Preliminary Technical Study

EUROPE-UKRAINE Energy Transition Hub

Roadmap for a climate-neutral, sustainable Ukrainian energy sector and its role in an integrated EU energy market

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Authors

Dàmir Belltheus Avdic | IKEM
damir.belltheus-avdic@ikem.de

Josefine Lyda, LL.M. | IKEM
josefine.lyda@ikem.de

Jana Karras | IKEM
jana.karras@ikem.de

Dr. Simon Schäfer-Stradowsky
IKEM
simon.schaefer-stradowsky@ikem.de

Dr. Hanno Butsch | BBH

Johannes Graetschel,LL.M.
IKEM
johannes.graetschel@ikem.de

Vera Grebe | BBH

Valentyn Gvozdiy | GOLAW

Prof. Christian Held | BBH

Dr. Ivo Hlaváček | Horizon 2

Ievgeniia Kopytsia
Yaroslav Mudryi National
Law University
ievgeniia.kopytsia@ikem.de

Vivien Lorenz | BBH

Dr. Jana Maruschke | IKEM

Oleksandr Melnyk | GOLAW

Dennis Nill | IKEM
dennis.nill@ikem.de

Sergiy Oberkovych | GOLAW

Carina Rastan | IKEM

David Siegler | BBH

Reviewers

Philipp Offenberg
Breakthrough Energy

Peter Sweatman
Climate Strategy & Partners

Designers

Julie Hertel
julie.hertel@ikem.de

Odile Stabon
odile.stabon@ikem.de

IKEM

Institut für Klimaschutz, Energie und Mobilität e.V.

Magazinstraße 15-16
10179 Berlin

+49 (0)30 408 1870 10
info@ikem.de
www.ikem.de

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Introduction

This publication is part of a triptych of preliminary studies – technical, financial, and legal – that make up the first stage of the Ukraine Energy Roadmap. This project, funded by Breakthrough Energy and carried out by the Institute for Climate Protection, Energy and Mobility (IKEM) and its project partners, aims to account for the current situation in Ukraine's energy system and chart a course towards a prosperous, modern, and innovative future for the country after the end of Russia's war of aggression. A fourth text presenting the joint conclusions and recommendations from the three studies will be published in parallel.

This study is subdivided into four sections: a description of Ukraine's current energy system, a catalogue of future energy pillars which will foster and enable a thriving and dynamic future, a comparative cost-benefit analysis of various types of electricity, and a section presenting the results of an expert survey that was carried out as part of the Energy Roadmap project.

The perspectives adopted in the analysis are strongly slanted towards sustainability, not least because of Ukraine's European perspective, which dictates substantial efforts towards climate neutrality in the medium term (more information on the legal aspects of Ukraine's reconstruction can be found in the preliminary legal study in particular). As much infrastructure in Ukraine is destroyed or damaged beyond repair, it is worthwhile to consider rebuilding in a way that leapfrogs European partners instead of reconstructing pillars of yesterday's economy that risk becoming stranded assets tomorrow. Moreover, in many cases, the least carbon-heavy economic choices are the most cost-efficient ones, certainly if the long run is taken into account.

The statistics quoted in the study may refer to seemingly arbitrary years. The reason for this is often simply the availability of statistics and their applicability to different parts of Ukraine's territory. Parts of Ukraine were occupied by Russia in 2014, which means that many official statistics after that date by definition exclude those areas. Things are even more complicated for the period after the beginning of the full-scale Russian invasion in February 2022, as the front line has shifted, and the collection of quality statistics may have been quite difficult (or has become classified).

The observations of the study are divided into three periods: the present, which includes the various effects of Russia's aggression against Ukraine since 2014, the first 24 months after the eventual end of the war, and the longer-term future beyond those first two years. The latter two are termed Phase 1 and Phase 2 in this text, and most of the recommendations are proposed for one or the other.

1. Energy in Ukraine today

The first part of this study is a description of Ukraine's current energy system, taking into account the situation before and during the various phases of Russia's aggressions since 2014. This focuses on demand as well as fossil and nuclear energy production and distribution. The outlook segment of each subsection considers the opportunities and challenges of reconstruction for the various sectors, with a special focus on technologies that promote sustainability and climate effects in compliance with Ukraine's European ambitions.

1.1. Energy Demand

This section provides a screening of the current state of energy demand in Ukraine and relevant trends in each sector. This includes energy efficiency measures, technologies, and practices employed in industries, buildings, transportation systems, and agricultural activities. Furthermore, the analysis explores the potential for innovative and promising technologies that can contribute to a more sustainable and efficient energy sector.

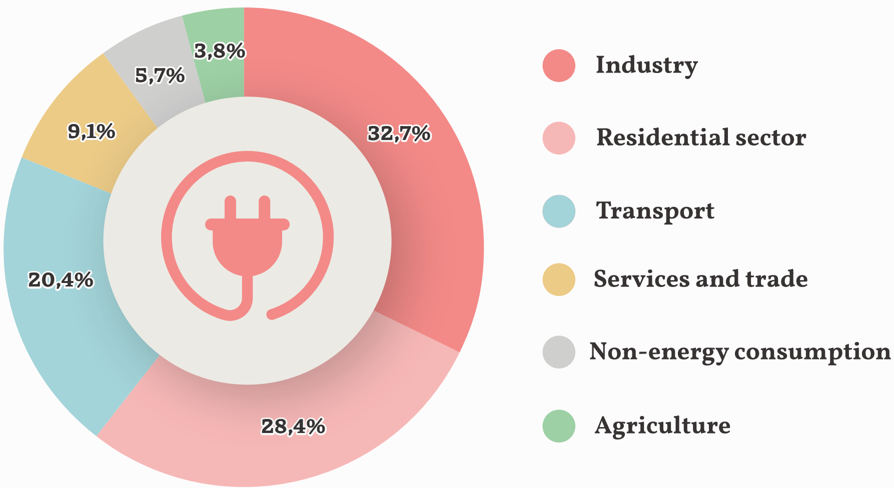

Figure 1: Final Energy consumption for 2020 in Ukraine by sector in thousand tons of oil equivalent
Source: Own illustration based on data from State Statistics Service of Ukraine, 'Final Energy Consumption for 2007-2021'.

Each part of this section describes the current status quo in the relevant sector and provides observations or recommendations about Phase 1 (the first two years after the cessation of hostilities) – focused on transitioning to a free-market economy, with a strong emphasis on reconstruction, energy security, and effective energy price management – and Phase 2 (the period that will start two years after the end of the war) – looking at the revitalization of Ukraine's energy systems and the definition of a new sustainable model for the future.

At the beginning of 2022, there were 17.7 million electricity consumers in Ukraine, including 17.2 million households and 0.5 million commercial customers. Russia's large-scale assault led electricity demand in 2022 to decrease by 30-35% to 85 TWh compared to 2021.[1] The consumption pattern also changed due to the shutdown of industrial enterprises and the massive displacement of consumers from eastern to western Ukraine. The total electricity generation in 2022 is expected to be 25% less than what was forecasted before the invasion. Since 24 February 2022, almost all consumers have been disconnected from the power supply for at least some of the time.[2]

More specific data on energy production and consumption is not published by the Ukrainian authorities for the years 2021 and onwards. Moreover, data for 2021 has not yet been released in September 2023 due to martial law. In 2020, with a consumption of almost 16 million tons of oil equivalent (mtoe), industrial activity was the largest final energy consumer before the war (as shown in Figure 1). The residen-

1 Enerdata, 'Ukraine Energy Information'; Cooperation for Restoring the Ukrainian Energy Infrastructure, 'Ukrainian Energy Sector Evaluation and Damage Assessment IV'.

2 Cooperation for Restoring the Ukrainian Energy Infrastructure, 'Ukrainian Energy Sector Evaluation and Damage Assessment IV'.

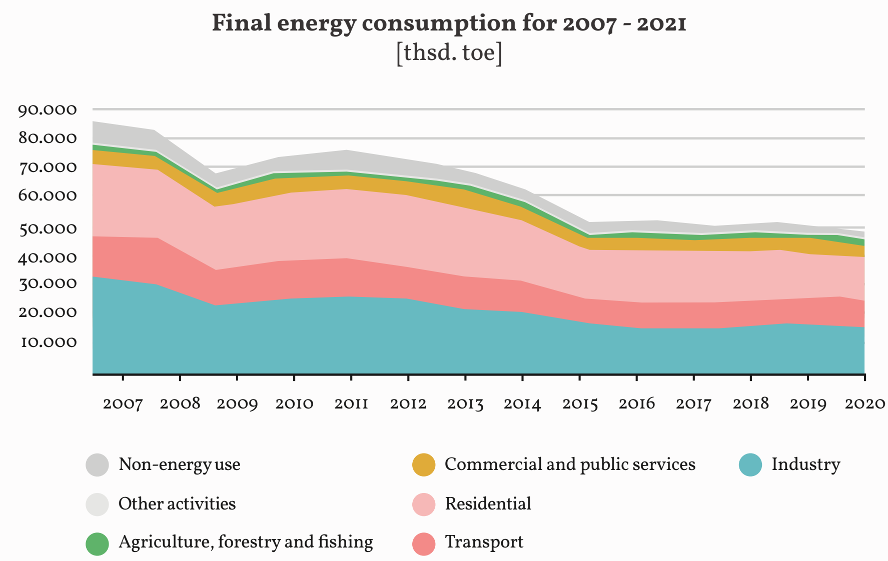

Figure 2: Development of final energy consumption by sector in Ukraine (excluding occupied areas) in million tons of oil equivalent from 2007 to 2021.
Source: Own illustration based on State Statistics Service of Ukraine, Final energy consumption for 2007-2021.

tial sector followed, accounting for 13.6 mtoe.[3] Ukraine's energy demand has been decreasing over the years before the war (see Figure 2). The country has undergone a substantial degree of deindustrialization after the fall of the Soviet Union, and underwent two significant recessions in 2009 and 2013-14, as well as loss of control over Crimea and a portion of the Donbas region, resulting in a decrease in total final consumption.[4]

1.1.1. Manufacturing

The industrial sector is the largest energy consumer in Ukraine. As shown in Figure 2 , its energy consumption has been steadily decreasing over the years due to major recessions in 2009 and 2013-14 and the loss of government authority over Crimea and part of the Donbass region. Despite this development, the Ukrainian industrial sector (16.0 mtoe) used as much energy in 2020 as the Polish industrial sector (15.9 mtoe) and, among the EU member states, only Germany (54.8 mtoe), France (25.5 mtoe), Italy (23.9 mtoe), and Spain (18.8 mtoe) consume more energy for industrial activity.[5]

