.g., Copenhagen, Vienna, etc.).

To further support the development of renewables in Zhytomyr, the city works with the national government and international organizations to secure funding and technical assistance. The city also promotes public awareness and education regarding the benefits of renewable energy sources. Overall, developing renewables in Zhytomyr is essential to reduce GHGs emissions and achieve more sustainable energy for the city and the region. Thus, such practice should be scaled up na-tionwide, contributing to building distributed energy and improving local energy resilience.

Also, the city of Rivne has received a grant of almost 1 mln EUR and joins efforts against climate change as part of the NetZeroCities Pilot Cities Program,[93] a two-year program funded by the EU un-der the European Union Mission.[94] So far, Rivne is the only city in Ukraine to implement innovative measures to improve adaptation to climate change and rapid decarbonization under the European program. Together with local higher education institutions, community organizations, and with the help of experts from the EU countries, Rivne will implement a wide range of measures, including creating an energy passport for the community, developing scenarios to reach net-zero CO_2 emissions by 2050, and teaching and promoting energy efficiency through municipal educational institutions. The Pilot Cities Program should be considered as opportunity to further knowledge sharing with other cities, replicating and scaling solutions that work in similar contexts.

4.2.3.2 Battery Energy Storage Systems

The first-ever pilot BESS project in Ukraine was implemented by a private energy company, DTEK, in 2021.[95] The BESS of 1 MW capacity and 2.25 MWh energy density was set up at the Zaporizhzhya TPP site in the city of Enerhodar. The TSO, Ukrenergo, developed a comprehensive test program, including testing the battery's ability to carry on load, check frequency oscillation response, and response time to incidents when the grid frequency exceeds the nominal value. The test proved the battery could change power from zero to full load in less than

92 This target comes from 2035 Ukraine's Energy Strategy adopted by the government in 2017 (https://zakon.rada.gov.ua/laws/show/605-2017-%D1%80#Text). During preparation of this study Energy strategy has been under revision. This target was not considered in REF.

93 Rivne received a grant and joins the fight against climate change. https://rivnerada.gov.ua/portal/view-content/16341

94 EU Mission: Climate-Neutral and Smart Cities. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en#:~:text=EU%20missions%20are%20commitments%20to,ensuring%20soil%20health%20and%20food

95 The first in Ukraine industrial energy storage system of DTEK passed the certification of NEC "Ukrenergo". https://dtek.com/media-center/news/ukraines-first-ever-dteks-industrial-energy-storage-system-certified-by-nec-ukrenergo/

0.6 seconds, which is 50 times faster than required by the Network Code. The battery's response time to the grid frequency events was 0.1 seconds.

Following the successful market participation tests, the lithium-ion battery was certified by TSO to provide ancillary services of frequency containment reserve (FCR), which is vital for enhancing grid resilience. Notably, except for hydropower plants, FCR has been provided mostly by coal-fired TPPs. Thus, expanding BESS deployment in Ukraine's power system could substantially reduce the carbon footprint of balancing and providing frequency regulation services and accelerate the transition to clean and decarbonized energy.

Another beneficial project is installing hybrid power generation systems at the hydropower plants (HPPs). Particularly, in June 2021, the Ukrainian Government approved the decision to attract a loan of 211 mln USD from the IBRD and the Clean Technologies Fund to Ukrhydroenergo as part of an investment project to increase the stability of the power system required for integration into ENTSO-E grid.[96] The funds will be used to install battery energy storage systems in combination with solar panels at five HPPs (Kyiv HPP, Kaniv HPP, Kremenchuk HPP, Middle Dnieper HPP, and Dniester HPP). The total capacity of the designed lithium-ion BESS is 197 MW, while the photovoltaic panels' capacity is 63.9 MW. Solar panels are planned to be utilized to cover own electricity needs of HPPs and charge battery storage systems.

Particularly, batteries will be combined with HPPs' units, establishing hybrid units that will provide a faster response to electrical load fluctuations in the grid. In this way, the wear and tear of hydraulic units and operating costs will be reduced. Additionally, installation of the hybrid power generation systems will expand the range and quality of auxiliary services provided by Ukrhydroenergo in the electricity market. The hybrid power generation systems installation project was initially planned to complete by 2024. According to the economic evaluation of the USAID, the payback period of the new systems is expected to be 5-6 years.[97]

96 Ukrhydroenergo will attract 211 mln USD from the International Bank for Reconstruction and Development and the Clean Technologies Fund for the implementation of an investment project to increase the stability of the energy system. https://www.kmu.gov.ua/news/ukrgidroenergo-zaluchit-211-mln-dolariv-ssha-dlya-realizaciyi-investicijnogo-proektu-pidvishchennya-stijkosti-energosistemi

97 "Creation of energy storage systems at "Ukrhydroenergo" facilities will promote the integration of UES to ENTSO-E", - Valeriy Nozdrin. https://uhe.gov.ua/media_tsentr/novyny/stvorennya-sistem-nakopichennya-energii-na-obektakh-ukrgidroenergo-spriyatime

5. DECARBONIZATION IN INDUSTRY

5.1 Priority Areas for Investments

The priority areas for investments within industrial technologies foremost include the most carbon intensive industries such as iron and steel and fertilizers production. However, while reaching net-zero economy it is essential to minimize emissions in all industries thereby mitigating the need in DAC facilities, as they are more expensive measures. In general, each industry possesses the potential of emission reductions by mean of technological improvements, shifts or carbon capture.

In steel production industry, the complete production chain needs and should be decarbonized: extraction, agglomeration/palletization, smelting. Iron and steel industry is among the largest industrial sources of CO_2 emissions, especially in the part of producing steel from iron ore, where coke is used as a reducing agent. One of the most prominent technological shifts aimed to decarbonize iron ore-processing chain relies on clean hydrogen as reducing agent[98]. The direct reduced iron (DRI) or sponge iron obtained this way without melting is charged then to electric arc furnaces (EAF), which need to be supplied with a carbon-free electricity source. There are requirements for the high quality of iron ore, hence investments in modern extraction and refining[99] equipment with higher levels of efficiency and which utilizes clean electricity[100], are of high priority. The availability of high-quality scrap allows for supplementing sponge iron in EAFs.

Replacement of fossil origin hydrogen with clean hydrogen in industrial processes, such as the production of ammonia and the following production of ammonium nitrate and other nitrogen-containing substances. This may imply the building of electrolyzers in chemical facilities or investing in supply from external hydrogen producers. Ammonium nitrate production is also dependent on methanol, hence its production also has to be decarbonized.

Clean methanol synthesis from biomass or electricity and recycled CO_2. Being widely used in chemical industries as a feedstock, and also considered as marine and road motor fuel, methanol depends on fossil fuels usage to be obtained via the generic process. The possible decarbonisation pathway foresees the combination of electrolytic hydrogen and recycled CO_2 from atmospheric air via a technology chain called Power-to-Methanol (PtM)[101]. In addition to electrolyzers which have to be constructed, investments are also required for Direct Air Capture plants (DAC) and necessary changes to reacting equipment where methanol is synthesized. Biogenic CO_2 from BECCS plants can also be used instead or in addition to DAC.

Methanol production from biomass via gasification is even more mature carbon-neutral technology, where forestry and agricultural waste, biogas from landfill, sewage, municipal solid waste (MSW) and black liquor from the pulp and paper industry replace fossil feedstock to produce necessary syngas, which is then conditioned for methanol synthesis in common facilities.

Replacement of fossil hydrocarbons as feedstocks in industrial processes which utilize CO_2, e.g. for urea production, with biogenic or atmospheric CO_2, where investments are needed to modify combustion equipment to be supplied with biomass or to construct DAC plants. Considering that it was a common practice to build urea producing plants adjacent to ammonia producing plants, where large quantities of CO_2 are released due to fossil fuels burning for high grade heat, and then ammonia is used for urea synthesis, decarbonisation of both technological chains ought to be performed simultaneously.

98 UNECE Technology Brief: Carbon Neutral Energy Intensive Industries. Retrieved from https://unece.org/sustainable-energy/cleaner-electricity-systems/carbon-neutral-energy-intensive-industries

99 AT Minerals. (2022, November 3). Dry beneficiation of Iron Ore. Mineral Processing. https://www.at-minerals.com/en/artikel/at_dry_beneficiation_of_iron_ore-3789713.html

100 World Steel Association. (2019). Steel's contribution to a low-carbon future and climate resilience. Retrieved from https://canadiansteel.ca/files/resources/Position_paper_climate_2019_vfinal.pdf

101 Innovation Outlook: Renewable Methanol. Retrieved from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf

Replacement of fossil hydrocarbon fuels in numerous existing industrial processes with bio- or synthetic fuels for energy purposes like process heat and machine drives. In this case, the major share of investments should be aimed at construction of synthesizing facilities and transporting infrastructure.

Direct electrification of industrial processes, which utilize fossil fuels for energy purposes like process heat and machine drives etc. can be applied in almost every industry at some extent. It is implied that clean electricity is used.

Production of high value chain chemicals (HVC): replacement of fossil hydrocarbons with unprocessed plastic waste (pyrolysis oil), bio-ligroin (bio-naphtha) or synthetic ligroin (from green hydrogen and climate neutral carbon). Electrification of the cracking process or investment in a completely new methanol-to-olefins process (MtO). The latter requires the methanol supply chain to be already decarbonized as described above.

Perspective modernization of production facilities and renovation of technologies may also include:

- improvement of existing processes' energy efficiency, including upgrading or replacement of equipment and expansion of the waste heat use;
- development of industrial on-site renewables: rooftop PV, small power plants and cogeneration installations supplied with bioenergy/clean synthetic fuels;
- creation of complete production chains for photovoltaic, wind and bioenergy power plant components, energy storages of different types, electrolysers and fuel cell manufacturing, electric transport manufacturing facilities, and the complete chain of battery production;

Beside direct investments, policy decisions regarding future technological solutions should also take into account broad economic impacts of the alternative energy supply options, in particular, whether associated fuel and technological supply chains could be developed and scaled up domestically or would they be largely of import origin. Having supply chains with a high share of domestic inputs (equipment, fuel, energy services, etc.) would be preferable both from the economic, as well as energy security points of view. For example, production facilities of the Ukrainian Zorya-Mashproekt[102] or Tubroatom (Ukrainian Energy Machines)[103] could be upgraded to be capable of building gas turbines operating on hydrogen or clean methane and steam turbines for large and small nuclear reactors. Other Ukrainian factories could be easily engaged in manufacturing and installation of CCUS and DAC, which are crucial for reaching net-zero emissions, and the need for respective equipment in Ukraine can reach up to 12 Mt and 18 Mt of CO_2 emissions captured annually.

5.2 Promising Investment Attraction Mechanisms

Technological modernization of industry needed to approach carbon neutrality requires the attraction of tens of billions of Euro of investments. According to modelling results, the industrial sector in the Carbon neutrality scenario may need up to 93 bln EUR. Meantime, the Industrial Investment Menu[104] of the National Recovery Plan envisages 26.3 bln USD in metallurgy and metalworking, 15.8 bln USD in machinery and 1 bln USD in mining projects by 2032.

The Ukrainian Government has already introduced several programs and incentives to support industries and encourage investments. Primarily, the Government launches the local machinery support program to ensure Ukrainian manufacturers' participation in electronic auctions at the Prozorro platform[105], expecting to stimulate manufacturing industry development via creation of demand for domestic products. As a result, tens of thousands of new jobs, increasing tax, GDP growth and other benefits are expected, which will accelerate the restoration

102 Zorya-Mashproekt. https://www.facebook.com/zorya.mashproekt

103 Tubroatom (Ukrainian Energy Machines). https://ukrenergymachines.com/en

104 Industrial investment menu of Ukraine. Annex to the National Recovery plan. https://uploads-ssl.webflow com/621f88db25fbf24758792dd8/62c18564ad95361b56e23d96_Add_K_2_Investment%20menu_Mineconomy.pdf

105 Ukrainian public procurement system Prozorro. https://www.opentenders.online/

of the Ukrainian economy[106]. Among products, which fit for the program, are ambulances, fire trucks, electric buses, separate parts such as engines, turbines, pumps and compressors, etc. The share of locally manufactured components in the product must be no less than 10%. Requirements do not apply to products from the countries, which have signed free trade agreements with Ukraine, as well as to the goods of the public procurement agreement participants.

In order to attract foreign direct investments, special regimes for investing in green energy, machinery, industrial parks, production of eco-vehicles and component, and other investment projects have been developed and implemented. UkraineInvest,[107] the Ukrainian government investment promotion office, has been created to assist investors to expand their business in Ukraine. From its inception as a consultative body, UkraineInvest has transformed into a full-fledged government institution committed to providing investors with "one-stop support" consisting of reliable, current information and advice on doing business in Ukraine. As of today, UkraineInvest has succeeded in helping to unlock nearly 4 bln USD of foreign direct investment. List of projects, including industrial facilities, which are available for privatization or modernization, could be found on UkraineInvest website.[108]

Existing legislation, including the Law of Ukraine "On State Support for Investment Projects with Significant Investments in Ukraine",[109] Law of Ukraine "On Industrial Parks"[110] and accompanying legislation, provides investment projects that meet specific criteria with state guarantees on stable legislation, compensation for losses caused by state bodies, as well as provides such investment projects with state support in various forms, such as:

- full or partial compensation of interest rates on loans for the purpose of the project;
- temporary exemption from corporate income tax;
- exemption from VAT payment for operations on import of new equipment and compo-nents;
- exemption from customs duties for importing of new equipment and components;
- construction at the expense of state, local budgets of related infrastructure facilities (highways, communication lines, heat, gas, water and electricity, utilities, etc.) necessary for the implementation of investment project;
- favorable land tax rates and rent payments for land of state and communal property;
- simplified procedure for granting right for use (lease) of land plots of state or communal property with the pre-emptive right for acquisition of such a land plot to the property after the expiration of a special investment agreement.