Iron and steel production accounted for over 8 mtoe, well ahead of the other branches of industry.[6] The most common energy sources are coal, peat, and natural gas. Biofuels, waste, and direct electricity (which is partly renewable) account for only a small part of the energy consumed.[7]

3 State Statistics Service of Ukraine, 'Енергетичні Потоки, Тис'.

4 International Energy Agency, 'Energy Security – Ukraine Energy Profile'.

5 Eurostat, 'Final Energy Consumption by Sector'.

6 State Statistics Service of Ukraine, 'Final Energy Consumption for 2007-2021'.

7 State Statistics Service of Ukraine, 'Енергетичні Потоки, Тис'.

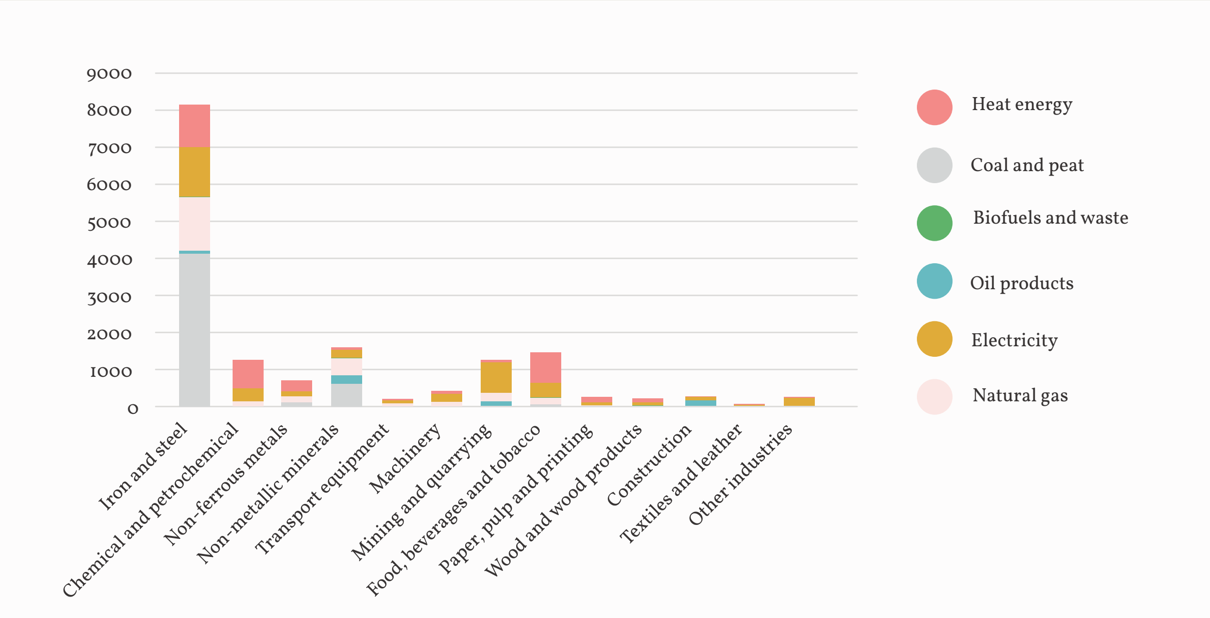

Figure 3: The energy consumption of industrial sectors in Ukraine in million tons of oil equivalent in 2020
Source: State Statistics Service of Ukraine, 'Energy Balance of Ukraine'.

Manufacturing plays a pivotal role in the Ukrainian economy, contributing significantly to both productivity and revenue generation. A number of essential products are made within the country's diverse industry landscape (shown in Figure 3). They include ferrous metals (Ukraine is one of the world's leading steel producers), transportation equipment, heavy machinery, and a wide array of chemicals, food products, and other goods. According to the Kyiv School of Economics, by early 2023 industry and enterprise assets had suffered damage equivalent to some USD 138 billion during the war.[8]

The production of cast iron, rolled steel, and steel pipes takes place primarily in the Donetsk Basin, the country's industrial heartland. Furthermore, Ukraine's heavy industries manufacture trucks, automobiles, railway locomotives, freight cars, seagoing vessels, electric generators, and turbines for hydroelectric, thermal steam, and gas applications. Additionally, a range of machinery for work such as hoisting and transportation is supplied for residential and industrial construction. The country's strong agricultural sector is supported by numerous processing plants, especially in Kharkiv, Odesa, Lviv, and Kherson, which produce a diverse range of agricultural equipment.[9]

Manufacturing applications are characterized by wide variation in the type and quantity of energy required. Industrial processes can require low-grade heat, high-grade heat, cooling, kinetic energy for motors and similar processes, energy for chemical processes, or electricity for applications such as computers or lighting. The decarbonization of the industrial sector is therefore associated with a range of different challenges.

The sector comprises a number of state-owned enterprises, many of which are inoperative (being in territories occupied during the Russian aggression) or inefficient and unprofitable. The Ukrainian government plans to privatize or wind down

8 Kyiv School of Economics, 'The Total Amount of Damage Caused to Ukraine's Infrastructure Due to the War Has In-creased to Almost $138 Billion'.

9 Stebelsky, Yerofeyev, and Makuch, 'Economy of Ukraine'.

most of these.[10] Realistically, reconstruction will depend largely on decisions and transitions undertaken by private-sector operators in an uncertain timeframe. The Ukrainian government will therefore foster the resurgence of a more efficient, more modern and greener manufacturing through regulation and supportive measures rather than direct operational decisions.

Ukraine's European ambitions mean that it will be compelled to work towards a decarbonized economy in the medium term. At the same time, the reconstruction of Ukraine's economy and infrastructure will itself consume energy and produce carbon dioxide and other greenhouse gases in addition to those generated by buildings and normal activities. The production of concrete and steel contributes significantly to greenhouse gas emissions. Cement is a major input for concrete. Worldwide, every year, more than 4 billion tons of cement are produced, contributing around 8% of annual global carbon dioxide emissions.[11] This issue can partly be mitigated by reducing the carbon intensity of steel and concrete (e.g., by procuring green steel – see chapter 2.2.3.2) or by reducing the overall need for these materials through alternative building practices.

1.1.1.1. Outlook

Ukraine's focus should be on rebuilding its industry using new clean technologies and creating new economic opportunities (see also chapters 1.2.3 Natural Gas, 1.2.5 Coal and the Coal Phase Out, and 2.2 Hydrogen and its Derivatives). Sustainability – not least in a European perspective – is a major part of that. This means, for instance, finding and managing access to the raw materials necessary for a clean reconstruction and **green new methods** in industrial processes. In the near term, the Ukrainian authorities should therefore, wherever possible, include **climate and sustainability considerations** in their privatization plans to make sure that future operators have clear strategies that will enable some degree of decarbonization within a reasonable timeframe (the exact definitions depending on the given industry sectors). Special care should be given to iron and steel production, which are particularly important to Ukraine's economy but have high energy consumption.

1.1.2. Residential Sector

In 2021 there were more than 17 million residential units in Ukraine.[12] As shown in Table 1, the largest share (50%) of final residential energy consumption is space heating. Water heating, cooking, lighting, and appliances account for the rest, with a rough share of 14-16% each. According to the Kyiv School of Economics, by the end of 2022, war damage in the housing sector was USD 54 billion (of a total of $138 billion). This included 149,300 damaged or destroyed housing units.[13]

A report by the consultancy Ukrainian Industry Expertise calculated in November 2022 that Ukrainian manufacturers could eventually provide 90% of the construction materials needed for reconstruction. The report included current energy-efficiency requirements (regardless of the state of the buildings before their damage). The calculation includes the "National Standard of Ukraine Determination of Average Indicators of Material Resource Costs Per Unit of Measurement of Functional Purpose". No other efficiency standards were considered.[14] Ukraine's Energy Strategy until 2050 refers to energy efficiency measures but does not mention circular economy principles or sustainable building measures.

10 Ukraine's Cabinet of Ministers, 'Ефективні державні підприємства'.

11 Lehne and Preston, 'Making Concrete Change: Innovation in Low-Carbon Cement and Concrete'.

12 State Statistic Service of Ukraine, 'Housing Stock by Regions'.

13 Kyiv School of Economics, 'The Total Amount of Damage Caused to Ukraine's Infrastructure Due to the War Has In-creased to Almost $138 Billion'.

14 Ukrainian Industry Expertise, 'Activating and Strengthening Ukraine's Reconstruction Capacity'.

		Type of end use in percent (%)						
		Total	Space heating	Space cooling	Water heating	Cooking	Lighting and appliances	Other end uses
Energy sources	Electricity	100.0	5.7	3.1	10.4	12.1	68.5	0.2
	Derived Heat	100.0	62.0	-	38.0	-	-	-
	Gas	100.0	59.8	-	12.5	27.7	-	-
	Solid fossil fuels, including coal and peat products	100.0	94.2	-	5.4	0.4	-	-
	Oil and petroleum products*	100.0	10.3	-	11.0	78.7	-	-
	Renewables and waste	100.0	97.2	-	2.8	0.0	-	-

Table 1: Final energy consumption in Ukraine's residential/households sector by type of end use in 2020, including fuel, excluding the territories in Crimea, Sebastopol, Donetsk and Luhansk occupied before 2022
Source: State Statistic Service of Ukraine, 'Final Energy Consumption in the Residential/Households Sector by Type of End Use'.

1.1.2.1. Outlook

The reconstruction of homes is a major priority for Ukraine now and will continue to be so in the postwar period. This will be subject to many needs and priorities, some more urgent than others. The government should focus on ensuring that people have a roof over their heads first and foremost. In situations where sustainable choices can be made at little additional cost, however, this should be considered early on. One effective approach to making Ukraine's residential sector greener would be to embrace a **circular economy model** that minimizes waste generation and maximizes resource efficiency throughout the entire lifecycle of buildings.[15] This can be achieved by prioritizing the use of **environmentally friendly materials** such as wood or carbon instead of steel alternatives or use green steel. The production of green steel is addressed in the chapters 1.2.3 Natural Gas, 1.2.5 Coal and the Coal Phase Out, 2.2 Hydrogen and its Derivatives. In addition, Ukraine should promote the reuse and **recycling of materials**, as well as – where possible – design structures that can be easily disassembled and repurposed. Ukraine can establish measures on resource efficiency within an improved **building standard** that also reflects the need to increase overall energy efficiency in buildings – for new housing, reconstruction of damaged buildings, and the renovation of existing structures (see also section 2.5 Energy Efficiency). This has intrinsic economic and resilience benefits, in addition to being more environmentally and climate-friendly.

Decarbonizing the different components of energy use in the residential sector will require a comprehensive **assessment on how to shift from fossil fuels to renewable and climate-neutral energy sources** while – especially in Phase 1 – using existing infrastructure wherever possible. Important areas will be, amongst others, finding appropriate energy sources for the extensive district heating systems (see section 2.3.3 District Heating), the **future role of hydrogen** as a replacement for natural gas(see section 2.2 Hydro-

15 Lehne and Preston, 'Making Concrete Change: Innovation in Low-Carbon Cement and Concrete'.

gen and its Derivatives), and the **electrification** energy consumption, e.g. with heat pumps (see section 2.3.4 Heat Pumps), that will need to be accompanied by an overall expansion of renewable energy generation in Ukraine.

1.1.3. Transport Sector

Ukraine's transport sector consumed just over 8 million tons of oil equivalent in 2020, making it the third largest energy consumer in Ukraine. As shown in Figure 4, by far the largest share of the energy consumption in the sector – some 85% – is caused by road transport, with the remainder shared among other types of transportation, like pipelines, railways, domestic aviation, and domestic navigation.[16]

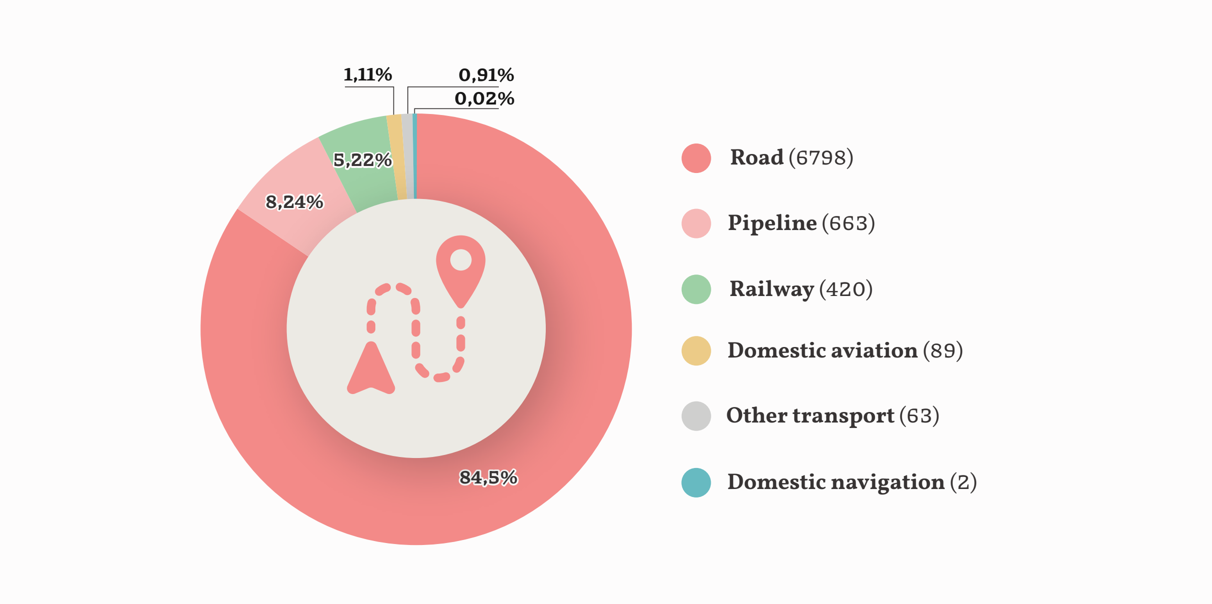

Figure 4: Final energy consumption of the transport sector in thousand tons oil equivalent in 2020
Source: Own illustration based on State Statistics Service of Ukraine, 'Енергетичні Потоки, Тис'.

Before the war, Ukraine's transportation system comprised a vast national road network of some 163,033 km. The country's railway network was also one of the most extensive in Europe, covering almost 20,952 km. A significant portion of the tracks, 9,926 km (47.4%), is electrified. Other transportation infrastructure available to Ukraine before the war included 13 seaports operating in the Azov and Black Sea basins and the Danube River Delta. Together, these ports had a total cargo handling capacity of approximately 230 million tons per year. There are also almost 1,570 km of navigable waterways throughout the territory. This dense transportation network is shown in Figure 5.

16 State Statistics Service of Ukraine, 'Енергетичні Потоки, Тис'

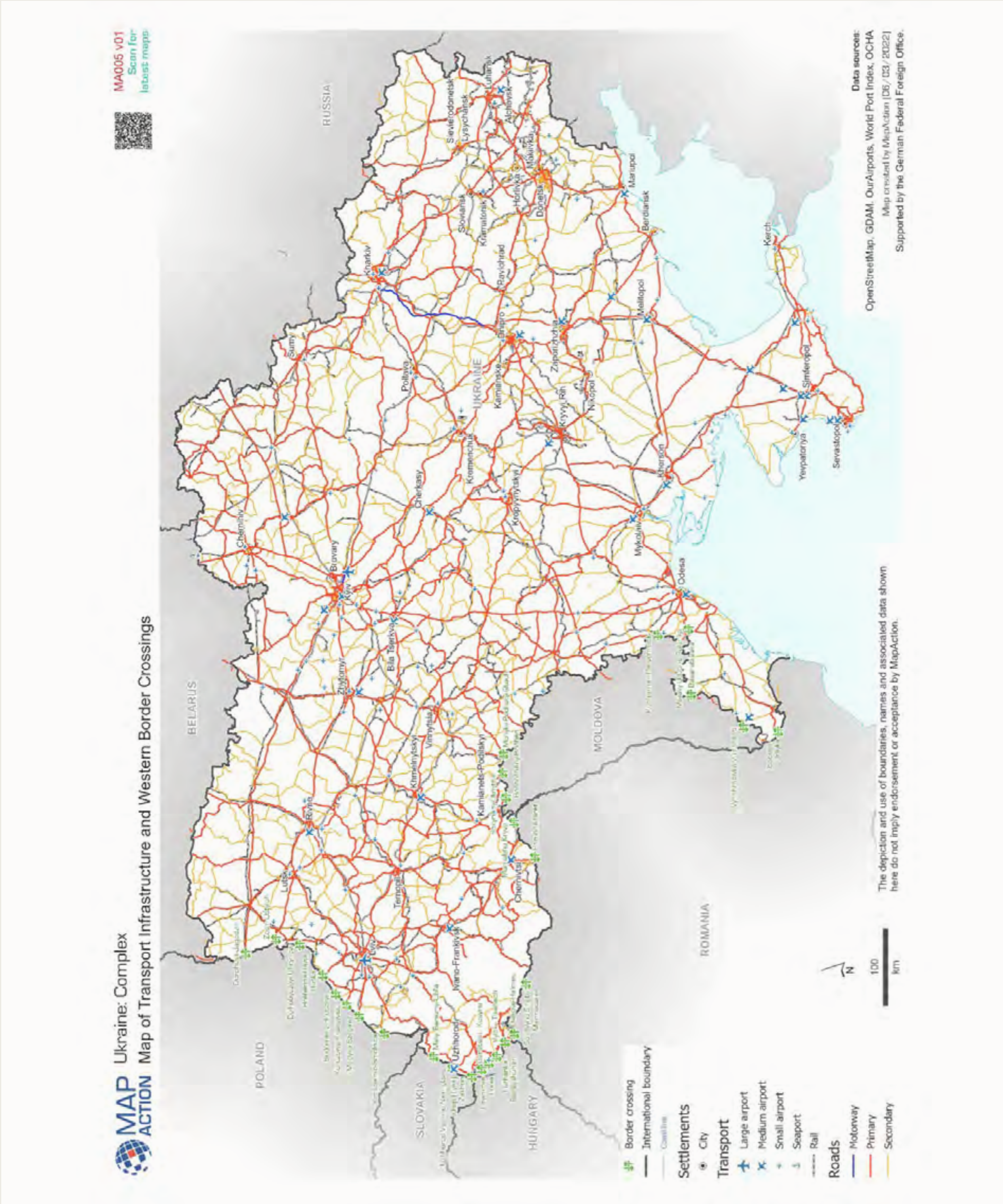

Figure 5: Map of the transport infrastructure and western border crossings of Ukraine
Source: MapAction, 'Ukraine: Complex Map of Transport Infrastructure and Border Crossings'.

The war has taken a heavy toll on infrastructure, with damage amounting to $35.6 billion by the end of 2022.[17] The full-scale Russian invasion saw railways come to play a pivotal role in both civilian and military logistics within the region. Due to the difficult terrain during the muddy season, and Russia's limited access to vehicles with off-road capability, rail transport has been the primary mode of moving troops and materiel. Consequently, railway nodes became strategic targets for Russian forces to maintain their supply lines and disrupt those of Ukraine. Simultaneously, the invasion led to significant shifts in Ukraine's import and export methods, with heavier reliance on rail transportation than during peacetime. This shift was necessitated by Russia's capture or blockade of several critical Black Sea Ports, which had traditionally handled a substantial portion of Ukraine's external trade.[18]

1.1.3.1. Outlook

The transport sector is in many ways less affected by war than the rest of the economy, consisting of many small parts that are more difficult to disrupt than large centralized systems. Even so, a great deal of infrastructure will need to be rebuilt and vehicles repaired or replaced. Where possible, this should be carried out in a sustainable way, with more renewable energy in transportation, as well as – where possible – a shift from individual to public transport. With its well-developed railroad network, Ukraine is well placed to maintain and increase high levels of public transport use.

In Phase 1, measures to achieve this could include:

- **Railroad Network Restoration and Electrification:** To lay the groundwork for a sustainable transport sector, immediate attention should be given to restoring Ukraine's pre-war railroad network and to start electrifying the complete network. This will serve as a resilient and efficient foundation for the transportation system, allowing for the seamless movement of both passengers and goods while minimizing emissions.

- **Policy Realignment:** In pursuit of a sustainable transport sector, it is imperative to realign the Energy Strategy of Ukraine until 2050 and the National Transport Strategy of Ukraine 2030. These strategies should be adjusted to prioritize the expansion of public transport networks and foster climate-friendly modes of transport. This alignment ensures that Ukraine's long-term development is in harmony with its commitment to greener transportation.

- **Integrated Urban Planning:** Sustainable cities require integrated urban planning that harmonizes city development with efficient transportation systems. Policies should encourage compact, walkable cities and efficient public transport options. By promoting smart urban planning, we can reduce congestion, pollution, and carbon emissions while enhancing the overall quality of life for residents.