Additionally, if the implementation of an investment project requires connection to the networks of heat, gas, water and electricity supply, utilities, etc., the state may assist (compensate) the investor in such connection within the framework of a special investment agreement.

Considering that many of prominent industrial technologies might be interlinked and dependent on each other feedstock or output (e.g. electrolytic hydrogen for steelworks and ammonia, captured CO_2 for urea, methanol for nitric acid and HVC), there arises a possibility to present complex projects with inclusion of stakeholders in different industries.

5.3 Case Studies

During the past years, many Ukrainian industrial companies performed measures of a different extent to increase energy efficiency of processes as a reaction to the rising prices for electricity, natural gas and petroleum products.

106 The Government is launch a program to support machinery. https://www.kmu.gov.ua/news/uriad-zapuskaie-prohramu-pidtrymky-mashynobudivnoi-promyslovosti

107 UkraineInvest. https://ukraineinvest.gov.ua/

108 Invest Atlas. https://ukraineinvest.gov.ua/wp-content/uploads/2020/02/Invest_atlas.pdf

109 Law of Ukraine "On State Support for Investment Projects with Significant Investments in Ukraine". https://zakon.rada.gov.ua/laws/show/1116-20#Text

110 Law of Ukraine "On Industrial Parks". https://zakon.rada.gov.ua/laws/show/5018-17#Text

However, there were no major investments in any kind of technology shift before the russian invasion. There were simply no incentives to perform such capital-intensive shifts due to very low carbon tax, as well as CBAM has not yet been imposed. On the other hand, large carbon-intensive enterprises had started to pay attention at global decarbonisation tendencies and had been in process of their future strategies development.

ArcelorMittal declared its intentions to achieve net-zero carbon emissions in steel production by 2050[111], which given the fact of owning one of the largest Ukrainian integrated steel plant in Kryvyi Rih, makes possible to assume implementation of two major carbon-neutral steelmaking routes (the Smart Carbon and the Hydrogen-DRI) after the war ends.

Metinvest Group, vertically integrated mining and metallurgical company and one of the largest employers in Ukraine, prior to the war had the plans to implement in 5-7 years a low-carbon steel technology on one of its plants in Zaporizhzhya or Mariupol[112]. The Northern Iron Ore dressing Works had been intended to be modernized for 1 bln USD with a high quality raw iron ore production chain to be used for low-carbon steel. In general, Metinvest planned to invest up to 1.5 bln USD annually to decrease carbon emissions by 90% by 2050[113].

Ukrplastic, Ukrainian manufacturer of packaging materials, has invested in new technology to reduce its carbon footprint. The company has introduced a new line of biodegradable films made from renewable materials such as corn starch and sugarcane. These materials are biodegradable and compostable, reducing the environmental impact of packaging waste and consumption of petroleum products and natural gas needed for production of packaging[114].

Ostchem, one of the largest chemical companies in Ukraine, has invested 218 mln UAH in energy efficiency measures, which resulted in 280.5 bcm of natural gas saving in the process of ammonia and nitric acid production, and correspondent reduction of GHG emissions[115].

In 2004-2009, almost 50% of the global solar silicon production capacities were located in Ukraine, and there was a complete cycle of photovoltaics production until 2010 when cheap Chinese photovoltaics flooded EU market and Ukrainian facilities faded except Quasar, Pillar and Prolog Semicor companies. Meanwhile in a recent years the industry started to restore, facing increase in demand owing to feed-in-tariff allowance for the use of domestic PV equipment, and companies Kness, Enhol, Solitec-Ukraine have entered the market. The potential of solar power plants capacities according to the CN scenario might reach 50 GW, set aside global market with a need for 4000 GW by 2030 according to the IEA Net-zero projection[116]. Given the different reasoning such as energy security and supply options variety, it is urgent to invest in development of local PV manufacturing facilities to meet demands of the domestic market and to become competitive at the global scale. For this to happen, to simplify the mechanism of achievement benefits from domestic equipment use for generating companies, increase in rate of allowances for subsequent to FiT supporting schemes, introduction of R&D tax incentives and other possible incentive measures are crucial for PV manufacturers growth during the next decade.

111 ArcelorMittal sets 2050 group carbon emissions target of net zero. https://corporate.arcelormittal.com/media/press-releases/arcelormittal-sets-2050-group-carbon-emissions-target-of-net-zero

112 Metinvest wants to use hydrogen to reduce CO_2 emissions (in Ukrainian). https://ecopolitic.com.ua/ua/news/metinvest-hoche-vikoristovuvati-voden-dlya-skorochennya-vikidiv-so2/

113 Metinvest plans to invest annually 1.5 bln USD in "green" metallurgy for 3-4 years. https://uprom.info/news/metal/metinvest-planuye-shhorichno-investuvaty-15-mld-protyagom-3-4-rokiv/

114 UKRPLASTIC Introduces Innovative Energy-Saving Technologies. http://chemunion.org.ua/en/news/188-ukrplastic-introduces-innovative-energy-saving-technologies.html

115 Environmental commitment of Ostchem. http://ostchem.com/en/ustoychivoe-razvitie/ekologiya

116 IEA (2022), Solar PV, IEA, Paris https://www.iea.org/reports/solar-pv

6. ACCELERATING NET ZERO TRANSPORTATION

In Ukraine in 2020, transport sector accounted for 39% of all air emissions and for 17% of country's CO_2 emissions[117]. Reducing GHG emissions by the transport sector is one of the primary tasks for mitigating climate change. In Ukraine, the level of motorization remains relatively low (211 light-duty vehicles per 1,000 people as of 2022 compared to 560 in the EU)[118]; however, emissions of pollutants from the Ukrainian road transport are significant, as the domestic car fleet is outdated, making Ukraine rank the second country globally in terms of the oldest car fleet[119]. As of 2022, the average age of a Ukrainian car was 22.7 years[120] compared to that in the EU of 11.8 years[121]. With the growth of the motorization level, energy consumption normally is also growing.

The role of the transport sector in decarbonization is twofold. On the one hand, passenger and cargo transportation may increase due to the economic growth, unless special measures are undertaken. So, growing rate of motorization coupled with the growing role of deliveries of goods are the activity drivers. On the other hand, the rolling stock of vehicles should be renewed using the latest technologies. According to the REF scenario, the use of energy in transport sector is projected to grow from 9.5 ktoe in 2020 to 12.9 ktoe in 2060. In the structure of private passenger transport, the share of electric cars would be 11.5% in 2060, which is negligible compared to the percentage of vehicles on gasoline (41%). The share of diesel-fueled cars in 2060 would be only 7.6%. In the overall vehicle structure, the lion's share (30%) in 2060 is anticipated to belong to new gasoline cars.

Nonetheless, the share of old cars (i.e., those older than five years) would be 11.5%, so this scenario anticipates particular renovation of the vehicles' fleet. Remarkably, the REF scenario does not expect the use of methane in vehicles in 2030 and on. Simultaneously, the number of cars on LPG would decrease five-fold in 2030 compared to 2015, and the use of LPG would continue by small cars unchangeable in 2040-2060, representing only 1% of the fleet in 2060. However, the number of electric motorcycles is expected to grow eleven-fold by 2060, representing 9% of all the vehicles fleet in 2060. The scenario anticipates the eight-fold growing share of gasoline-fired motorcycles, with a peak in their use in 2040-2045. Also, in 2025-2035, a small percentage of hybrids (with gaso-line). Overall, the absolute number of vehicles in 2060 is projected to be insignificantly higher compared to 2015, but it would have a slightly different structure (in particular, more motorbikes are anticipated, as well as a minimal share of EVs); however, a smaller number of population in 2060 together with a higher number of road vehicles means the higher level of motorization in Ukraine in 2060. Under the CN scenario, the energy consumption by transport sector is projected to decrease from 9.5 ktoe in 2020 to 5.7 ktoe in 2060. In the structure of the vehicles fleet under the CN scenario, in 2060, more than half (63%) of all the vehicles fleet would be EVs. More importantly, in the overall structure of the fleet, 51% would be brand-new vehicles, whereas the share of old EVs would decrease, reaching 11% of the entire vehicle fleet in 2060. There would be a very insignificant share of gas-fired (methane) vehicles, which are projected to cease after 2025. The CN scenario does not anticipate the operation of diesel-fueled cars in 2060. Electric motorbikes are projected to gain popularity since 2030 and on so that their share in the entire road fleet structure would reach 14% in 2060, allowing modal shift to be one of the reasons for the decreasing energy consumption of transport sector. Remarkable is the operation of the hydrogen-fired vehicles in 2035-2055, whose share is projected to be 20%-16% of the entire fleet in 2035-2055, respectively. The hydrogen-fueled cars would be used more to cover the demand for long-distance transportation; however, vehicles for small-distance trips will also be available. Similarly to the REF scenario, the number of vehicles on LPG would decrease five-fold in 2030 compared to 2015. It is interesting to note that the number of road vehicles under the CN scenario is projected to be lower than that under the REF scenario,

117 SSSU (2022) Air emissions total and carbon dioxide emissions. State Statistics Service of Ukraine https://ukrstat.gov.ua

118 FRA (2022) Automotive Industry Review №83 Results of the year 2021. The Federation of the Automotive Industry of Ukraine and the Federation of Employers of the Automotive Industry of Ukraine https://fra.org.ua/uploads/media/file/0001/08/6e2d63ec57ae93ad4b9fff3d0e543508d0d9e054.pdf

119 FRA (2021) Summary of the presentation and discussion "Cars: driving cannot be disposed of" The Federation of the Automotive Industry of Ukraine and the Federation of Employers of the Automotive Industry of Ukraine https://fra.org.ua/uk/pc/priess-tsientr/ofitsial-nyie-soobshchieniia/pidsumki-prezentatsiyi-ta-obgovorennia-avtomobili-yizditi-ne-mozhna-utilizuvati

120 FRA (2022) Automotive Industry Review №83 Results of the year 2021. The Federation of the Automotive Industry of Ukraine and the Federation of Employers of the Automotive Industry of Ukraine https://fra.org.ua/uploads/media/file/0001/08/6e2d63ec57ae93ad4b9fff3d0e543508d0d9e054.pdf

121 ACEA (2022) Average age of the EU vehicle fleet, by country https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/

which means that the same demand for transportation could be met with a smaller number of vehicles, which is especially important given the projected decrease of population in Ukraine by 2060 compared to 2015. The number of road vehicles in 2060 is projected to be lower than in 2015.

In the structure of the public intercity and urban transport under the REF scenario, the electric fleet's growth is anticipated. In urban transport, the role of trams and trolleybuses is projected to grow, whereas the role of the metro is projected to remain insignificant. However, gasoline and diesel trucks are projected to dominate the structure of freight transportation. The use of methane for freight transportation will peak in 2030, and its use will cease in 2050. In navigation, the existing types and structures of fuels are projected to remain by 2060.

Under the CN scenario, biofuels are projected to be used in aviation and navigation starting in 2040 and on, reaching their peak in 2060. Buses (both intercity and urban) would be electric, and their share would grow steadily by 2060. Urban buses on gasoline and diesel fuel are projected to cease by 2030. Navigation will play a specific role since 2030, and since 2040 it would use biofuels, almost entirely being transferred to it in 2050. New diesel trucks would be popular in freight transportation until 2050, with the peak of their use in 2030-2040.

Nonetheless, electric trucks could gain momentum since 2030, with the peak of their use in 2060, comprising as much as 72% of the entire transportation fleet in 2060 (excluding light and light-duty transportation means). LPG is also projected to be used for freight transportation from now and until 2060; however, their share would remain insignificant and is projected to decline by 2060. In 2030-2050, trucks on methanol are expected to be used. The fleet of urban metro under the CN scenario is projected to remain the same as under the REF scenario. Overall, the CN scenario presumes a slightly higher share of vehicles and means of transportation, especially in 2050. Still, the fleet of means of transportation would be the same in 2060.

Therefore, **renovation and further electrification of the vehicles fleet should be prioritized in Ukraine. Since** 2016, Ukraine has increased the import of passenger vehicles from the EU almost four-fold, so the number of imported cars from the EU reached 210 thousand units[122]. However, the age, technical condition, and emissions characteristics of the imported vehicles remain in question. Even though the import of cars to Ukraine from abroad may continue, seeing as one of the measures to renew the vehicle fleet of Ukraine, the latter should be mainly focused on EVs and hybrids, to a smaller extent. It means that EVs should gradually replace cars ICE. They are expected to improve air quality in settlements, especially in cities, and reduce noise pollution. It is especially relevant for the so-called last-mile delivery services, which gain the possibility to deliver goods at night due to lower noise levels. In Ukraine, the EV market is proliferating.

To ensure the further and more rapid electrification of transport, further development of infrastructure is needed (networks of charging stations and home chargers, availability of repairs, availability of service stations), as well as available affordable electricity. To ensure the EVs market grows, several policy measures are needed, such as fiscal preferences, in particular, tax reduction when buying or using an EV, and the presence of savings resulting from cheaper "fuel" compared to gasoline or diesel fuel.