- **Support for Electrification:** To curb emissions from the transport sector, it is essential to provide substantial support for the electrification of vehicles, including electric cars and electrified logistics. This not only reduces the carbon footprint of transportation but also positions Ukraine at the forefront of the electric mobility revolution.

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17 Kyiv School of Economics, 'The Total Amount of Damage Caused to Ukraine's Infrastructure Due to the War Has Increased to Almost $138 Billion'.

18 Latschan, 'Ukraine: Will the Railroad Decide the War?'

In Phase 2, Ukraine could take the following steps:

- **Boost Public Transport:** Accelerating the development and promotion of public transport is paramount. Expanding services, improving connectivity, and making public transportation the preferred mode of mobility will not only reduce emissions but also enhance accessibility for all citizens, contributing to a more inclusive society.

- **Electrify Railways:** Prioritizing the electrification of the railway system is a key step towards sustainability. If accompanied by expansion of renewable energy generation, this transition will significantly decrease the carbon emissions associated with freight and passenger transport.

- **Phase-Out Combustion Engines:** In alignment with global trends, Ukraine should establish a clear path to phase out new combustion engines in automobiles and other transport sectors. This gradual transition, leading to a ban on combustion engines, will give citizens and companies an incentive to switch to electric vehicles or other carbon-free alternatives. Naturally, it can only take place in parallel with a vast expansion of low-carbon electricity production.

- **Expand Charging Infrastructure:** To facilitate the widespread adoption of electric mobility, it is essential to increase the availability of public charging infrastructure across the country. This infrastructure expansion will ensure convenient access for electric vehicle owners, thereby accelerating the shift towards cleaner transportation options, which can be incentivized further by subsidies for electric vehicles.

- **Promote Carbon-Neutral Fuels:** For segments of the transport sector that cannot be easily electrified, promoting the use of green fuels such as biofuels, hydrogen, or synthetic fuels is crucial. These alternatives to fossil fuels reduce emissions and contribute to a cleaner, more sustainable transport ecosystem.

1.1.4. Commercial and Public Services

Public services include public hospitals, public education, policing, administrative structures, and other governmental services. Commercial services, as defined by the State Statistic Service of Ukraine, comprise warehousing, mail and courier activity, temporary accommodation and catering, information and telecommunications, real estate transactions, professional, scientific, and technical activity, activity in the sphere of administrative and support servicing, education, health care and provision of social aid as well as art, sport, entertainment, and recreation.[19] The government's ability to deliver public services is a key measure of recovery and therefore has a clear priority.

These processes mainly consume energy in the form of electricity and space heating. The sector accounted for a total final energy consumption of 4.9 million tons of oil equivalent in Ukraine in 2020, making it the second smallest.[20] Even so, it has a particular symbolic and practical importance, since it includes services such as schools and hospitals. A large and increasing number of buildings housing critical government services in Ukraine – hospitals, schools, police stations, etc. – are installing solar panels to ensure a more secure power supply (see section 2.1.3 Solar Power for more details).[21]

19 State Statistic Service of Ukraine, 'Volume of Services Sold by Service Rendering Enterprises by Type of Economic Activity over the IV Quarter 2021'.

20 State Statistics Service of Ukraine, 'Final Energy Consumption for 2007-2021'.

21 Birnbaum, 'Ukraine Found an Unlikely Tool to Resist Russia: Solar Panels'.

There are more avenues that the commercial and public services sector can pursue to work toward decarbonization, such as switching to renewable energy sources and improving efficiency. There are a number of existing programs that support the energy-efficient modernization of public buildings. The European Investment Bank (EIB), for instance, has an ongoing project providing up to €300 million in loans for energy efficiency improvements in public buildings in Ukraine, including administrative structures, schools, kindergartens, cultural buildings, and hospitals.[22]

Even before the full-scale Russian invasion in February 2020, the EIB already estimated the investment needs for the renovation of public buildings in Ukraine to be at least €2 billion. A great deal of damage to public and commercial infrastructure has been done since then – according to the Kyiv School of Economics, at the end of February 2023, this amounted to some €1.8 billion.[23]

1.1.4.1. Outlook

As with other sectors, commercial and public services will have to be rebuilt at various speeds depending on priorities and needs. A crucial aspect is **energy independence and resilience.** To achieve this, during Phase 1, the government should implement the following:

- **Energy Efficiency Programs:** To set the stage for a more energy-efficient public sector, the government should develop comprehensive energy efficiency programs. These programs will drive efficiency improvements across administrative services, reducing overall energy consumption and contributing to the larger goal of decarbonization.

- **Solar Technology Integration:** Kickstarting the decarbonization process requires immediate action. Government intervention should prioritize supplying critical structures with technology for solar power generation, small-scale generators based on biomass, and reliable systems for energy storage. This initiative can reduce dependency on fossil energy sources and encourage a shift to renewables.

- **Building Reconstruction for Efficiency:** A critical step in Phase 1 is the reconstruction of service buildings with advanced energy efficiency measures. Incorporating modern, sustainable technologies and designs will significantly decrease energy use, aligning with the overall decarbonization objective.

- **Setting Decarbonization Benchmarks:** Establishing clear and achievable decarbonization benchmarks for both the commercial and public services sectors is essential in Phase 1. These targets, specific to types of buildings such as schools, hospitals, or offices, will serve as guiding principles, motivating stakeholders to actively engage in sustainable practices.

22 European Investment Bank, 'Ukraine Public Buildings Energy Efficiency'.

23 Kyiv School of Economics, 'The Total Amount of Damage Caused to Ukraine's Infrastructure Due to the War Has Increased to Almost $138 Billion'.

Phase 2 will build on these measures while taking further steps toward sustainability:

- **Renewable Heating Systems Implementation:** Moving into Phase 2, the focus shifts towards the implementation of renewable heating systems in existing service buildings. This transition from conventional heating methods to renewable alternatives is a crucial step towards a low-carbon future.
- **Enhanced Energy Efficiency Measures:** A sustainable future necessitates the implementation of enhanced energy efficiency measures in existing buildings. These measures should encompass advanced insulation, smart energy management systems, and efficient lighting, collectively contributing to reduced energy consumption and lower emissions.
- **Mandatory Solar Roofs:** By introducing an obligation for solar roofs on public buildings, the government and its agencies can promote decentralized renewable energy generation and set an example for private companies and individuals.

1.1.5. Agricultural Sector

With over 40 million hectares of arable land and a well-developed agricultural sector, Ukraine ranks among the world's largest agricultural producers and exporters. Prior to Russia's invasion, approximately 70% of the country's total area was utilized for farming, and around 106 million tons of grains and oil crops were harvested in 2021. Agriculture accounts for approximately 4% of Ukraine's final energy consumption.

The agricultural sector contributes 11% to Ukraine's gross domestic product (GDP) and accounts for 40% of the country's exports, which amounted to USD 22.4 billion in 2020 and $27.8 billion in 2021.[24] Ukraine plays a crucial role as an exporting country for various agricultural commodities as well as wood pellets. Moreover, it serves as a major provider of rapeseed and sunflower feedstock for European biodiesel production.[25]

The war has had significant impact on the agricultural sector in Ukraine. In addition to vast amounts of contamination across large areas, there have been bottlenecks in labor force, tools, and equipment, leading to dropping production capacity and challenges to domestic food security.[26] The estimated overall value of damages and losses for agricultural enterprises in the crop and livestock sectors amounted to USD 3.85 billion.[27]

Agriculture directly and indirectly contributes to greenhouse gas emissions and, consequently, climate change. The primary greenhouse gas emissions produced in the agricultural sector are methane, nitrous oxide, and carbon dioxide. Carbon dioxide emissions originate in energy use both before and after farming activities, such as the use of fuel in agricultural machinery, as well as from changes in above- and below-ground carbon stocks resulting from land use and land use changes.[28]

The issue of ecological sustainability is increasingly gaining importance in Ukraine. The EU accession process naturally requires that Ukraine eventually adopt the entirety of European law. As such, the country has committed to implementing measures

24 Levkovych and Pyvovar, 'Analyse: Monitoring der Landnutzungsänderung in der Ukraine am Beispiel der Region Schytomyr'.

25 ETIP Bioenergy, 'Bioenergy in the Ukraine'.

26 FAO, 'Ukraine: Impact of the War on Agricultural Enterprises'.

27 FAO.

28 Soto Embodas et al., 'The Contribution of Precision Agriculture Technologies to Farm Productivity and the Mitigation of Greenhouse Gas Emissions in the EU'.

for environmental protection, biodiversity preservation, and species conservation. This includes conducting environmental impact assessments before undertaking certain agricultural projects.

Ukraine is well known for its agricultural production, but forests do cover 16% of its territory, or 9.7 million hectares.[29] The forestry sector is not very important in economic terms – in 2021, it was estimated to be approximately 1.1-1.2 % of the country's GDP.[30] Around half of annual timber production is exported.[31] Approximately 20% of Ukraine's forest lands have been damaged as a result of the war, and much of the rest is subject to illegal logging.[32] Managed sustainably, forests can be an indispensable resource in the reconstruction process, however. They also have a major climate protection dimension. The 2035 State Forest Strategy of Ukraine sets a goal for raising the level of greenhouse gas absorption by Ukrainian forests at to 75.6 million tons of carbon dioxide equivalent through the introduction of sustainable forest management, increasing the forest cover up to 18%, and transition to close-to-nature forestry approaches.[33]

1.1.5.1. Outlook

Agricultural activities in Ukraine can benefit from many of the same measures recommended above for manufacturing, buildings, and transport. The promotion of **combined use of land for agricultural activities and power generation** and increased energy generation from **biomass** can contribute to improved efficiency and a net reduction of overall emissions (see section 2.1.5 Bioenergy and 2.3.2 Combined Heat and Power for more information on this topic).

Forests provide economic value and act as carbon sinks, absorbing and storing carbon dioxide from the atmosphere. For this and many other important reasons (e.g., biodiversity, air quality, flood and erosion control), Ukraine should **take further steps to preserve its forests**. These measures can include a review and strengthening of existing legal frameworks on forest protection, establishing a system for sustainable forest management, and by creating more protected areas.

29 Zhanna Bezpiatchuk, 'A Billion New Trees Might Not Turn Ukraine Green'.

30 Kyiv School of Economics, 'Ринок Деревини Та Лісоматеріалів України: Як Працює Та Що Стримує Розвиток?'

31 Beckmann et al., 'Ukraine: A Sustainable Economic Recovery for People and Nature'.

32 WWF, 'Nature-Based Solutions in Forestry, Water and Agriculture for Restoration of Ukraine and Climate Change Adaptation: Summary for Policymakers'.

33 WWF.

1.2. Energy Generation

Energy generation in Ukraine is a multifaceted and evolving landscape. The country relies on a mix of energy sources, including renewable energy, nuclear energy, coal, and natural gas. Notably, Ukraine's nuclear power sector plays a prominent role in electricity generation, while efforts to diversify and increase the share of renewables are gaining momentum. The country's energy mix is shown in Figure 6.

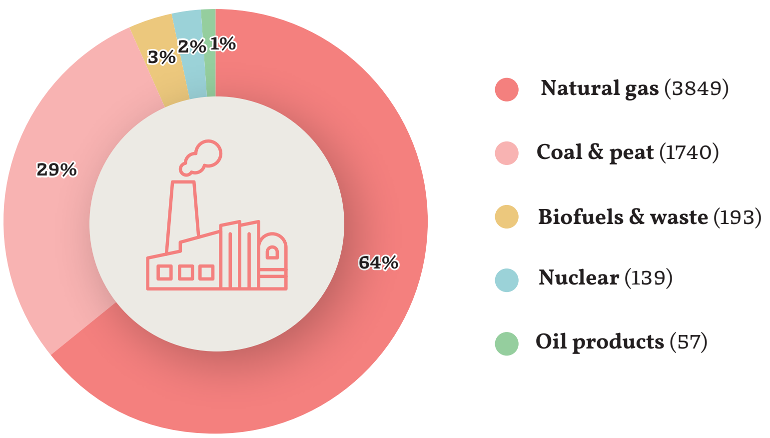

Figure 6: Total primary energy supply including heat and electricity in Ukraine by source, 2020[34]

1.2.1. Renewable Energy

Ukraine's renewable electricity sector has been developing rapidly, with the share of renewable sources in electricity supply increasing from 1.7% in 2007 to 6.6% in 2020, or some 5.7 million tons of oil equivalent.[35] At the beginning of 2022, total installed renewable capacity connected to the grid amounted to 9.5 GW (excluding 0.6 GW of capacity in areas occupied by Russia before February 2022). More information on renewable energy generation and future development can be found in section 2.1.

1.2.2. Nuclear Energy

With a generation of 83 TWh per year, Ukraine is the world's seventh-largest producer of nuclear power. Nuclear provides 28% of the country's installed electrical capacity (13.1 GW net capacity), originating in four nuclear plants which house 15 Soviet-era VVER reactors: two V-213 models with a capacity of 440 MW each, and 13 units (11 V-320 models, one V-302 and one V-338 model) with a capacity of 1000 MW each. The state company Energoatom owns and operates all of Ukraine's functional nuclear plants, as well as the small hydro plants which provide load-follow-

34 State Statistics Service of Ukraine, 'Енергетичні Потоки, Тис'.

35 State Statistics Service of Ukraine, 'Energy Consumption from Renewable Sources for 2007-2021'.

ing.[36] The plant at Zaporizhzhia is Europe's largest and has a net capacity of 5.7 GW, close to half the country's total. Two of its six reactors were shut down in February 2022 when the Russian invasion began, and the rest during the period of the Russian occupation after March 2022.[37]

Ukraine has traditionally received nuclear expertise and fuel primarily from Russia, but this state of affairs has gradually been shifting since the beginning of Russian aggression in 2014, when it became stated government policy to diversify energy and component suppliers.[38] For instance, Ukraine used to send its radioactive waste to Russia at great cost, but opened a nuclear waste repository within the Chornobyl exclusion zone in 2021.[39] This was briefly overrun by Russian forces in February-March 2022, during which time on-site equipment worth millions of dollars was pillaged. As of August 2022, the site is again used for nuclear waste storage.[40]

The Energy Strategy of Ukraine until 2050, elaborated by the Ministry of Energy and approved by the Cabinet of Ministers on 1 May 2023, created a new framework that takes into account the consequences of the war and has stronger sustainability ambitions, explicitly aiming for carbon neutrality in 2050. The strategy rests on three pillars, of which one is "modern and safe nuclear generation" (the other two are renewable energy sources and the modernization and automation of transmission and distribution systems, which are discussed in section 2 The Future Pillars of Ukraine's Energy System). The strategy explicitly mentions making the most of cutting-edge nuclear technology, including small modular nuclear reactors.[41]
In August 2021 Energoatom signed an agreement with the US nuclear power company Westinghouse Electric Company to establish five new AP1000 reactors – a Gen III+ design with a capacity of some 1100 MW – at a range of existing nuclear power sites in Ukraine.[42] This agreement was partly realized in November 2021 with the signature of a contract for two new AP1000 units at the Khmelnitsky site, and extended in June 2022 by a new agreement with Westinghouse increasing the total number of AP1000 reactors to be delivered from five to nine.[43]

Moreover, in April 2023, Energoatom signed a contract with the US producer of nuclear reactors Holtec International to deploy 20 new small modular nuclear reactions of the type SMR-160 in Ukraine. The contract also foresees the establishment of manufacturing capacities in Ukraine to ensure that much of the work involved in producing and installing the reactors can take place within the country.[44] The SMR-160 is a light water pressurized reactor with a capacity of 160 MW which runs on low-enriched uranium and can generate process heat for industrial use and hydrogen production. According to Energoatom, the small modular reactors will boost the country's energy security and replace thermal power capacities that have been destroyed during the Russian invasion. The new reactors are planned to be online by March 2029.[45]

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36 International Energy Agency, 'Market Design: Ukraine Energy Profile Analysis'.

37 Kraev, 'Energoatom Shuts Down Zaporozhye-5 and -6 as Rest of Fleet Remains Safe and Operational'.

38 Westinghouse Electric Company, 'Energoatom and Westinghouse Advance Clean Energy Throughout Central and Eastern Europe'; Interfax Ukraine, 'Energoatom, Westinghouse Extend Contract on Nuclear Fuel Supplies until 2025'; World Nuclear Association, 'Nuclear Power in Ukraine'.

39 Karmanau, 'Ukraine Opens New Nuclear Waste Site at Chernobyl'.

40 World Nuclear News, 'Chernobyl Waste Processing Operations Resume'.

41 Ministry of Energy of Ukraine, 'Україна – Енергетичний Хаб Європи'.

42 Westinghouse Electric Company, 'Energoatom and Westinghouse Advance Clean Energy Throughout Central and Eastern Europe'.

43 World Nuclear Association, 'Nuclear Power in Ukraine'.

44 Holtec International, 'Ukraine's Energoatom and Holtec International Sign Cooperation Agreement to Deploy SMR-160 Reactors in Ukraine'.

45 Ukrainska Pravda, 'Ukraine's Nuclear Energy Company Energoatom Plans to Build 20 Nuclear Power Units in Ukraine'.

While existing nuclear plants provide plentiful electricity at little cost, the economic argument for an expansion of nuclear power is complex (see section 3 Cost-Benefit Analysis of Different Sources of Electricity). For one thing, nuclear power is not normally flexible enough to counterbalance an expansion of intermittent renewables. Modelling carried out by the Danish Energy Agency in 2019 suggested that the reduction of energy intensity and increase in renewables foreseen in the Energy Strategy of Ukraine until 2035 would mean that there was no need for expansion of nuclear power generation in Ukraine – in fact, assuming that the Energy Strategy were put into place as planned, even the existing nuclear power plants would not be fully utilized in 2025. Any new reactors – specifically reactor 3 planned at Khmelnitski – are therefore recommended in that analysis to be delayed until 2030-2035 at the earliest. According to the modelling, the resulting optimization of the commissioning of the new reactor would reduce total investment required by €270 million.[46]

Another issue that needs to be kept in mind and is linked to the threat from Russia is that a shortfall of electricity due to a major power source being destroyed or taken offline may destabilize the grid – and this is potentially a very large problem with a source of electrical power the size of a nuclear reactor. Since Ukraine is now linked to the synchronous grid of Continental Europe, the latter may potentially be at risk too in case of a nuclear plant being taken offline or disconnected from the grid for whatever reason.

1.2.2.1. Phase 1

Ukraine's foremost objective concerning its nuclear power plants is to **maintain their operational integrity** and ensure consistent electricity production. The majority of the country's reactors had reached the end of their initial design lifetimes around 2020; however, thorough safety reassessments led to their operational extension.[47] Ongoing safety enhancements and **modernization initiatives**, often in collaboration with European nuclear power companies, are vital for the sustained efficiency of these plants.[48]

According to the International Energy Agency, Ukraine possesses the requisite expertise to ensure the safe operation of its nuclear plants. Nevertheless, **fostering international partnerships** is encouraged to facilitate knowledge sharing and support experimental facilities, such as irradiation facilities, research reactors, and hot cells. Likewise, Ukraine is anticipated to maintain the capacity to educate and train nuclear technicians, engineers, and scientists within its academic institutions, renowned for their longstanding expertise in relevant subjects.

However, financial considerations may pose challenges to upholding nuclear energy generation.[49] As of March 2018, Energoatom reported financial constraints, citing difficulties in covering the costs of nuclear power purchases with the revenue generated from electricity sales.[50]

46 Diachuk et al., 'Long-Term Energy Modelling and Forecasting in Ukraine'.

47 Organisation for Economic Co-operation and Development, 'Monitoring the Energy Strategy of Ukraine 2035'.

48 World Nuclear Association, 'Nuclear Power in Ukraine'.

49 International Energy Agency, 'Market Design: Ukraine Energy Profile Analysis'.

50 World Nuclear News, 'Energoatom Counts Cost of Regulatory Changes'.

1.2.2.2. Phase 2

The precise composition of Ukraine's energy mix for the year 2050 remains uncertain. However, it is evident that the country has initiated a significant program which aims to expand its nuclear power generation capacity.

Nuclear energy exhibits several advantages over conventional fossil fuels, and it is essential to note that **EU programs and strategies do not preclude its use** – the EU taxonomy in fact lists it as a sustainable technology. Nonetheless, nuclear power may not always represent the most cost-effective choice, particularly considering potentially scarce capital resources. Given the potentially high financial costs and risks, the expansion of nuclear energy should undergo a **careful cost-benefit analysis** that considers other sustainable alternatives – but also, for instance, the benefits of exporting excess energy to Europe in the form of electricity or pink hydrogen (assuming that enough interconnecting capacity and hydrogen infrastructure can be built). Such an approach would ensure that Ukraine's energy investments align with its long-term goals and deliver optimal value for its financial commitments.