In Ukraine, the goal of electrification is provided by the National Transport Strategy for the period until 2030, which sets the goal of electric transport in domestic communication at 75% by 2030[123]. There are already specific preferences for this, in particular, the VAT exemption for imported electric vehicles is valid until 2023, the excise duty on electric vehicles is lower than that of hybrid passenger cars (the excise duty on electric vehicles is 1 Euro/kWh of battery capacity), and the 5% import duty has been abolished; until 2034, the sales profit received from the sale of electric chargers, vehicles and their parts produced in Ukraine is exempt from taxation; until 2031, vehicles equipped with electric motors will be exempted from value added tax (VAT) on the introduction into Ukraine and delivered on the territory of Ukraine[124]; until the end of 2035, the profits of enterprises producing electric vehicles, as

122 ACEA (2022) EU passenger car exports, main destinations (in units) https://www.acea.auto/figure/eu-passenger-car-exports-main-destinations-in-units/

123 Decree of the CMU " On the approval of the National Transport Strategy of Ukraine for the period until 2030 " dated May 30, 2018 No. 430 https://zakon.rada.gov.ua/laws/show/430-2018-p#Text

124 Law of Ukraine No. 1660-IX "On Amendments to Chapter XX "Transitional Provisions" of the Tax Code of Ukraine on Stimulating the Development of the Ecological Transport Industry in Ukraine."

well as electric engines, lithium-ion (lithium-polymer) batteries and chargers for them, are exempt from taxation[125]; until 2031, transport is exempt from VAT and import duty for enterprises that create or modernize their production facilities for the production of electric transport[126]; fines have been introduced for parking vehicles with internal combustion engines in parking spaces marked as spaces for electric cars. New green numeric plates were introduced to designate electric vehicles and new road signs.

Considering the growth of the fleet of electric vehicles in Ukraine, the charging infrastructure is also growing. As of November 2021, Ukraine had 3244 charging stations with 7661 charging terminals or four electric cars per charging terminal[127]. However, it is necessary to encourage local governments to install municipal EV chargers and promote EV charging infrastructure by adopting municipal and regional EV charging infrastructure programs, including measures to simplify land acquisition procedures.

EVs need to be included in the public procurement system, that is, the purchase by state authorities of goods and services, the promotion of which is stimulated. In Ukraine, examples of the action of this tool are the purchase of electric cars to form the fleet of the Kyiv City State Administration, as well as the National Police of Ukraine. In pre-war times, the volume of public procurement in Ukraine annually reached 13% of GDP; thus, at least half of the publicly procured vehicles should be EVs.

Electrification of not only private motor vehicles but also public ones should take place. In addition, the role of public transport for the transportation of passengers (in contrast to the use of individual cars) should increase. To do this, the network of public transport routes should be user-friendly, like all public transport infrastructure, especially considering the current and projected climate change. Updating the public transport fleet will contribute to increasing the attractiveness of public transport as such. Electric buses will play a unique role, corresponding to the concept mentioned above of electrification of public transportation. Electric buses can be a part of low-carbon strategies of cities and/or regions.

Hydrogen may offer benefits being a low-carbon fuel, offering two-three times higher efficiency compared to combustion technologies. To enable the use of hydrogen in transport, the infrastructure and the legislation for the hydrogen use need to be created. Additionally, support measures to form the infrastructure are needed, because infrastructure for hydrogen is more expensive than that for EVs, and hydrogen vehicles (FCEV) themselves are more expensive than battery EVs[128].

As stated above, biofuels are projected to be used in aviation and navigation. To ensure the presence of biofuels on the market, the availability of R&D, production facilities, blending infrastructure, and respective legislation are to be guaranteed in the country. Ukraine has attempted to establish its biofuel market for light-duty vehicles, but it still needs to be made available. Nonetheless, the introduction of the sustainability criteria for the biofuel feedstock is required, together with the expansion of the list of types of fuel that can be considered components of biofuel, in particular, bio-DME (dimethyl ether produced from biomass), bio-ETBE (ethyl-tert-butyl ether made using bioethanol), biomethanol (methanol produced from biomass), bio-ETAE (ethyl-tert-amyl ether produced from using bioethanol) and others[129].

Specific preferences have been introduced for owners of biogas vehicles; in particular, until 2026, the import of internal combustion engine cars running exclusively on methane or biogas into the customs territory of Ukraine will be exempt from VAT; until 2031, operations of importing goods into the customs territory of Ukraine for enterprises

125 Law of Ukraine No. 1660-IX "On Amendments to Chapter XX "Transitional Provisions" of the Tax Code of Ukraine on Stimulating the Development of the Ecological Transport Industry in Ukraine."

126 Law of Ukraine No. 1661-IX "On Amending Item 4 of Chapter XXI "Final and Transitional Provisions" of the Customs Code of Ukraine on Stimulating the Development of the Ecological Transport Industry in Ukraine."

127 AutoGeek (2021) In Ukraine, the number of charging stations for electric cars was counted for the first time: four cars per filling station https://autogeek.com.ua/zarydni-stancii/#:~:text=На%20один%20термінал%20в%20Україні,3244%20станції%20з%207661%20терміналом

128 Dash, S.K.; Chakraborty, S.; Roccotelli, M.; Sahu, U.K. (2022) Hydrogen Fuel for Future Mobility: Challenges and Future Aspects. Sustainability, 14, 8285. https://doi.org/10.3390/su14148285

129 Draft Law on Amendments to Certain Legislative Acts of Ukraine Regarding Mandatory Use of Liquid Biofuel (Biocomponents) in the Transport Sector No. 3356 dated 04/17/2020 http://w1.c1.rada.gov.ua/pls/zweb2/webproc4_1?pf3511 =68617 that have, create or modernize production facilities for the industrial production of methane or biogas vehicles are exempt from VAT; until the end of 2035, the profit of car manufacturers, which are engaged exclusively in the production of vehicles with internal combustion engines on methane or biogas, is exempt from taxation. The freed funds are used for R&D, creation or re-equipment of the material and technical base, increased production volume, and implementation of the latest technologies[130].

Standards for CO_2 emissions must be introduced. Emission standards are an effective means of public policy in the transport sector aimed at reducing CO_2 emissions and creating indirect benefits for human health. Provisions similar to Regulation (EU) 2019/631 are to be adopted in Ukraine, while these provisions have entered into force in the EU since 2020. The regulation sets an emission threshold of no more than 95 g CO_2/km for new passenger cars and 147 g CO_2/km for new light commercial vehicles. From 2021 to 2024, the corresponding emission threshold is reduced by 10 g/CO_2/km. From 2025 onwards, the average level of emissions of both passenger and light vehicles should decrease by 15% compared to 2021.

Increasing taxes on (fossil) fuel for road transport and differentiated fuel tax rates depending on the carbon content will help to increase the attractiveness of cars with alternative characteristics (e.g., electric vehicles or fuel cell cars). Fixed tolls/road tolls/charges at differentiated rates depending on energy efficiency can be established for heavy vehicles and vehicles of a particular type (e.g., on conventional diesel engines), which will indirectly encourage the use of cars on alternative fuels. The introduction of annual taxes on certain types of motor vehicles can facilitate the transition to the use of motor vehicles on alternative types of fuel. Stimulation of the purchase of new cars is possible both through direct subsidies, fees depending on the mileage (the higher the mileage, the higher the payment rate), and by limiting the registration of outdated vehicles (which is valid in Ukraine)[131].

In Ukraine, since 2016, the EURO-5 standard has been required for new imported cars, buses, trucks, and tractors[132], whereas used light-duty vehicles imported into Ukraine must meet the EU-RO-2 standard, and imported buses must meet the EURO-3 standard. The EURO-6 standard will come into force in Ukraine in 2025, although its implementation has already been postponed many times. In 2022, (as of October 2022), the share of imported vehicles older than 10 years in 2022 reached 69%[133], which is a continuation of the existing trend and one of the most affordable measures of the existing fleet renewal.

130 Law of Ukraine "On Amendments to Section XX "Transitional Provisions" of the Tax Code of Ukraine on Stimulating the Development of the Ecological Transport Industry in Ukraine" No. 1660-IX dated 07/15/2021

131 Hill, N., Windisk, E., Klymenko, O. Development of National Transport Policy on Regulation of CO_2 Emissions and Energy Consumption by Road Transport in Ukraine October 28, 2016 p.30.

132 Law of Ukraine No 2739-IV "On some issues of import into the customs territory of Ukraine and the first state registration of vehicles".

133 FRA (2022) Automotive Industry Review #84. The Federation of the Automotive Industry of Ukraine and the Federation of Employers of the Automotive Industry of Ukraine https://fra.org.ua/uploads/media/file/0001/08/834b235bec3bef294488b14757c5adf29ada92fd.pdf

7. NATURAL GAS SECTOR IN CARBON-NEUTRAL ECONOMY

The achievement of the carbon-neutral economy goals by 2050 anticipates a gradual decrease in the total final consumption of natural gas by 30% by 2035 compared to 2020 (reduction of consumption by 4.3 bln cbm). At the same time, by 2035, natural gas would continue to account for about ¼ energy supply in the final consumption. After 2035, natural gas consumption would decrease rapidly reaching of 1% in the FEC in 2050, which would determine its role change in the energy supply of certain categories of consumers and the need to adapt gas transportation infrastructure to new market conditions.

The total final consumption of natural gas will be reduced by the introduction of **energy efficiency measures** in heat supply, **changes in the behavior** of consumers, and replacement of natural gas with carbon-neutral synthetic methane and biomethane. However, reducing natural gas consumption will necessitate significant changes in the gas distribution system after 2035, since the volumes of low-carbon gases distributed after carbon neutrality achievement are twice lower than it was in 2020. Excessive unclaimed gas distribution system capacities will become a significant burden for end consumers, this will increase the operating costs and gas losses. Accordingly, the gas transportation network of Ukraine will require significant investments in the redesign of the distribution system in accordance with the estimated demand and adaptation of the gas transmission system to the conditions of its use with new alternative low-carbon types of gases.

By 2045, the residential sector should cease using natural gas for cooking purposes, which necessitates the adaptation of the state regulatory policy to stimulate appropriate infrastructure transformation and change the behaviour of end users. This would require significant changes in public policy to stimulate the residents to shift from natural gas to electricity in cooking, which should ensure decreasing in natural gas consumption for cooking by 60% by 2035 compared to 2020. At the same time, the population is anticipated to start using alternative low-carbon types of gases for cooking from 2040, which will also contribute to the superstition of natural gas. The set of state policy measures should include, in addition to changes in tariffing for gas supply for residential cooking needs, as well as measures that would stimulate domestic enterprises to produce electrical appliances for cooking. It will also be necessary to ensure a large-scale modernization of distribution and local power grids for their adaptation to a significant increase of households' share in electricity load curve.

Natural gas consumption by industry until 2030 would remain mainly at a constant level with a slight tendency to reduction, which is due to the technological features of natural gas use in industrial processes. The replacement of natural gas with other energy resources would occur with new technologies becoming cheaper, increasing energy efficiency and innovation implementation, which would require significant investment in relevant research studies.

At the same time, after 2030, natural gas consumption in industry under the Carbon Neutrality scenario would rapidly reduce in the final energy consumption to 10% in 2040 and 2% in 2050. The decrease in natural gas consumption is expected in all sub-sectors in industry, but the greatest reduction should occur in metallurgy, which should reduce consumption by 90% by 2040 compared to 2020 (by 2.1 bln cbm); in other industries gas consumption is reduced by 45% (by 0.51 bln cbm).

The final non-energy consumption of natural gas in the Carbon Neutrality scenario would reduce gradually by 2050. From 2030 onwards, natural gas is replaced there by biomethane and from 2045 – by carbon-neutral synthetic methane.

Achievement of the carbon-neutral by 2050 predefines substitution of the natural gas with alternative low-carbon types of gases. By 2050 the share of low-carbon types of gases would reach 8%, replacing about 2.6 bln cbm of natural gas. The use of low-carbon gases would intensively increase in the buildings and transport sector. In particular in the buildings sector, the use of low-carbon gases for heating in rural areas and for water heating in multi-apartment houses could become more common. However, in order to facilitate corresponding technological changes, appropriate government policies are needed to attract investment and stimulate R&D that should reduce the cost of low-carbon gas technologies. It is necessary to establish decentralized facilities for production of low-carbon gases with an adaptation of the existing gas transport infrastructure and/or construction of new networks that would meet the new market conditions. It is also essential to guarantee market conditions for the household appliances that could use low-carbon gases, meanwhile given the priority for domestically localized manufactures.

The listed measures are needed to a little extent if natural gas is superseded with biomethane or synthetic green methane, since their chemical content is almost identical.

Achieving the Carbon Neutrality scenario involves drastic changes in the use of natural gas for water heating. In 2050, **the use of natural gas for water heating in private rural houses would decrease by 50% and in urban areas by more than 90%**. Such a reduction would require correspondent state policy to stimulate the transition of consumers to other types of fuel/ energy sources and, accordingly, the replacement of water heating equipment if needed.

The CN scenario envisages reduction in the use of natural gas for space and water heating, which would require investments in the thermal modernization of the housing stock, upgrade and redesign of the district heating infrastructure, imposition of higher requirements for the construction of new residential buildings, the decommission of outdated district heating gas plants and, accordingly, their replacement mainly with technologies based on low-carbon gases or heat pumps.

According to modelling results, **the consumption of natural gas for the space heating by households will be stable until 2030**, and for some categories of household it may even increase compared to 2020 (increase by 7%). However, after 2030, residential consumers in urban areas and after 2035 residential consumers in rural areas could begin to sharply reduce the consumption of natural gas for space heating, with a total reduction of 98% by 2045 (by 1.7 bln cbm). The reduction of natural gas consumption could be achieved through the implementation of energy efficiency measures and the use of various alternative sources of energy (biomethane, synthetic methane, hydrogen, solar collectors and heat pumps).