The **long-term storage of spent nuclear fuel** is also a perennial issue – but the waste processing and disposal facility at Chornobyl is designed to last at least 100 years, and there is research into radioactive waste disposal in geological formations.[51] Of course, due to the high sensitivity of this issue, such plans should proceed only with the greatest caution, and perhaps with a stronger democratic mandate than is normally required for other types of pollution.

1.2.3. Natural Gas

In 2021, there were some 542 issued licenses and 25 large companies operating in the oil and gas exploration and production sector in Ukraine, including three state-owned companies and 22 private companies with Ukrainian and foreign investments. Ukraine has Europe's third-largest natural gas reserves, equivalent to up to 719 billion cubic meters.[52] The largest reserves are located in the Poltava, Kharkiv, and Lviv regions and on the Black and Azov Seas shelf.

Main gas production regions before the war were the Poltava and Kharkiv regions (with about 90% of total production). Over the last 20 years, the volume of natural gas production in Ukraine was about 20 billion cubic meters per year (about 55 million cubic meters per day). Natural gas makes up 7% of Ukraine's electricity generation.[53] The share is predicted to grow after 2030 to provide balancing for electricity from renewable sources and help reduce the share of coal generation.[54]

51 Shogenov, 'Radioactive Waste Disposal in Geological Formations in Ukraine'.

52 Ernst & Young Audit Services LLC, 'Extractive Industries Transparency Initiative: National Report of Ukraine'.

53 Ritchie and Roser, 'Ukraine: Energy Country Profile'.

54 Cahill and Palti-Guzman, 'The Role of Gas in Ukraine's Energy Future'.

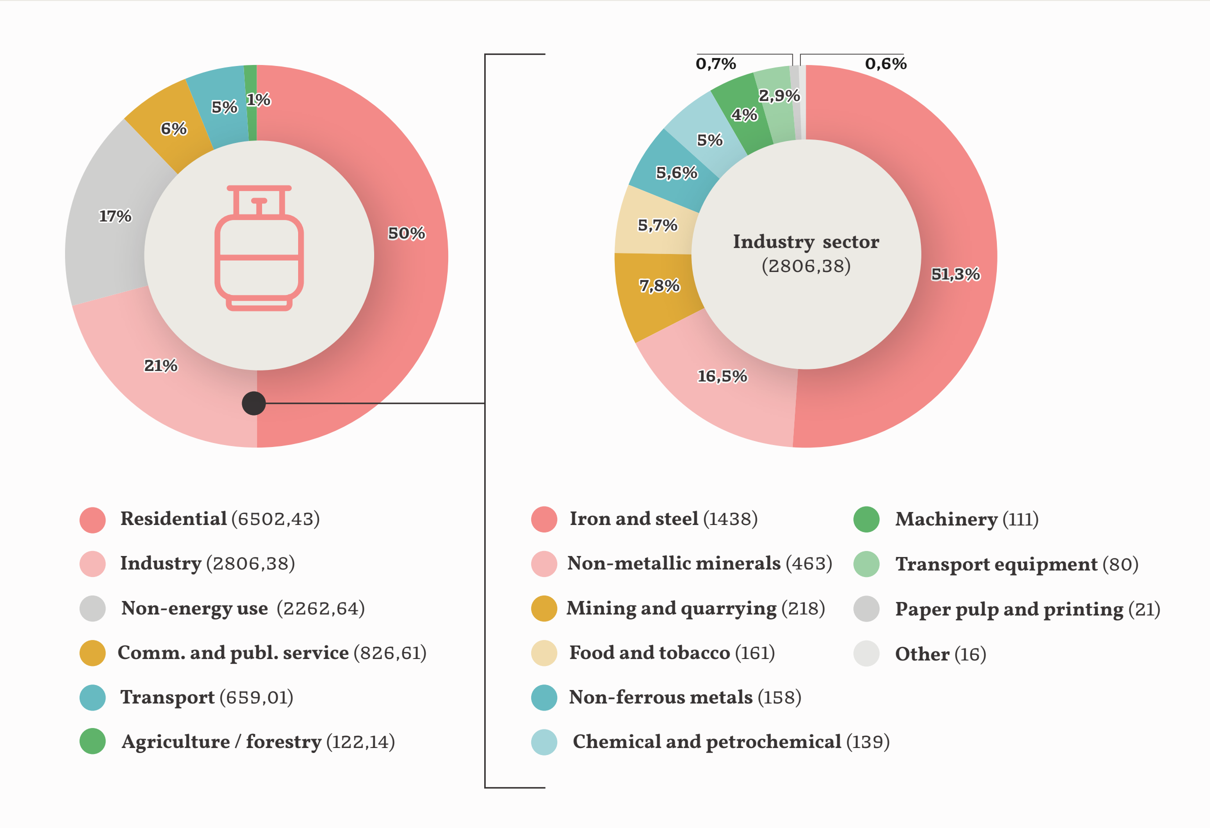

Figure 7: Final Gas Consumption in Ukraine by Sector in 2020, in thousand tons of oil equivalent
Source: Own Illustration, based on State Statistic Service of Ukraine, “Energy Balance of Ukraine”.

As shown in Figure 7, in 2020 natural gas was used in every economic sector. The main consumer was the residential sector, which accounted for half of the final consumption.

The second largest consumer, manufacturing, used up 21%. As shown in Figure 8, during the war the consumption of natural gas decreased between 7 and 36%, depending on the region.

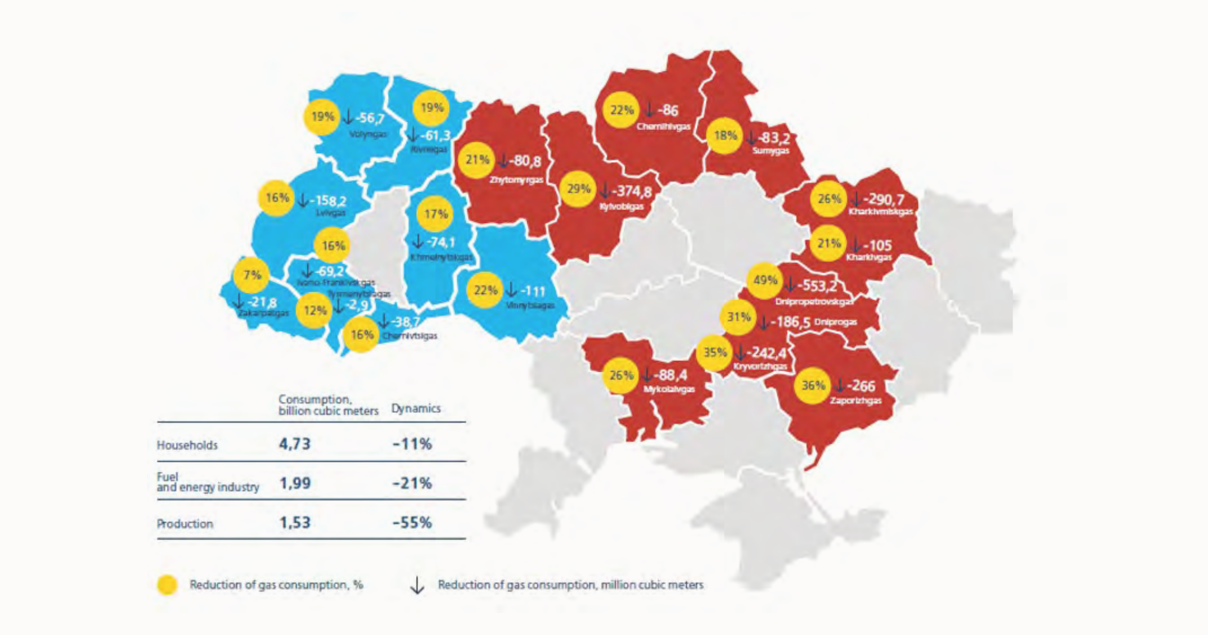

Figure 8: The impact of military actions on gas consumption in volume of gas consumption for 10 months in 2022
Source: RGC, 'Ukrainian Natural Gas Distribution Network Renovation'.

To decarbonize the natural gas sector, there is a need to electrify certain processes and to shift to climate-neutral green fuels, e.g., through power-to-X processes. (see 2.1.5 Bioenergy and 2.2 Hydrogen and its Derivatives). (Obviously, as mentioned elsewhere, electrification and the expansion of power-to-X-processes will increase demand for renewable energy systems (see also section 3.2 Renewable Energy).

Another important factor regarding the use of natural gas is transmission and distribution. Ukraine has a gas transportation system that consists of a highly dense network of primary and secondary pipelines, along with significant storage facilities. The system spans a total of 38,600 km, with 22,200 km dedicated to main transmission pipelines and 16,400 km designated for distribution pipelines. Powering the system are 72 compressor stations, boasting a combined capacity of 5,443 MW. It has the capability to transport up to 80 billion cubic meters per year of gas for domestic consumption, both sourced locally and imported. The transmission pipelines in Ukraine as a former gas transit state could move up to 142.5 billion cubic meters per year of gas from Russia and Belarus to European countries further west.[55] Ukraine's gas transportation system also comprises the second-largest storage capacity in Europe. There are 13 underground gas storage facilities in total, with a collective working capacity of 30.9 billion cubic meters per year.[56]

Much of this infrastructure can be used with biomethane without adaptations or with hydrogen or its derivatives by admixing them into natural gas or adapting the infrastructure. There is more on this topic in section 2.2.4 Hydrogen Transmission.

55 Sudzha entry point is the only operating energy point transporting Russian gas through Ukraine. Reuters, 'Russian Gas to Europe via Ukraine Rises'.