In the commercial sector, natural gas consumption will consequently decrease until 2040 mainly due to the implementation of energy efficiency measures. At the same time, unlike the residential sector, this sector does not show a significant role of low-carbon gases in replacing the use of natural gas. Instead, in 2030 biomass, heat pumps and district heating will account for 95% of energy used for space heating.

CN scenario involves drastic changes in the use of natural gas for water heating. **In 2050, the use of natural gas for water heating in private rural houses would decrease by 100% and in urban areas by – 97% compared to 2020**. As expected, heat pumps, electricity, and after 2040 – biomethane, synthetic gases and solar collectors would fully replace natural gas for water heating. Such a reduction if gas consumption would require implementation of appropriate state policies to stimulate the transition of consumers to other types of energy resources and, accordingly, the replacement of water heating equipment.

8. MODERN ROLE OF BIOENERGY

8.1 Expected Demand for Biofuel in Ukraine

Biomass is considered as carbon-neutral; thus, bioenergy is expected to play a crucial role in the carbon neutrality pathway. Biomass is at the intersection of several sectors - energy (in terms of feedstock used for energy purposes), agriculture (in terms of feedstock production), and industry (in terms of numerous other applications of biomass use, such as for the production of bioplastic, etc.). Policy measures in the bioenergy sector are aimed at its more intensive development and progress toward carbon neutrality.

Ukraine has significant biomass potential, the lion's share of which is agricultural crop waste, corn (grown for energy purposes), and dedicated energy crops. Ukraine has relatively low forest coverage (16%), and the potential of forest biomass and sunflower husk is already 90% utilized, so there is no room for further expansion. In the structure of biomass use, woody biomass takes about 81%, agrobiomass is 17% (straw, dung, sunflower husk), and the remainder 2% is solid landfills[134]. As of 2022, Ukraine's area of dedicated energy crops was 6.4 thousand ha[135], of which 3 thousand ha are sown with willow and 2 thousand ha – with miscanthus. Energy crops are planted mainly in the Western and Central Ukraine. There is about 8 mln ha of unproductive (marginal) land in Ukraine. Of these, about 3.5 mln ha have been removed from crop rotations due to low fertility, susceptibility to erosion, or excessive moisture[136].

Biomass in Ukraine is used mainly to produce heat and electricity: using biomass, 756 GWh of electricity and 32,971 TJ of heat were produced in 2020[137]. In 2020, in Ukraine, in the structure of primary renewable energy production, the largest share of renewable energy belonged to biomass – 74.6%. Primary supply of bioenergy and waste increased by 27% and amounted to 4,243 ktoe in 2020 (compared to 3,349 ktoe in 2019)[138].

REF scenario doesn't reflect the crucial role of bioenergy. Under the REF scenario, the use of biomass in TPES is projected to remain approximately the same in 2060 as in 2020. Under the Carbon Neutral scenario, the role of bioenergy is expected to grow eight-fold, reaching 33451 ktoe in TPES by 2060. Under REF in 2060, the role of biomass in FEC is projected to decrease by 60% compared to 2020. In contrast, under the CN scenario, the share of biomass would grow two-fold compared to 2020, reaching 4757 ktoe in 2060. It would allow biomass to take a 15% share in FEC in 2060.

The growing interest in biomass in Ukraine became especially obvious in the light of the Russia-Ukraine war and related energy crisis, with the spiked prices for natural gas and continuous threats of fossil-based infrastructure destruction. In the future, one may expect this interest to grow because, after the war ends, Ukraine will have large areas of land contaminated with heavy metals, remaining suitable for the dedicated energy crops plantations. Municipalities and even traditional energy companies (e.g., SC "Naftogaz of Ukraine") are doing their best to shift from natural gas for heating to biomass as fuel. Ukraine also remains a significant exporter of biomass for heating (in the form of pellets) to the EU, even though the Russia-Ukraine war significantly affected the supply of woody biomass to the EU[139].

Under the REF scenario, in 2060, the installed capacity for electricity generation from biomass would reach only 1.18 GW (out of 54.4 GW of all installed capacity), generating 5.15 billion kWh. In contrast, under the CN scenario,

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134 UABio (2022) Electricity from biomass and CHP. https://uabio.org/biopower-and-chp/

135 Pryshliak, N. (2021). potential possibilities of growing bioenergy crops for the production of solid biofuels. Agrosvit 1-2. http://www.agrosvit.info/pdf/1-2_2021/5.pdf

136 Pryshliak, N. (2021). potential possibilities of growing bioenergy crops for the production of solid biofuels. Agrosvit 1-2. http://www.agrosvit.info/pdf/1-2_2021/5.pdf

137 SSSU (2021) State Statistics Service of Ukraine. www.ukrstat.gov.ua

138 SAEE (2021) Reaching the targets of National Renewable Energy Action Plant of Ukraine until 2020. State Agency of Energy Efficiency and Energy Saving of Ukraine. URL: https://saee.gov.ua/uk/news/4043

139 USDA (2022) EU Wood Pellet Annual https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=EU%20Wood%20Pellet%20Annual_The%20Hague_European%20Union_E42022-0049.pdf the biomass capacity is expected to reach 7 GW (out of 129 GW of all installed capacity) and might produce 28.6 billion kWh which is 10% of the total electricity generation. Biomass is projected to be used for heat production as well. Under the REF scenario, in 2060, biomass would amount at 1022 ktoe in both bioenergy CHPs and district heating plants. In contrast, under the CN scenario, biomass would provide 3,231 ktoe of heat, ensuring 44% of all heat produced in 2060.

Biomethane is expected to gain momentum in 2035-2045, reaching the record-high 5443-6838 ktoe, respectively. The largest share of it would be consumed by industry, reflecting the possibility and ability to substitute natural gas; biomethane would also be used for electricity production in gas power plants, with peak demand for biomethane in 2045. Biomass is massively used for hydrogen production via biomass steam reforming technology starting from 993 ktoe in 2030 and 10567 ktoe by 2060. From 2050 to 2060 BSR competes with electrolyzers, which share is no more than 12% of all hydrogen produced, amounting to about 1300 ktoe of hydrogen. The perspectives of hydrogen production are discussed in the following section.

To enable the sound development of bioenergy, several policy measures are needed. In particular, the prioritization of the bioenergy sector is required through the development and adoption of the long-term Bioenergy Strategy and Roadmap, which would define policies for bioenergy and assess the need for investments to achieve intermediate and final indicators and provisions of the Strategy and Roadmap.

To make the prices for biomass and biomass supply predictable, an electronic platform for biomass trade needs to be created (biomass burse). The biomass burse will create a market mechanism of trade, enable administrative responsibility for non-fulfillment of trade obligations, and contribute to the introduction of mandatory requirements for the quality of biomass. These provisions are relevant for Ukraine because currently, CHPs can often be supplied with wood chips of unsatisfactory quality, and sellers can manipulate contractual terms or refuse to provide the feedstock. Ukrainian power exchange cannot fulfill the functions that are expected to be fulfilled by the biomass burse.

Additional policies are needed to promote dedicated energy crop plantations. Energy crops for bioenergy needs can be grown on 4 mln ha of infertile or marginal land. Their use will allow to substitute up to 20 mln cbm. Such policies may include grants to start the plantation, lowering of the land rent to at least 5% of the normative monetary assessment of the land value, the extension of the land rent agreement to 20 years minimum, import tax waivers for the imported equipment and machinery, VAT exemption for seedlings and shoots of energy crops, which are not commercial products (as energy crops can be used as energy feedstock on average after they reach three years of age).

Biomass is considered a CO_2-neutral fuel. However, energy from biomass in Ukraine remains subject to CO_2 tax, adversely affecting solid biomass projects. Therefore, biomass-fired projects should be exempt from CO_2 tax. To do so, a registry of biomass installations needs to be created.

Other particular measures for further deployment of bioenergy in Ukraine may include adoption of the law on dedicated energy crops to put this type of agricultural activity in a regulatory framework; establishment of nurseries of energy crops in all regions of Ukraine; creation of soft loans program for farmers willing to establish dedicated energy crops plantations; support of research and development in the field of feedstock planting and agro-energy processing; finding a sustainable long-term source of funds to pay the feed-in tariff for biomass and biogas companies (and cover the existing debts).

The current economic impetus for biomass-derived heat is that the cost of heat from other sources than natural gas is established at 90% of the price of heat obtained from natural gas. In Ukraine, heat from natural gas is heavily subsidized, whereas the heat from biomass is not subsidized, making biomass-fired CHPs unprofitable. Therefore, a provision about 90% of the costs of heat from natural gas needs to be revised.

Biomethane production potential in Ukraine is 7.8 bln cbm. Biomethane can be used in industries that are difficult to decarbonize, as well as in transport without need to change natural gas distribution infrastructure, transformation and final consumption technologies which might lead to significant investment savings towards the net-zero economy. Ukraine already has primary legislation for biomethane, and the development of secondary legislation is to follow. The current economic incentive for developing biogas projects is the feed-in tariff of EUR 0.1239/kWh without reducing the tariff coefficient until the end of 2029. The cost of biomethane production in Ukraine ranges from 630-660 EUR/thousand cbm[140]. As of late 2022, biogas purification to biomethane remains costly; therefore, additional state support is needed, for instance, in the form of a separate tariff for biomethane or a feed-in tariff for electricity from biomethane. In addition, the CO_2 emitted in the process of biogas purification can be captured and either stored, resulting in negative emissions or utilized as raw material in industries or green synthetic methane production, which is another carbon-neutral form of methane. Enabling measures for biomethane output on an industrial scale include the development of a special financing program aimed at the reduction of the cost of its production, as well as the introduction of a guarantee of origin system.

General obstacles that impede bioenergy development in Ukraine are diverse. The financial barriers include the high upfront cost, especially for biogas and biomethane projects, the high cost of capital, the lack of long-term borrowings, and the lack of the designated source of project funding against the feed-in tariff. The regulatory obstacles include incomplete legislation, especially for biomethane, and a general lack of vision on the importance and role of bioenergy in general and bioeconomy in particular. Overall, biomass is not yet considered a vital energy carrier, which is confirmed by the mismanagement of biomass. Still, spiked natural gas prices and high dependence on imported fossil fuels will promote a better understanding of the opportunities that biomass may provide.

8.2 Biomass Market and Infrastructure

8.2.1 Priority Areas for Investments

The priority areas for investment into bioenergy technologies include, but are not limited to, the use of biomass for heat and electricity output, the production of biomethane and hydrogen (via biomass steam reforming technology), and the production of liquid transport fuels. Under the CN scenario, the share of biomass would reach 15% in FEC in 2060. Under this scenario, biomass may provide up to 10% of the entire electricity generation and 44% of the total centralized heat generation; therefore, massive investments are needed for biomass-fired combined heat and power plants. The role of biomethane could be unprecedented in 2035-2045; both anaerobic digestion and thermal gasification technology may have good prospects, making biomethane a principal synthetic gas (compared to hydrogen and synthetic methane). If Ukraine chooses to develop energy plantations, they may become one of the feedstock sources for thermal gasification technology. The industry is expected to be the primary consumer of biomethane, which may provide a decent substitution for natural gas in most sectors except the chemical industry. In transport under the CN scenario, the role of biofuels is projected to be enormous in 2040 and on, yet surpassing only electricity and oil products (which are projected almost to vanish by 2060).

The perception of biomass as an energy carrier is ongoing significant changes: biomass was traditionally used for centuries for heating and cooking; later, biomass was claimed to be a CO_2-neutral fuel. Nowadays, the EU is revising its position regarding the possibility of biomass combustion[141], and the respective decision is projected to be embodied in the upcoming RED III Directive. Ukraine, an Energy Community contracting party and the candidate for the EU accession, has and will have an obligation to implement the existing and upcoming legislation. Given the demand for energy for heating, Ukraine is to find solutions and implement heat production technologies other than natural gas, and biomass technologies could substitute natural gas. Substitution of natural gas is a matter of national security. Yet, the limitations of biomass combustion may impose significant restrictions on the sector's development, so the government of Ukraine must find a balance between the commitments within the EU directives and meeting domestic energy needs. It is also the case with the so-called first-generation biofuels (those produced from edible feedstocks), whose production should no longer be expanded.

140 Geletukha G. (2021) Why should Ukraine start producing biomethane as soon as possible? https://greendeal.org.ua/chomu-ukrayina-maye-yaknajshvydshe-prystupyty-do-vyrobnycztva-biometanu/?fbclid=IwAR26jLnmdvfxvWFgWmBG_XnB9f8cZVaz2OPv7KF_FcAituXer3yAuvPhP-U

141 Ahamer, G. (2022) Why Biomass Fuels Are Principally Not Carbon Neutral. Energies, 15, 9619. https://doi.org/10.3390/en15249619

8.2.2 Promising Investment Attraction Mechanisms

Deployment of biomass projects requires significant investments, which is especially the case for biogas and biomethane projects. The bulk share of the investments required should be the funds of private companies. As the Russia-Ukraine war continues, Ukraine needs investments not only to restore the destroyed facilities, but also to build them back better and following the principles of Green Recovery, which has to become an imperative and main principle of the post-war reconstruction.

BBefore the war, Ukraine managed to attract relatively significant investments into the clean energy, but those were mostly investments into solar and wind energy, to a smaller extent. Biomass significantly lags behind[142]. In terms of post-war clean energy technology development, Ukraine has prioritized eleven pillars, requiring at least 114 bln EUR (Table 8.1). To reach the latter, Ukraine considers the possibility to establish a Development Bank.