56 International Energy Agency, 'Ukraine Energy Profile'.

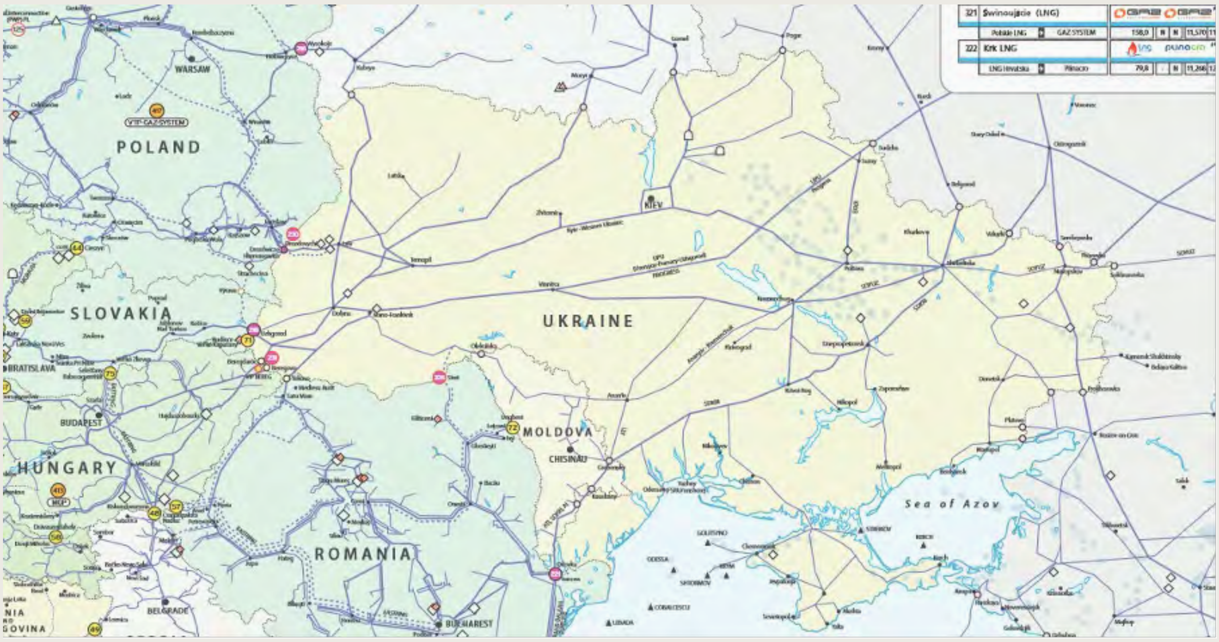

Figure 9: Gas Transmission System in Ukraine in 2021
Source: EntsoG, 'The European Natural Gas Network 2021'.

Gas transmission in Ukraine is operated by LC Gas, the country's transmission system operator (TSO). This monopoly provides for the transportation of natural gas to and within Ukraine and to and from countries to its west. It was established in 2019 to fulfill Ukraine's international obligations as a member of the Energy Community, ensuring the independence of the country's gas TSO.[57] As shown in Figure 9, Ukraine's gas transmission grid is already connected to several EU member states, enabling substantial potential to export to the EU. In March 2023, the Polish and Ukrainian gas TSOs made plans for future cooperation, hydrogen and biomethane included.[58]

1.2.3.1. Phase 1 and 2

Following the end of the war, Ukraine should strategically plan a **comprehensive overhaul of its gas production, consumption, and transmission infrastructure**. Central to this transformation is the adaptation of the generation and transmission system to meet the requirements of a substantial medium-term expansion in renewable electricity generation. There will be a particular **need for adequate balancing capacity**, much of which is expected to be derived from gas turbines. Notably, the latest gas turbine models offer high efficiency and cost-effectiveness, presenting a more climate-friendly alternative to other fossil energy sources (see section 3 for further details).

Ukraine's Soviet-era **natural gas grid** surpasses its current needs and is progressively deteriorating. **Extensive sections need to be decommissioned**, while others require repairs or modernization. Prior to the war, Ukraine estimated that the comprehensive upgrade of the grid would incur a cost of €10 billion over 10-15 years (this includes losses from inefficiencies and leaks, as well as illegal draining by users).

57 Gas Transmission System Operator of Ukraine, 'Key Facts'.

58 Habibic, 'Polish and Ukrainian Gas TSOs Plot Future Cooperation, Hydrogen and Biomethane Included'.

Looking ahead, some pipelines might be **repurposed for hydrogen**, aligning with the EU's vision of incorporating Ukraine into a forthcoming European hydrogen ecosystem as a net exporter.[59] Additionally, integrating biogas into this restructured energy landscape merits careful consideration, as it can further contribute to Ukraine's sustainable energy goals while enhancing energy security.

In the longer term, Ukraine should focus on retrofitting and leapfrogging. Favoring the energy transition may mean preferring electricity, biogas, and hydrogen investments over gas. Natural gas facilities and liquid natural gas terminals that could potentially be converted into multi-fuel hubs in the future may be considered, but energy efficiency and clean, renewable energy should be prioritized.[60]

In the event of complete cessation of Russian gas supply, Ukraine's pipeline system must undergo **optimization** to serve both the domestic market and facilitate trade with neighboring countries. Ensuring consistent and adequate pressure within the pipelines will then be a top priority. This optimization process will be crucial for safeguarding Ukraine's energy security and enhancing its capacity to meet domestic demands while fostering regional energy cooperation.[61]

1.2.4. Oil and Petroleum Products

Ukraine is estimated to have oil reserves of approximately 85 million tons, with around 51% in the north and center of the country, 36% in the west and 13% in the south. Oil and gas condensate production in 2021 was some 6,660 tons a day, or 2.4 million tons per year. Two state-owned companies accounted for around 80% of total oil production and 23 private enterprises – featuring both Ukrainian and foreign investments – for the remainder in 2021. A significant portion of the country's oil reserves are located in areas occupied by Russia in mid-2023 and the volume of oil production in those oilfields has decreased substantially.[62]

Ukraine has 19 oil pipelines with a total length of some 3,500 km and 176 pumping stations. They were built to transport oil from Ukrainian oilfields and seaports to consumers in Ukraine as well as for transit from Russia. In 2021, a total of 15.7 million tons were transported, of which 12.7 million tons were Russian oil transiting west to Slovakia, Czechia and Hungary. There is significant damage to this infrastructure too due to the war. Since the beginning of the full-scale war in February 2022, more than 30 oil depots were destroyed or damaged throughout Ukraine.[63]

59 Cahill and Palti-Guzman, 'The Role of Gas in Ukraine's Energy Future'.

60 Cahill and Palti-Guzman.

61 Pirani, 'The Ukrainian Gas Sector to 2030'.

62 Ernst & Young Audit Services LLC, 'Extractive Industries Transparency Initiative: National Report of Ukraine'.

63 Cooperation for Restoring the Ukrainian Energy Infrastructure, 'Ukrainian Energy Sector Evaluation and Damage Assessment IV'.

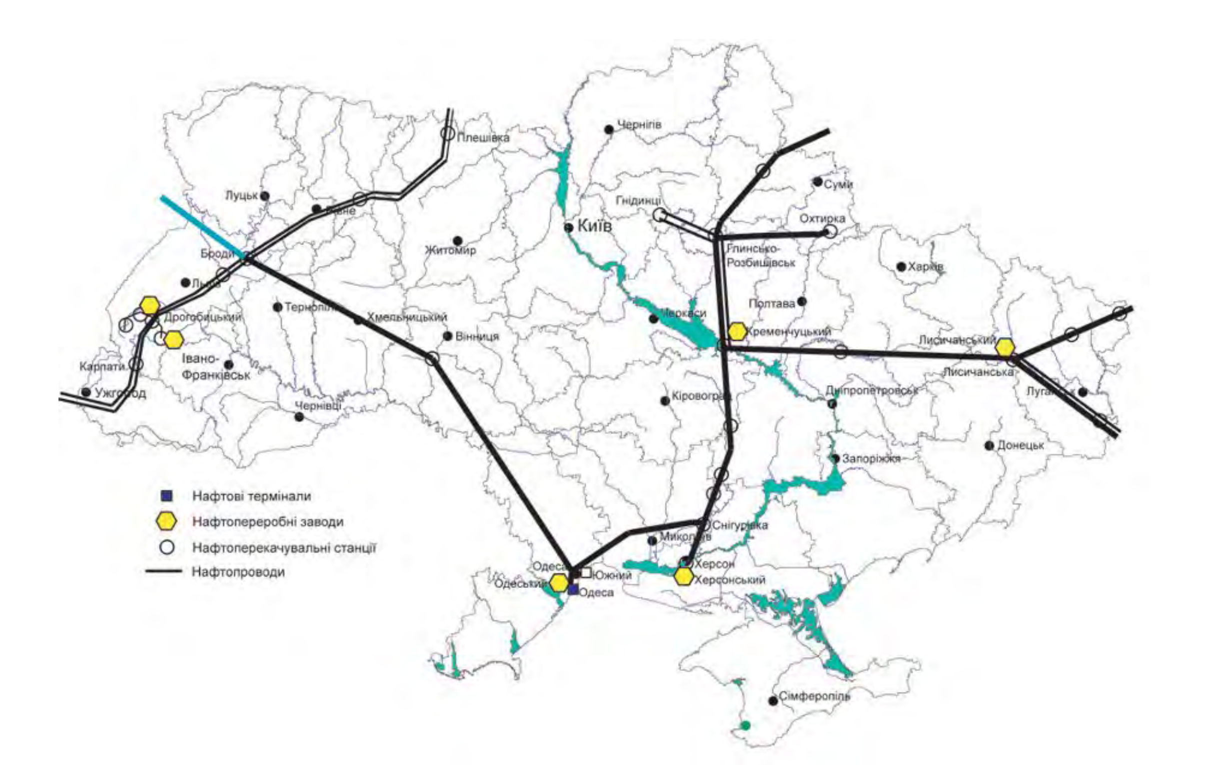

Figure 10: Schematic overview of the magistral oil pipelines in 2013[64]

Since 2014 there have been two functional refineries in Ukraine: Kremenchuk Refinery (with a capacity of up to seven million tons per year) and Shebelynka Gas Processing Plant (a capacity of about 0.5 million tons per year). These two plants used to cover a quarter of Ukraine's demand for oil products, which was 12.35 million tons in 2021. They were shut down when Russia's full-scale war began in February 2022 and later damaged or destroyed, making them inoperable. Ukraine now imports all of the oil and petroleum products it needs; this amounted to 5.8 million tons from January to October 2022. While this is some 13% less than during the same period in the preceding year, it cost around 70% more.[65]

Between October and December 2022, Russia launched massive missile attacks on Ukraine's energy infrastructure, leading to significantly increased demand for gasoline and diesel needed to power emergency generators – record volumes of oil products were imported in December 2022, mainly from Poland, whose exports of oil products shot up elevenfold.[66] Imports from Bulgaria in 2022 increased by a factor of 1000 (from a very low amount) to more than €800 million – an amount that represents one percent of that country's entire GDP. Ukraine has jumped from eighth to third place among Bulgaria's trade partners. Most of this comes from Bulgaria's only refinery, which is owned by the Russian oil company Lukoil

64 Geograf.com.ua, 'Oil Transport Systhem Ukraine'.

65 Cooperation for Restoring the Ukrainian Energy Infrastructure, 'Ukrainian Energy Sector Evaluation and Damage Assessment IV'.