TABLE 8.1

Priority areas for investments within low-carbon energy transition of Ukraine

ITEM	INVESTMENTS NEEDED, bln Euro
Build out 5-10 GW RE and ~3.5 GW hydro and pumped hydro capacities	15
Increasing nuclear capacity (prolongation, safety, higher utilization of existing capac-ities, and 2 GW new blocks at Khmelnytskyi NPP)	14
Biofuels market development (liquid, gaseous)	4.2
Localizing nuclear value chain (sustainable uranium mining, plant for fuel production, waste storage)	1.3
Increase gas production from existing fields, develop tight gas fields	18
Build 1.5–2 GW peaker and 0.7–1 GW of storage	2.8
Localize RE equipment production	2
Build out 15 GW electrolyzer capacities	7
Develop H_2 transport infrastructure (including export infrastructure)	2
Build 30+ GW RE for H_2 production	38
Build smart grids	5-10

Source: *Ukraine's National Recovery Plan. National recovery Council. July 2022 https://uploads-ssl.webflow.com/621f88db25fbf24758792dd8/62c166751fcf41105380a733_NRC%20Ukraine%27s%20Recovery%20Plan%20blueprint_ENG.pdf*

There are several ways to attract the finance into the deployment of biomass projects in post-war times. They may include lending and irrevocable financial assistance (primarily from the international financial institutions); newlyfound and potential recovery funds, such as Recovery Fund, "RebuildUkraine" Facility (EU) and securities (eg., green bonds).

In pre-war times, lending through the international financial institutions, i.e., international debt-based finance, was the most popular financing option for clean energy projects. Hopefully this option will become available after the end of war provided the availability of limited equity guarantees through war-risk insurance[143]. The main expectation from the debt-based finance is the provision of the soft loans for the projects within dedicated target programs (which could be the bioenergy program), and the difference between the market interest rate and the soft-loan rate is covered by the international lending facility. Also, the matter of vital importance is provision of the so-called "long"

142 Trypolska, G.; Riabchyn, O. Experience and Prospects of Financing Renewable Energy Projects in Ukraine. International Journal of Energy Economics and Policy. 2022, 12(1), 134-143.

143 Hudak, V., Volker, K. (2022) Invest in Ukraine renewable energy to help solve Europe's energy crisis https://euobserver.com/opinion/156337 money to ensure the bankability of the projects. Ukraine plans to strengthen the Investment Promotion Agency to attract FDIs[144]. Other measures to mobilize the private finance would include establishing donor guarantees and introduction of war insurance[145], as military risk may remain high even after the end of war (when and if the end of war is declared).

There are several initiatives of international organizations (IMF, World Bank) aimed at the post-war reconstruction of Ukraine in the short- and medium run. There are several international funding entities created, such as Ukraine Energy Support Fund, and potentially the "RebuildUkraine" Facility. The "RebuildUkraine" Facility is suggested to be created by the EU, being a mixture of grants and loans, embedded in the EU budget[146]. Additionally, the EU member states may develop their own financial programs for rebuilding Ukraine, such as Germany that announced its intentions to rebuild energy infrastructure of Ukraine[147].

A special fund to finance clean energy projects is expected to be created in Ukraine. For this purpose, the draft law No. 8433 "On amendments to chapter VI "Final and Transitional Provisions" of the budget code of Ukraine regarding the use of funds from accounts for the support of Ukraine" was adopted and now awaits to be signed by the President of Ukraine[148]. It provides for the creation of the State Fund for Decarbonization and Energy-Efficient Transformation. It is projected to start operation since 2024. The Fund will be filled from environmental tax[149].

The National Investments Fund of Ukraine, after being created, had to issue securities against 3.74 mln USD[150]. With the war outbreak, the National Investment Fund of Ukraine temporarily manages the forcibly removed objects, the property rights of which belong to Russia[151]. Additionally, there are several government-led funds for the restoration of Ukraine, such as Economic Recovery and Transformation Fund, Destroyed Property and Infrastructure Restoration Fund, which potentially may be transformed into assistance funds after the war's end[152].

According to the COP27 Resolution, countries may sell their emissions reduction units (UNFCCC 2022)[153]. Ukraine might also potentially use this mechanism, inter alia, to ensure the development of biomass projects.

Ukraine has primary[154] and secondary legislation[155] in place for issuing the green bonds. They can be issued by state/government agencies, as well as by individual companies.

These are specific sources of finance, which potentially may include bioenergy projects. However, the main necessary factor that would enable the foreign direct investments, is the end of war. Additionally, before introduction of specific policies aimed at the growing share of biomass in the energy mix, some general measures need to be implemented first. The subsidies for natural gas need to be gradually removed. During the last several heating seasons, there are formally three prices for natural gas in Ukraine – for industry, for commercial sector and for

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144 Ukraine's National Recovery Plan. National recovery Council. July 2022 https://uploads-ssl.webflow.com/621f88db25fbf24758792dd8/62c166751fcf41105380a733_NRC%20Ukraine%27s%20Recovery%20Plan%20blueprint_ENG.pdf

145 Ukraine's National Recovery Plan. National recovery Council. July 2022 https://uploads-ssl.webflow.com/621f88db25fbf24758792dd8/62c166751fcf41105380a733_NRC%20Ukraine%27s%20Recovery%20Plan%20blueprint_ENG.pdf

146 https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3121

147 Krone (2022) Kiew warnt Flüchtlinge: „Bleiben Sie im Ausland!" Krone 2022 https://www.msn.com/de-at/nachrichten/other/kiew-warnt-flüchtlinge-bleiben-sie-im-ausland/ar-AA13mBJI

148 https://www.kmu.gov.ua/en/news/z-2024-roku-v-ukraini-zapratsiuie-spetsfond-dlia-realizatsii-proektiv-enerhoefektyvnosti

149 Bilyavsky, M. (2021) Ukraine and Global Decarbonization Policy https://razumkov.org.ua/uploads/article/2021_Ukraine%20and%20the%20Global%20Policy%20of%20Decarbonisation.pdf

150 https://zakon.rada.gov.ua/laws/show/987-2021-%D0%BF#Text

151 Decree of the Cabinet of Ministers of Ukraine dated May 10, 2022 No. 552 "Some issues of implementation of the Law of Ukraine "On the basic principles of forced seizure in Ukraine of objects of property rights of the Russian Federation and its residents"

152 https://www.kmu.gov.ua/gromadskosti/fondi-vidnovlennya-ukrayini

153 UNFCCC (2022) Guidance on cooperative approaches referred to in Article 6, paragraph 2, of the Paris Agreement and in decision 2/CMA.3 https://unfccc.int/sites/default/files/resource/cma2022_L15_adv_1.pdf

154 SCU (2020) Law of Ukraine dated June 19, 2020 No. 738-IX "On Amendments to Certain Legislative Acts of Ukraine on Simplifying Investment Attraction and Introducing New Financial Instruments" https://zakon.rada.gov.ua/laws/show/738-20#Text

155 CMU (2022) Order of Cabinet of Ministers of Ukraine dated February 23, 2022 No. 175 Kyiv "On the approval of the Concept for the introduction and development of the green bonds market in Ukraine" https://zakon.rada.gov.ua/laws/show/175-2022-p#n7 residential sector. These three prices distort the market of biomass as an energy carrier, leaving no economic rationale to substitute the natural gas to the households and to the facilities from other sectors that have biomass boilers, because the price for the biomass have spiked due to growing demand from industry.

Energy efficiency of buildings needs to be improved. Reforming the tariff system based on market pricing will lead to an increase in tariffs for final consumers. At the same time, the modernization of the housing stock should increase the energy efficiency of buildings, which will allow more efficient use of the unit of heat and, accordingly, less consumption.

Policy measures in the bioenergy sector are aimed at its more intensive development, and progress towards carbon neutrality. Adoption of long-term biomass Strategy and Roadmap is needed. Although the production of energy from renewable sources, as well as the use of RE in the transport sector (including through the use of biomass), provides for several policy documents, Ukraine needs to legislate a long-term Strategy and Roadmap for bioenergy, provide economic and regulatory tools, as well as assess the need for investment to achieve the intermediate and final indicators and provisions of the Strategy and Roadmap. The Strategy and the Roadmap should both be in line with the provisions of the current policy documents and provide for a more ambitious development of bioenergy.

Additionally, the completion of the biomethane registry and introduce biomethane into the energy program documents are required for its consumption in the transport sector, industry and others; obligations for the consumption and development of biomethane market in Ukraine need to be established..

8.2.3 Case Studies

8.2.3.1 Negative Experience: Liquid Biofuels

Ukraine has undertaken numerous attempts to develop the market of liquid biofuels (bioethanol and biodiesel). Significant expectations were imposed on bioethanol output, as Ukraine had extensive production capacities of sugar refineries. Some of them were refurbished to produce ethanol (the biological compound of fuel) so that the installed capacities able to produce ethanol constitute about 300 kt. In 2012, a blending mandate requirement was implemented, which spurred the market's development. In 2015, the requirement was abolished within the claimed general course for industry deregulation. Since then, the biodiesel output has ceased, and the available production facilities were refurbished to produce the colorants. Some preferences were introduced, such as potential taxation discount or return of the expenditures to adapt the vehicle to use biofuels for vehicle owners, as well as the slightly lower excise tax for bioethanol than the excise for fossil fuels. Sadly, these measures were not enough. Ukraine continued to plant and export rapeseeds (a major feedstock for biodiesel) and managed to arrange a trade with ethanol, primarily with the EU countries. The statistics for 2021 are collected but have yet to be available due to martial law. Still, before 2021, the amount of exported ethanol approximately reached the amount of imported and consumed ethanol. In other words, the bulk amount of ethanol produced in Ukraine is exported (mainly to the EU), whereas the domestic market is far from being saturated with imported ethanol (Table 8.2). Given the restrictions of EU legislation regarding the feedstock for biofuels, Ukrainian companies are fully capable of producing ethanol from the sugar beet molasse, which meets the requirements of the RED II.

TABLE 8.2

Production and consumption of biofuels in Ukraine, kt

PRODUCTS	2013	2014	2015	2016	2017	2018	2019	2020
Production	66	26	16	6	21	4	70	C[156]
Import	0	38	46	58	54	56	70	77
Export	0	0	-9	-6	-4	-4	-7	0
Domestic supply	66	64	53	58	70	56	133	77

Source: *State Statistics Service of Ukraine*

156 Classified data. It means that the number of producers does not exceed two entities.

With the outbreak of war, Ukraine became a net importer of petroleum products when Russian forces destroyed Ukrainian oil refineries. In addition, Ukrainian ports were blocked by the Russian Navy and military. As a result, Ukraine temporarily lost its ability to export grain by sea. Before the war, Ukraine exported up to 60 mln t of cereals per year (for example, in the marketing year 2020/2021, Ukraine exported 17.5 mln t of wheat and 23.5 mln t of corn). The Black Sea blockade allowed Ukraine to export up to 2 mln t of grain per month, or 24 mln t per year. Abundant grains must be processed inland due to limited grain storage options. The production of first-generation biofuels is already the solution to this problem, even though it is not entirely in line with the provisions of RED II. In terms of raw material availability, the remaining 23 mln t of grain, even with a low starch content (60%), can be converted into 8.28 bln liters of ethanol (360 liters with 60% starch content per ton). It is usually the case for wheat and barley, but corn contains mainly 70% of starch, producing 20 liters of ethanol). If ethanol has a density of 0.783 kl/l, 8.28 bln liters is equivalent to 6.8 mln t of ethanol. In 2020, Ukraine consumed 1.77 mln t of gasoline. Regarding the feedstock availability, Ukraine has 3.7 times more ethanol than can be consumed as gasoline (on a volume basis). Considering the production facilities, Ukraine can already secure the E10 blend with a slow increase to E30.

The overall failure of the market spread of liquid biofuels occurred due to numerous reasons, in particular, the lack of proper policies to spur the development of the market coupled with the over-regulation of ethanol production; there were no penalties and basically no entities responsible for the implementation of the liquid biofuels market, as the entire topic of liquid biofuels is in on the intersection of several industries (agriculture, ethanol output, oil processing, etc.); additionally, one may suspect (but difficult to prove) quite powerful lobby in the oil industry. Ukraine had significant expectations in the electrification of its transport. Still, the destruction of energy infrastructure by Russian Federation, along with the occupation of the Zaporizhzhya nuclear power plant, raise questions about the feasibility of electric mobility expansion in the short-run, together with the need to enable technological shifts in cargo transportation, air and marine transportation. Nonetheless, in 2023, Ukraine still needs to develop its biofuels market as it is, first of all, a matter of national fuel security, together with the obligations taken within the Energy Community..

8.2.4 Positive Experience: Biomethane

Ukraine has a feed-in tariff for electricity from biogas at EUR 0.1239/kWh until the end of 2029. Ukraine has 53 biogas plants with a total capacity of 103.4 MW operating against the feed-in tariff. The investments into biogas are higher than in solar and wind; thus, biogas is a prerogative of agroholdings or large companies in Ukraine, implementing projects with a capacity of at least 2.5 MW[157], while the available agricultural potential allows the construction of small stations.

The Russia-Ukraine war, coupled with other factors, resulted in the significant growth of natural gas prices, making biomethane quite attractive for Ukrainian producers. Available technologies allow producing biomethane by refining the biogas or gasifying solid biomass. Globally, 90% of biomethane is produced by refining biogas[158], but commercialization of thermal biomass gasification is projected to be widespread in the coming decades. Biomethane use is appropriate in industries where it is not easy to reduce CO_2 emissions, as well as in transport. In contrast, biomethane allows both to avoid CO_2 emissions that would arise from using natural gas and avoid methane emissions, which is a more dangerous greenhouse gas than actual CO_2. Biomethane can be used in road transport, and in Ukraine there is already a relatively extensive network of methane filling stations: as of 2021, there were more than 600 of them.

In Ukraine, there is significant potential for the production and use of biogas and biomethane due to the available feedstock and a developed gas supply system. There is a technical possibility of connecting biomethane producers to medium and low-pressure gas distribution networks for the local supply of biomethane as a substitute for natural gas[159] because, in terms of chemical properties, biomethane is an analog of the latter. Ukraine's economically

157 Trypolska, G.; Kyryziuk, S.; Krupin, V.; Wąs, A.; Podolets, R. (2022) Economic Feasibility of Agricultural Biogas Production by Farms in Ukraine. Energies, 15, 87. https://doi.org/10.3390/en15010087

158 Definition & Properties Production Processes - ETIP Bioenergy. https://www.etipbioenergy.eu/images/ETIP_B_Factsheet_Biomethane.pdf

159 Definition & Properties Production Processes - ETIP Bioenergy. https://www.etipbioenergy.eu/images/ETIP_B_Factsheet_Biomethane.pdf feasible biomethane potential is 7.8 bcm, equal to a quarter of the pre-war volume of natural gas consumption. The main obstacle to the large-scale production of biogas (and, accordingly, biomethane) is the high cost of equipment and infrastructure.

Several steps were made relatively fast by the government and legislative bodies in Ukraine to enable the development of biomethane. In particular, the Law of Ukraine, "On Amendments to Certain Laws of Ukraine Regarding the Development of Biomethane Production" (2021)[160], was adopted, which introduces the concept of biomethane into the legal field. In 2022, the Resolution of the CMU "On the Procedure for the Operation of the Biomethane Register" was approved, creating the Biomethane Register, which is an integral part of the biomethane market. The Resolution of the NCSREU introduced specific changes regarding the content of the molar mass of oxygen to enable the access of biomethane to the gas transportation and distribution networks. Additionally, in late 2022, the definition of the digestate from biogas installations was defined in the legislation[161], enabling agricultural companies partially substitute the organic fertilizers (which, in turn, reduce the consumption of natural gas for their output and as a feedstock).

Ukrainian companies already have experience with biomethane. One of the pioneers in implementing biogas and biomethane projects in Ukraine is vertically integrated holding MHP. It launched its first biogas plant at the poultry farm "Oril Lider" (Dnipropetrovsk region) in 2013. The plant's capacity was 5 MW, reaching its full capacity in 2014. The overall investments were 15 mln USD. In 2019, the plant Biogaz Ladyzhyn (Vinnytsia region) was launched, with the installed capacity of the first unit of 12 MW. The overall capacity is projected at 24 MW, being the largest poultry biogas plant globally. It produces electricity sufficient for 35 thousand households and yet can meet only 40% of the MHP energy demand. It substitutes 5.4 mcm of natural gas. The overall annual CO_2 emissions reduction is 500 kt[162]. In 2020, MHP built a biomethane pipeline at the Biogaz Ladyzhyn plant (more than 10 km), which cost 1 mln Euro[163]. In 2021, MHP signed a memorandum of understanding and strategic partnership between MHP Eco Energy and Ellman Engineering (Germany) in the project: "Biological methanation of "green hydrogen". The memorandum and its further implementation are based on the cooperation between Ukraine and Germany in implementing the 12 MW Biogas Ladyzhyn MHP project. Integrating the production of green hydrogen into the existing technologies of anaerobic fermentation of biomass and organic waste makes it possible to increase the power and efficiency of biogas complexes. Three stages of cooperation are anticipated; laboratory research, the experimental part, and implementing the developed technologies in practice. It will make it possible to get the first pilot projects in Ukraine and the EU, which can then be multiplied on an industrial scale[164].

As for smaller companies, as of mid-2022, 26 companies in Ukraine intended to produce 206 mcm of biomethane per year[165]. As of early 2023, there are at least four companies in Ukraine that install equipment to switch the electricity output from biogas into the production of biomethane (such as the MHP mentioned above; UTC; Teofipol Energy Company). Some companies decided to produce bioethanol without biogas (such as Vitagro). Those are primarily agricultural-industrial companies that plant and process agricultural feedstock. In April 2023, Gals Agro became the first company producing biomethane and selling it to the natural gas grid[166].

In early 2023, Ukraine and the European Union signed a memorandum on a strategic partnership in renewable gases (hydrogen, biomethane, and other synthetic gases). The "biomethane" case study promises to be successful due to several reasons, in particular because it anticipates a certain level of energy independence for local biomethane

160 Law of Ukraine "On Amendments to Certain Laws of Ukraine Regarding the Development of Biomethane Production" dated October 21, 2021 No. 1820-IX https://zakon.rada.gov.ua/laws/show/1820-20#Text

161 Law of Ukraine "On the introduction of amendments to some laws of Ukraine regarding the improvement of state regulation in the field of handling pesticides and agrochemicals" No 2775-IX dated November 16 2022 https://zakon.rada.gov.ua/laws/show/2775-20#Text

162 Biogas Plants MHP https://mhp.com.ua/uk/pro-kompaniiu/biogaz-ta-mhp-eko-enerdzi

163 Dombrovsky O. Prospects for using biomethane in the agro-industrial complex of Ukraine. Online seminar "Prospects for biomethane production and consumption in Ukraine" June 23, 2020 https://www.youtube.com/watch?v=W5R2erQXE3o&t=4092s

164 https://mhp.com.ua/uk/news-mhp/Меморандум%20про%20%20стратегічне%20партнерство%20між%20МХП%20Еко%20Енерджи%20та%20%20Ellman%20Engineering

165 НКРЕП знизила вимоги до молярної частки кисню в природному газі з метою розвитку ринку біометану в Україні 02.08.2022 https://cutt.ly/w0CMgt2

166 https://agravery.com/uk/posts/show/v-ukraini-vidkrivsa-persij-biometanovij-zavod producers; there is significant interest in biogas from the EU (as a potential large importer of biomethane, whereas EU expects to cover with biogas up to 62% of its gas demand by 2050[167]); the biomethane market would spur the employment in rural areas; and the government of Ukraine with the help of civil society (e.g., Bioenergy Association of Ukraine) and other stakeholders did their best to implement the necessary legislation.

Implementation of new, contemporary technologies is important from several points of view:

- Companies try to operate and remain competitive in conditions of scarcity of essential resources (such as energy for heating, technological processes, and often water).
- These companies provide direct employment to individuals who work at these companies and indirect jobs in IT, the chemical industry, industrial engineering, and many others. Often these companies are the only industrial employer in town, so their social role should be considered.
- Companies must resort to the best contemporary technologies in the conditions strengthening domestic and foreign climate policies, which not only has numerous benefits for the environment and people but also enables access to financial resources and enables the export of goods (which, in turn, is essential in the view of the European Green Deal).
- The technologies they implement often have high mitigation potential, but they also offer adaptation benefits, which matters in conditions of always-scarce funds for adaptation.

167 EBA (2023) EBA Statistical Report 2022. European Biogas Association https://www.europeanbiogas.eu/wp-content/uploads/2022/12/EBA-Statistical-Report-2022_-Short-version.pdf

9. HYDROGEN REVOLUTION

Use of hydrogen is considered as one of the key decisions that will make it possible to reach net-zero economy on European continent and worldwide due to its multiple possible applications as energy carrier or raw material in all sectors. This simplest element can be used by itself as H_2 molecule or as a core for more complex synthetic substances like ammonia, methane, methanol and variety of hydrocarbons given the economic or technical reasoning.

For being crucial in net-zero emissions achievement, hydrogen has to be produced using low-carbon electricity, heat or feedstocks. There are color codes[168,169], within the energy industry used to differentiate between the different most common or most prominent hydrogen origins, of which green, blue, turquoise, purple, pink and red are carbon-free, carbon-neutral or low-carbon.

BOX 1 Types of Hydrogen

Hydrogen from renewable sources:[170]

- green hydrogen is produced through water electrolysis process (70% to 90% efficiency) by employing surplus or direct renewable electricity, mainly from solar and wind power plants. In this case, hydrogen also considered as electric fuel under power-to-gas concept (P2G) and is totally carbon-free;
- yellow hydrogen uses only solar electricity for powering electrolysis;
- hydrogen produced from biomass via steam reforming, gasification, bioenergy plants electricity etc. have not been given a color code, however since the biomass is a carbon-neutral emission source the hydrogen produced of it is also a carbon-neutral. It is possible also to enable CO_2 capture for these technologies for producing negative emissions or further utilization of climate-neutral carbon. There are also suggestions to assign silver and golden color to hydrogen produced from biomass with release of CO_2 into the atmosphere and with capture respectively.[171]

Hydrogen from fossil sources:

- blue hydrogen is sourced from fossil natural gas with capturing and storing 90-95% of CO2 underground (carbon sequestration, CCS). As only 5% to 10% of CO_2 is emitted, the blue hydrogen production process is categorized as low-carbon, yet wide use of such hydrogen production technology significantly complicates achievement of net-zero emissions since more efforts have to be done to cut and absorb emissions throughout economy. Companies are also trying to utilize the captured carbon, then it is called carbon capture, storage and utilization (CCUS) but utilization is not essential to qualify for blue hydrogen. There is also a problem that utilized fossil carbon then anyway emitted to the atmosphere causing cumulative surplus of CO_2 unless it is captured and stored or directed into long-life products;
- turquoise hydrogen is made via natural gas pyrolysis and emits no CO_2, as the solid carbon is deposited instead and can be easily buried or stored. Hence, the technology is climate-neutral and carbon-free (meaning CO_2 under "carbon", not an actual solid carbon), but utilization of fossil natural gas would still cause GHG emissions in the supply chain while it is mined or transported;

170 https://lpdd.org/wp-content/uploads/2020/09/LPDD-Model-Law-State-Legislation-Decarbonize-Electricity-Generation.pdf

171 https://www.linkedin.com/pulse/biohydrogen-what-color-code-ortium-technologies/?_l=en_US

168 https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum

169 https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/

- black and brown hydrogen originates from hard coal and lignite respectively and possesses significant carbon intensity;
- grey hydrogen is made from natural gas without emissions capturing. It is less carbon intensive as black or brown hydrogen yet still about 60g of CO_2 is emitted[172] per MJ of hydrogen produced.

Hydrogen from nuclear power;

- pink hydrogen is also produced via water electrolysis, but it uses nuclear electricity. Nuclear heat can also be used to increase the electrolysis efficiency;[173]
- purple hydrogen is made using both nuclear electricity and heat through combined electrolytic and thermochemical splitting of water. Concentrated solar power[174][175] as high-temperature renewable source can be also used to drive thermochemical cycle of hydrogen production;
- red hydrogen is obtained through the high-temperature catalytic splitting of water using nuclear thermal energy as an energy source.

172 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/798243/H2_Emission_Potential_Report_BEIS_E4tech.pdf

173 https://www.energy.gov/sites/default/files/2015/01/f19/fcto_nuclear_h2_r%26d_plan.pdf

174 https://www.energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting

175 Konstandopoulos, A. G., Syrigou, M., Pagkoura, C., Sakellariou, K., Lorentzou, S., & Dimitrakis, D. A. (2021). Solar fuels and industrial solar chemistry. Concentrating Solar Power Technology, 677–724. https://doi.org/10.1016/b978-0-12-819970-1.00005-0

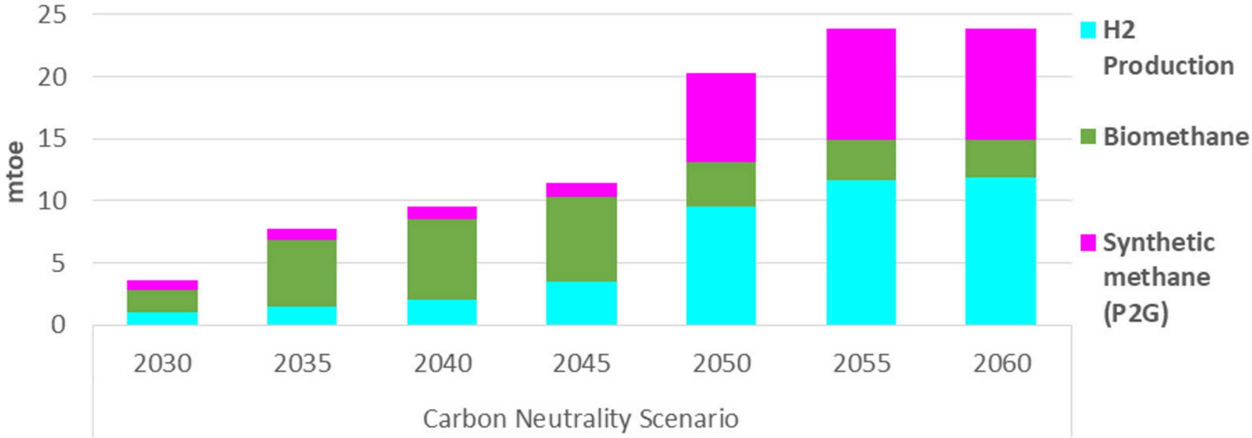
The theoretic maximal annual renewable energy potential as electricity output, which can be used for green hydrogen production in Ukraine, according to the Institute of Renewable Energy, NASU, (IRE)[176] is at 68 bln ktoe, or 2.7 thrln kWh with capacities of 874 GW. Using only solar and wind power plants this in turn amounts to 505 bln cbm of H_2 annually (equivalent of 160 bln cbm of natural gas) as technically achievable according to IRE or 337 bln cbm according to IRENA forecast. Current Energy strategy foresees clean electricity generation of up to 25 bln kWh which amounts to 5.5 bln cbm of H_2. Estimated forecast of "green" electricity and hydrogen production (given 4.5 kWh/ cbm or 50.6 kWh per 1 kg of H_2) to be used in Ukrainian Integrated Power System for balancing needs is up to 52.5 bln kWh of electricity and 2.6 bln cbm of H_2 by 2035.

According to the modelling results, under Reference scenario which has no imposed emission constraints, hydrogen is not viable. On the contrary, to achieve the carbon-neutral economy by 2050 in CN scenario (Figure 9.1), hydrogen production needs to start in 2030 with 993 ktoe and reach 9600 ktoe in 2050 with further growth to 11800 ktoe by the end of horizon in 2060. As it were mentioned before, the absolute majority of hydrogen comes from biomass steam reforming technology and electrolyzers appear after achievement of net-zero emissions **when electricity becomes less marginal and biomass prices slightly rise**.

176 https://unece.org/sites/default/files/2021-03/Hydrogen%20Roadmap%20Draft%20Report_ENG%20March%202021.pdf

FIGURE 9.1

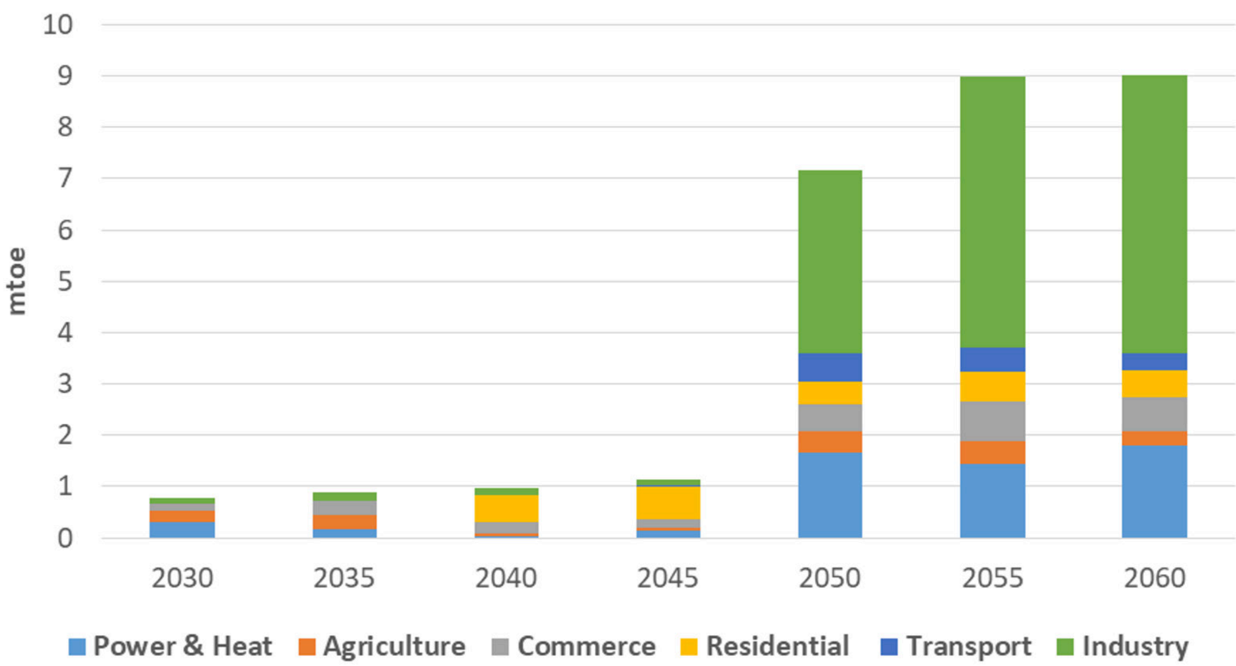
Low-carbon fuel production under the carbon neutrality scenario



Depending on the time period, from 32% to 79% of all hydrogen might be converted into clean synthetic methane, which is streamlined then to every final consumption sector and power & heat production as a carbon-neutral substitution for natural gas along with biomethane. Industry is the largest consumer of synmethane amounting to 3,573 ktoe in 2050 (50% of the total) and 5,426 ktoe in 2060 (60% of the total) as it grants the opportunity to decarbonize hard-to-abate processes with emissions linked to non-energy use of fossil methane (Figure 9.2). Conversion of hydrogen into synmethane is feasible owing to abundance of captured at biogas-purification and, which is more important, direct air capture (DAC) facilities of climate-neutral carbon from the atmosphere, hence H_2 and CO_2 can be combined using the methanation process into climate neutral molecules of CH_4. It is the DAC which would start to massively operate right few years before 2050 and absorb 14 to 18 Mt of climate-neutral CO_2, which boosts 7 times the volumes of synmethane produced.

FIGURE 9.2

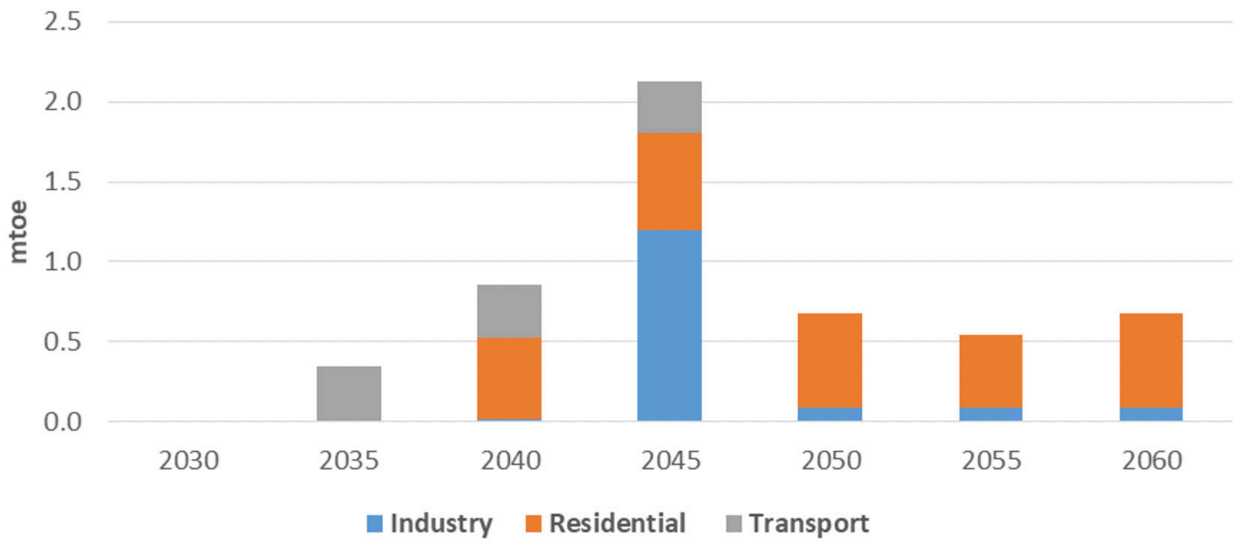
The use of clean synthetic methane by sector under the carbon neutrality scenario



Compared with the widely used synthetic methane, which might utilize all of existing natural gas infrastructure, pure hydrogen (Figure 9.3) finds itself consumed only in industry, residential and transport (liquid H_2 in fuel cell EVs) in 5.5 times lesser overall volumes than synmethane. Moreover, the total consumption would spike in 2045 at the last efforts to achieve net-zero and then rapidly would fade in industry, disappear in transport, however, would stays almost constant in residential sector.

FIGURE 9.3

The use of clean hydrogen by sector under the carbon neutrality scenario



The results show that additional efforts that need to be performed to make natural gas infrastructure suitable for pure hydrogen delivery, as well as manufacturing of new energy equipment, which can be fueled with H_2, lower calorific value and energy conversion efficiency, might cause significant obstacles for pure hydrogen expanse in case of other clean fuel alternatives presence. Even if the alternative is more complex and includes the very hydrogen in its content, but is devoid of the aforementioned drawbacks.

The potential and extent of the existing national gas transmission system use for hydrogen transportation in Ukraine has been planned to be explored thoroughly. In the summer of 2020, the Regional Gas Company had began research work on 5 objects of the gas transmission system, within which experiments have been conducted on the possibility of transporting hydrogen of different levels of concentration. Apparently, completion of this research has been postponed until the end of the war.

There were two documents prepared that envisage hydrogen development in Ukraine: Draft Roadmap for production and use of hydrogen in Ukraine[177] and Hydrogen strategy of Ukraine[178]. According to them, in a short term it is anticipated that hydrogen is transported in the gaseous state in tanks by trucks. In the medium-term horizon - transportation of liquid hydrogen by railway routes and water transport, in particular, along the Danube river[179], which can be a source of fresh water for electrolysis (0.002 m³ of freshwater is used to produce 1 cbm of H_2[180]). In the long run - the use of gas pipeline infrastructure to transport hydrogen in large volumes, including export. At the same time, it was planned to start in 5-10 years the supply of hydrogen mixtures by gas distribution pipelines to household consumers for cooking use, space heating and hot water.

177 https://unece.org/sites/default/files/2021-03/Hydrogen%20Roadmap%20Draft%20Report_ENG%20March%202021.pdf
178 https://www.ive.org.ua/wp-content/uploads/ENG-Hydra-Beauty-final.pdf
179 https://hydrogen.ua/en/news/1281-blue-danube-an-opportunity-to-develop-the-hydrogen-economy-in-ukraine
180 Institute for Renewable Energy at the National Academy of Sciences of Ukraine.

The Roadmap of Implementation of Hydrogen Technologies in Ukraine consist of three phases in a sequence of steps. The phases mostly coincide with the three stages of the updated Energy Strategy of Ukraine (ESU) adopted in August 2017, though this Strategy needs to be updated during Phase 1 of the Hydrogen Roadmap in order to reflect the newest developments towards hydrogen economy. The document also outlines actions and measures at the regional and municipal level. Currently, the Energy Strategy implementation is divided into three following stages:

1. The first stage (2021-23) aims to create liberalized, competitive energy markets and minimize state inference in their performance.

2. The focus of the second stage (2024-26) is on developing energy infrastructure and integrating it with the European system and attracting necessary investments to the energy sector.

3. Finally, the third stage (2027-29) is concerned with sustainable development: meeting GHG emissions reduction targets; rapid development of renewables; and ensuring energy security by further boosting gas production, including unconventional gas and offshore drilling, after achieving gas self-sufficiency in the second stage.

The overall goal of the Hydrogen Strategy is to make hydrogen an important element of the new energy system of Ukraine that enables to meet a significant share of clean energy needs in energy sector itself, as well as in industrial and transport sectors. The provisions of the Hydrogen Strategy of Ukraine outline the main strategic directions for the implementation of hydrogen technologies in Ukraine, the goals and the main priorities and measures that must be implemented to achieve these goals.

The development of the energy sector heavily based on hydrogen is expected to provide by three phases:

Short-term goals (2022–2025) are to create a basis and infrastructure for the energy system based on hydrogen and to launch the export of green hydrogen. It is necessary to create all conditions for the launch of the green hydrogen production in 2024–2025 getting benefits from the international cooperation in achieving the goals of the EU Hydrogen Strategy, which provides for Ukraine 10 GW capacity of hydrogen production for export to the EU by 2030.

Medium-term goals (2026–2030) are to diversify primary energy sources due to the growth of hydrogen production. At this stage, it is necessary to focus on increasing investment to raise production of hydrogen to 12–15 GW to meet the expectations of the EU market (10 GW) and launch a domestic market of hydrogen technologies to stimulate the use of hydrogen in all sectors.

Long-term goals (2031–2050) are to guarantee the rapid expansion of the domestic hydrogen market in all sectors: electricity, housing and communal services, transportation, agriculture and industry. Ukraine should also modernize and adopt the transportation system, making a shift from the transportation and distribution of natural gas mixed with hydrogen to the pure hydrogen. This will allow using the gas transportation system as an energy storage for subsequent consumption in domestic and export markets.

ANNEX - ASSUMED CAPITAL EXPENDITURE COSTS ACROSS TECHNOLOGIES

A1.1 Nuclear Power Plants

TABLE A.1

Extension of the operational life of existing units of NPPs

PARAMETERS	2020-2050
The cost of Extension of the operational life for 20 (30) years, USD /kWe	300 (400)
Fixed Operation and Maintenance Expenses, USD / kWe	73.35
Variable Operation and Maintenance Expenses, USD /MWh	1,65
Efficiency, %	33
Net Capacity Factor (Availability factor), %	80
Heat Rate, MWh • of heat production / MWh of electricity production, %	0,03

TABLE A.2

New big units of NPPs (1000-1200 MW)

PARAMETERS	2025-2100
CAPEX, USD / kWe	6850
Fixed Operation and Maintenance Expenses, USD / kWe	73.35
Variable Operation and Maintenance Expenses, USD /MWh	1,65
Decommission Cost, % of CAPEX	400
Efficiency, %	33,8
Net Capacity Factor (Availability factor), %	93
Heat Rate, MWh · of heat production / MWh of electricity production, %	0,04
Lifetime, years	80
Period of construction, years	5
Potential year of start of operation, year	2031
Self-consumption of electricity, %	5

TABLE A.3

New small nuclear reactors (160 MW)`

PARAMETERS	2025-2100
Overnight Capital Cost, USD/kWe	6850
Fixed Operation and Maintenance Expenses, USD/kWe.	73.35
Variable Operation and Maintenance Expenses, USD/ MWh	1.65
Decommission Cost, USD /kW	400
Efficiency, %	32
Net Capacity Factor (Availability factor), %	98
Lifetime, years	80
Period of construction, years	3
Potential year of start of operation, year	2025
Self-consumption of electricity, %	5

A1.2 Thermal Power Plants

TABLE A.4

Gas TPPs

PARAMETERS	2020-2050			
	Combined Cycle	Combustion Turbine	Steam Turbine	Fast Start Internal Combustion Engine
CAPEX, EUR/ kWe	1000	600	920	1000
Fixed O&M Expenses, EUR/ kWe	20	11.9	16.6	20
Variable O&M Expenses, EUR/MWh	2	4.1	2.1	0.555
Decommission Cost, % of CAPEX	2	2	2	2
Efficiency, %	60	40	42	50
Net Capacity Factor (Availability factor), %	50	50	50	50 (as balancing ~1.5%)
Lifetime, years	35	30	30	35
Heat Rate, %	0.05	0.05	0.05	

TABLE A.5

Bioenergy TPPs

PARAMETERS	2020	2025	2030	2035	2040	2045	2050
	Wood Biomass						
CAPEX, EUR/ kWe	2800	2800	2600	2500	2400	2200	2000
Fixed O&M Expenses, EUR/ kWe	30						
Variable O&M Expenses, EUR/MWh	6.12						
Decommission Cost, % of CAPEX	1.5%						
Efficiency, %	24						
Net Capacity Factor (Availability factor), %	50						
Lifetime, years	30						
	Biomass from Waste of Agri-Food Complex, etc.						
CAPEX, EUR/ kWe	2890	2800	2700	2600	2500	2300	2100
Fixed O&M Expenses, EUR/ kWe	30						
Variable O&M Expenses, EUR/MWh	6.12						
Decommission Cost, % of CAPEX	1.5%						
Efficiency, %	23						
Net Capacity Factor (Availability factor), %	50						
Lifetime, years	30						
	Biogas						
CAPEX, EUR/ kWe	4400	4300	4200	4100	4000	3900	3800
Fixed O&M Expenses, EUR/ kWe	30						
Variable O&M Expenses, EUR/MWh	6.12						

	Biogas						
Decommission Cost, % of CAPEX	1.5%						
Efficiency, %	42						
Net Capacity Factor (Availability factor), %	50						
Lifetime, years	30						
	Energy Crops						
CAPEX, EUR/ kWe	2900	2800	2700	2600	2500	2300	2100
Fixed O&M Expenses, EUR/ kWe	30						
Variable O&M Expenses, EUR/MWh	6.12						
Decommission Cost, % of CAPEX	1.5%						
Efficiency, %	24						
Net Capacity Factor (Availability factor), %	50						
Lifetime, years	30						
	Industrial Waste						
CAPEX, EUR/ kWe	2890	2800	2700	2600	2500	2300	2100
Fixed O&M Expenses, EUR/ kWe	30						
Variable O&M Expenses, EUR/MWh	6.12						
Decommission Cost, % of CAPEX	1.5						
Efficiency, %	23						
Net Capacity Factor (Availability factor), %	50						
Lifetime, years	30						
Heat Rate, %	0.05						

TABLE A.6

Gas TPPs with CCS

PARAMETERS	2020-2050	
	Combined Cycle + CCS	**Combustion Turbine + CCS**
Overnight Capital Cost, EUR/kW	2450	2050
Fixed O&M Expenses, USD/ kWe..	24	14.3
Variable O&M Expenses, USD/ MWh	2	4.1
Efficiency, %	51	34
Availability factor, %	50	50
Lifetime, years	35	30
Heat Rate, %	0.05	0.05

TABLE A.7

Coal TPPs

PARAMETERS	2020-2050			
	IGCC	Supercritical Parameters	Subcritical Parameters	Circulating Fluidized Bed
CAPEX, EUR/ kWe	1800	1300	1600	1700
Fixed O&M Expenses, EUR/ kWe	63	43	30	27
Variable O&M Expenses, EUR/MWh	5.8	6	6	6
Decommission Cost, % of CAPEX	5	5	5	5
Efficiency, %	46	43	39	43
Net Capacity Factor (Availability factor), %	50	50	50	50
Lifetime, years	35	40	35	35
Heat Rate, %	0.15	0.15	0.15	0.15

TABLE A.8

Extension of the operational life of existing coal TPPs

PARAMETERS	2020-2050
CAPEX, EUR/ kWe	950
Fixed Operation and Maintenance Expenses, EUR/ kWe	33
Variable Operation and Maintenance Expenses, EUR/MWh	18
Decommission Cost, % of CAPEX	5
Efficiency, %	33-40
Net Capacity Factor (Availability factor), %	34-62
Lifetime, years	30
Heat Rate, %	0.04

TABLE A.9

Coal TPPs with CCS

PARAMETERS	2020-2050			
	IGCC	Supercritical Parameters	Subcritical Parameters	Circulating Fluidized Bed
CAPEX, EUR/ kWe	4400	3900	4650	4300
Fixed O&M Expenses, EUR/ kWe	75	52	36	34
Variable O&M Expenses, EUR/MWh	5.8	6	6	6
Decommission Cost, % of CAPEX	5	5	5	5
Efficiency, %	39	37	33	36
Net Capacity Factor (Availability factor), %	50	50	50	50
Lifetime, years	35	35	35	35
Heat Rate, %	0.15	0.15	0.15	0.15

A1.3 Cogeneration or Combined Heat and Power Plants

TABLE A.10

Bioenergy CHPs

PARAMETERS	2020	2025	2030	2035	2040	2045	2050
	Wood Biomass						
CAPEX, EUR/ kWe	3400	3300	3200	3100	3000	2900	2800
Fixed O&M Expenses, EUR/ kWe	50						
Variable O&M Expenses, EUR/MWh	6						
Decommission Cost, % of CAPEX	1.5						
Efficiency, %	20						
Net Capacity Factor (Availability factor), %	50						
Lifetime, years	35						
	Biomass from Waste of Agri-Food Complex						
CAPEX, EUR/ kWe	3400	3200	3100	2900	2900	2800	2800
Fixed O&M Expenses, EUR/ kWe	56						
Variable O&M Expenses, EUR/MWh	6.6						
Decommission Cost, % of CAPEX	1.5						
Efficiency, %	19						
Net Capacity Factor (Availability factor), %	50						
Lifetime, years	35						
	Biogas						
CAPEX, EUR/ kWe	5400	5200	5100	5000	4800	4500	4500
Fixed O&M Expenses, EUR/ kWe	56						
Variable O&M Expenses, EUR/MWh	3.4						
Decommission Cost, % of CAPEX	1.5						
Efficiency, %	25						
Net Capacity Factor (Availability factor), %	50						
Lifetime, years	35						
	Energy Crops						
CAPEX, EUR/ kWe	3400	3300	3200	3100	3000	3000	3000
Fixed O&M Expenses, EUR/ kWe	50						
Variable O&M Expenses, EUR/MWh	6						
Decommission Cost, % of CAPEX	1.5						
Efficiency, %	20						
Net Capacity Factor (Availability factor), %	50						
Lifetime, years	35						

TABLE A.11

Gas CHPs

PARAMETERS	2020-2050	
	Combined Cycle	**Steam Turbine**
CAPEX, EUR/ kWe	800	920
Fixed O&M Expenses, EUR/ kWe	42	42
Variable O&M Expenses, EUR/MWh	1.55	1.55
Decommission Cost, % of CAPEX	2.0	2.0
Efficiency, %	50	45
Net Capacity Factor (Availability factor)*, %	50	50
Lifetime, years	35	30
Heat Rate, %	1.5	1.5

** Availability factor is in the range from 46 - 90%*

TABLE A.12

Gas CHPs with CCS

PARAMETERS	2020-2050	
	Combined Cycle + CCS	**Steam Turbine + CCS**
Overnight Capital Cost, EUR/kW	2450	2050
Fixed O&M Expenses, USD/ kWe..	24	14.3
Variable O&M Expenses, USD/ MWh	2	4.1
Efficiency, %	51	34
Availability factor, %	50	50
Lifetime, years	35	30
Heat Rate, %	0.05	0.05
Heat Rate, %	1.5	1.5

TABLE A.13

Coal CHPs

PARAMETERS	2020-2050	
	Combined Cycle	**Steam Turbine**
CAPEX, EUR/ kWe	1200	1100
Fixed O&M Expenses, EUR/ kWe	52	52
Variable O&M Expenses, EUR/MWh	5.76	5.76
Decommission Cost, % of CAPEX	5.0	5.0
Efficiency, %	36	33
Net Capacity Factor (Availability factor), %	50	50
Lifetime, years	35	35
Heat Rate, %	1.5	1.5

TABLE A.14

Extension of the operational lifetime of existing CHPs

PARAMETERS	2020-2050	
	Gas	**Coal**
CAPEX, EUR/ kWe	280-650	880-1300
Fixed O&M Expenses, EUR/ kWe	41-51	51
Variable O&M Expenses, EUR/MWh	0.3	1.0
Decommission Cost, % of CAPEX	2.0	5.0
Efficiency, %	25-34	16-26
Net Capacity Factor (Availability factor)*, %	50	50
Lifetime, years	15	15
Heat Rate, %	1.55	1.1

** Availability factor is in the range from 46 - 90%*

TABLE A.15

Fuel cells power plants

PARAMETERS	2020-2050	
	TTP	**CHP**
Overnight Capital Cost, EUR/kW	844	844
Fixed O&M Expenses, $/ kWe..	62	62
Variable O&M Expenses, $/ MWh	14	14
Efficiency, %	50	50
Availability factor, %	85	60
Lifetime, years	10	10
Heat Rate, %	–	0.64

A1.4 Other Power Plants

TABLE A.16

Solar power plants

PARAMETERS	2020	2025	2030	2035	2040	2045	2050
	PV Plant Size (without tracker)						
CAPEX, EUR/ kWe	750	725	700	630	560	510	475
Fixed O&M Expenses, EUR/ kWe	15						
Net Capacity Factor (Availability factor), %	12.5						
Lifetime, years	25						
Decommission Cost, % of CAPEX	1%						
Construction time, years	1						

	PV Plant Size (with tracker)						
CAPEX, EUR/ kWe	920	850	800	720	645	590	540
Fixed O&M Expenses, EUR/ kWe	17.3						
Net Capacity Factor (Availability factor), %	14.5						
Lifetime, years	25						
Decommission Cost, % of CAPEX	1%						
Construction time, years	1						
	PV Roof Panel						
CAPEX, EUR/ kWe	900	875	850	800	750	700	600
Fixed Operation and Maintenance Expenses, EUR/ kWe	12						
Net Capacity Factor (Availability factor), %	13.0						
Lifetime, years	25						
Decommission Cost, % of CAPEX	1%						
Construction time, years	1						

TABLE A.17

Wind power plants

PARAMETERS	2020	2025	2030	2035	2040	2045	2050
	Onshore						
CAPEX, EUR/ kWe	1665	1350	1350	1350	1325	1275	1225
Fixed O&M Expenses, EUR/ kWe	25	25	26	28	37	40	40
Net Capacity Factor (Availability factor), %	36						
Lifetime, years	20						
Decommission Cost, % of CAPEX	1%						
Construction time, years	1.5						

TABLE A.18

Hydro power plants

PARAMETERS	2020-2050		
	Large	**Pump Storage**	**Small**
CAPEX, EUR/ kWe	3000-3300	1500	3000-3150
Fixed O&M Expenses, EUR/ kWe	45	45	59
Decommission Cost, % of CAPEX	3.0	3.0	3.0
Net Capacity Factor (Availability factor), %	33-36	26	30
Lifetime, years	60	60	40

TABLE A.19

Geothermal power plants

PARAMETERS	2020-2050
CAPEX, EUR/ kWe	3800-4000
Fixed Operation and Maintenance Expenses, EUR/kWe	143.5
Decommission Cost, % of CAPEX	1.0
Net Capacity Factor (Availability factor), %	35-55
Lifetime, years	25

TABLE A.20

Storage electricity technologies

PARAMETERS	2020	2025	2030	2035	2040	2045	2050
CAPEX, EUR/ kWh	600	570	542	514	489	464	441
Fixed O&M Expenses, EUR/ kWh	8.6	8.1	7.6	7.0	6.5	6.5	6.5
Variable O&M Expenses, EUR/MWh	2.50	2.20	1.91	1.61	1.32	1.32	1.32
Efficiency, %	92%						
Availability factor (8 hours per day), %	33.3						
Construction time, years	3						
Lifetime, years	10						

A1.5 Supply Sector

TABLE A.21

Hydrogen technologies

TECHNOLOGY DESCRIPTION	INPUT	STARTING YEAR	FUEL INPUT LEVEL	AFA. %	LIFE-TIME, years	CAPEX, mln EUR/ (PJ/year)	FIXED O&M COST, mln EUR/PJ	VARIABLE O&M COST, mln EUR/PJ
H_2 Electrolyser Centralised	Electricity	2030	1.43	90	10	21.9	0.44	
H_2 HT Steam Electrolyser Centralised	Electricity	2030	1.07	90	10	40.3	0.81	
	Heat		0.20					
H_2 SMR Centralised	Nat. gas	2030	1.35	90	10	10.6	0.53	0.51
H_2 Electrolyser De-centralised	Electricity	2030	1.43	90	10	27.3	0.55	
H_2 SMR De-centralised	Nat. gas	2030	1.50	90	10	21.9	1.09	0.51
H_2 Liquefaction	Hyd. gas	2035	1.00	75	10	9.5	0.57	
	Electricity		0.21					

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