66 Cooperation for Restoring the Ukrainian Energy Infrastructure.

and operates mainly with Russian oil imported to Bulgaria in a derogation from EU sanctions.[67]

In other words, Ukraine is still importing significant amounts of oil which originates in Russia and feeds Russian state coffers, in turn helping sustain Russia's invasion. This perverse state of affairs of course holds across Europe, which has been spending eye-watering amounts on Russian hydrocarbons since the beginning of Russia's aggression on Ukraine in 2014. Together with pollution and greenhouse gas emissions, this is perhaps the best argument for the greening of Ukraine's and Europe's economies.

Oil products are mainly consumed by the transport sector, which accounts for three quarters of all demand (see Figure 11). To phase out oil products, it is therefore necessary to shift the transportation sector from dependence on oil products to renewable energy carriers. (There is more information on this in the section 2.5 Energy Efficiency section of this study.)

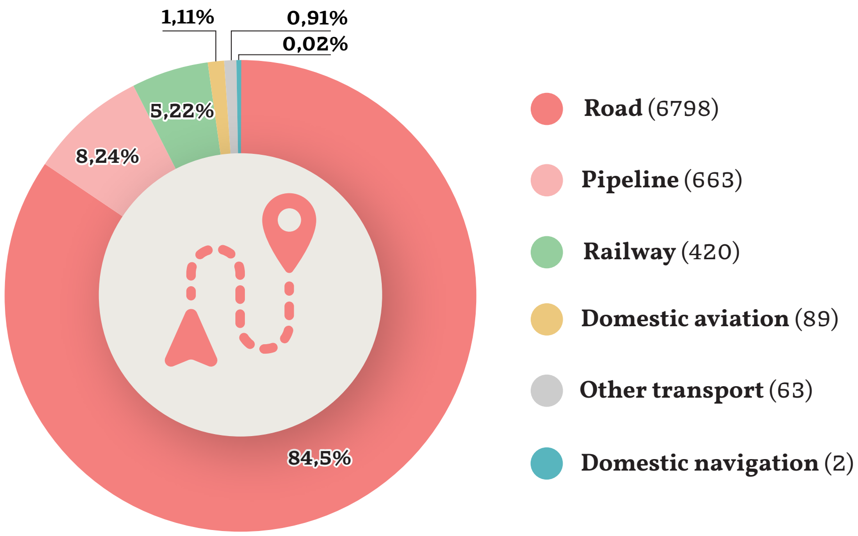

Figure 11: Final consumption of oil products in thousand tons of oil equivalent in 2020 in Ukraine
Source: Own illustartion, based on State Statistic Service of Ukraine, 'Energy Balance of Ukraine'.

67 Kotseva and Nikolov, 'Investigation: Ukraine Buys Huge Amounts of Russian Fuels from Bulgaria'.

1.2.4.1. Phase 1

Despite the compelling reasons to expedite the transition away from fossil fuels, both universally recognized and specific to Ukraine, it is essential to acknowledge that such a shift cannot occur overnight. Following the cessation of the conflict, Ukraine will face the task of **rebuilding its infrastructure** for the distribution of oil and petroleum products, particularly for vehicular use. This should focus on providing the necessary supply for overall reconstruction, a functioning economy, and citizens' basic mobility needs while also considering the **medium-term decrease in demand** associated to rising levels of electromobility and the phase out of combustion engines.

1.2.4.2. Phase 2

Any efforts going beyond the provision of a basic energy supply – the reconstruction or expansions of oilfields, refineries, and other facilities in the oil and petroleum sector – should be conducted with utmost diligence and with a particular regard to **avoiding fossil lock-ins**. Technical solutions to make the distribution and consumption of oil and petroleum products greener and more efficient include more energy-efficient pipes (graded and not right angular), bet-ter pipe insulation, more heat recovery, and variable speed drives for transport.

This assessment should encompass overarching strategies and climate policies that affect the medium and long-term demand, such as the fossil phase-out and gradually rising prices for oil and petroleum related to **carbon pricing**. On the other hand, infrastructure can provide a base for the deployment clean technologies such as **power-to-liquid, hydrogen**, or **biofuels**, to mention but a few.

Questions of **energy security** should also be addressed: reducing oil consumption can help minimize the exposure to Russian (or other suppliers) influence on oil distribution a price risks related to the volatile fossil energy markets.

On a practical level, decision makers also need to consider the **opportunity costs** inherent in directing resources towards reinforcing fossil fuel infrastructure. This consideration holds heightened significance, given the substantial expenses and prolonged construction timelines associated with such infrastructure projects, which may potentially result in **stranded assets** over the medium term. Such resources could otherwise be invested profitably in the **expansion of renewable energy generation**, distribution, and deployment. As in many other fields, a clean slate effect can be helpful in allowing Ukraine to leapfrog into a greener future.

1.2.5. Coal and the Coal Phase Out

Ukraine's coal reserves include the full range of coal types, from anthracite to lignite, including thermal and coking coal. The country's hard coal reserves rank sixth largest in the world. Reserves of anthracite and bituminous coal are estimated at 32 gigatons (Gt), while reserves of sub-bituminous coal and lignite are assessed at 2 Gt.[68] About 92.4% of Ukraine's total coal reserves are located in the Donetsk hard coal basin (Donbas).

It is important to note that more than 70% of the country's installed coal plant capacity has passed the threshold of 250,000 hours of operation. A suboptimal mode of operation (part-load and cycling) leads to slow response and low ramping rates, making it inefficient and ineffective to operate the daily load regulation and grid balancing by the old coal plants.[69]

Before the start of the war, in 2021, there were 47 coal mines in operation. In 2013, before the Russian occupation of the Donbas region, there had been 151. There are currently 95 mines in the Ukrainian territories occupied by Russia, including 28 privately owned and 67 state-owned ones.[70] About 60% of the country's coal deposits are in regions now occupied by Russia, as shown in Figure 12 below.

Figure 12: Natural gas, coal, uranium, and lithium deposits in Ukraine in February 2022
Source: Own illustartion, based on State Statistic Service of Ukraine, 'Energy Balance of Ukraine'.

68 International Energy Agency, 'Ukraine Energy Profile'.

69 Wärtsilä Energy Solutions, 'Flexibility to Future-Proof the Ukrainian Power System: Solving the Ukrainian Green-Coal Paradox'.

70 Cooperation for Restoring the Ukrainian Energy Infrastructure Project Task Force, 'Ukrainian Energy Sector Evaluation and Damage Assessment X'.

In 2020, Ukraine produced 12.75 million tons of oil equivalent (mtoe) in coal and peat. Some 11.04 mtoe were imported, as shown in Figure 13.[71] About 60% of the coal imports in 2020 originated in Russia.[72] In 2021, Ukraine imported USD 2.09 billion worth of coal briquettes, making it the twelfth-largest importer in the world. Moreover, coal briquettes were the fifth most imported product in Ukraine.[73] The data shows the high dependency on imports from Russia within the coal sector. During the war of aggression, coal imports decreased dramatically – imports from Russia dropped to zero in March 2022 (see Figure 14).

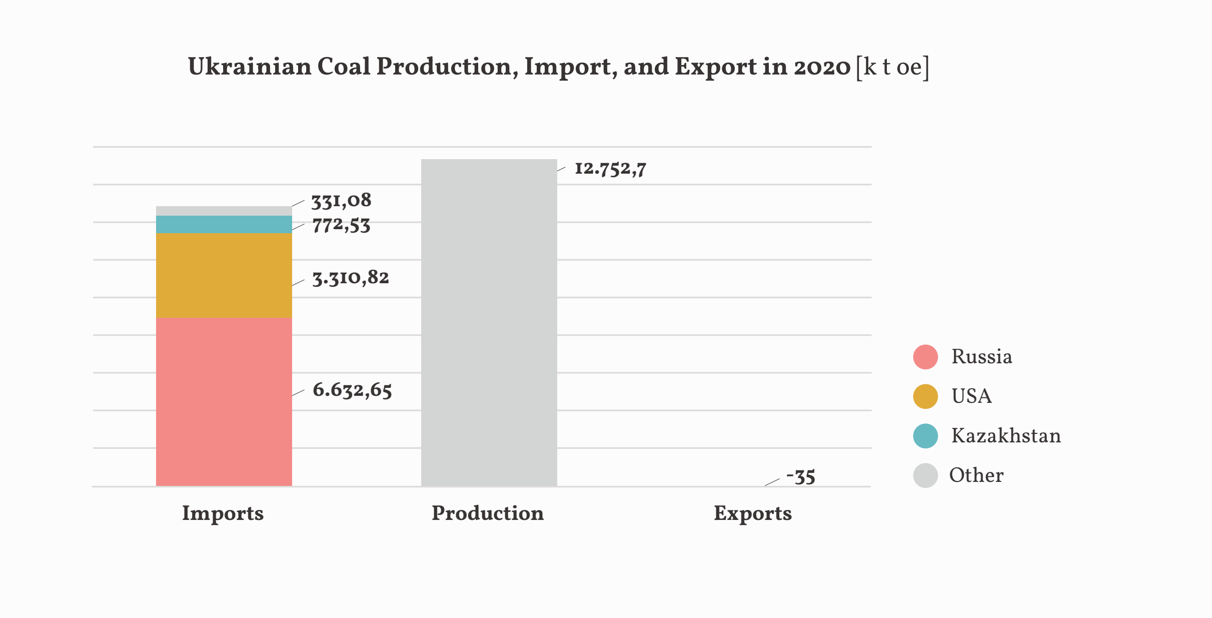

Figure 13: The production, import, and export of coal in Ukraine in 2020 in thousands of tons of oil equivalent
Source: Own illustration, based on State Statistic Service of Ukraine, 'Energy Balance of Ukraine'.

71 State Statistic Service of Ukraine, 'Energy Balance of Ukraine'.

72 The Coal Hub, 'Ukraine's Coal Imports down 67% in Jan-Aug 2022'.

73 Observatory of Economic Complexity, 'Ukraine Profile'.

Figure 14: Ukraine's coal imports from January to September 2022 in thousands of tons
Source: The Coal Hub, 'Ukraine's Coal Imports down 67% in Jan-Aug 2022'.

Another important topic is the coal industry as an employer and economic factor. According to Low Carbon Ukraine, around 40,000 people are currently employed in state-owned mining companies, many of them in sectors linked to the coal industry. Ukraine's largest employer, DTEK, is part of the sector and employs some 70,000 workers. Aurora Energy Research estimates that a coal-phase out would lead to a loss of around 55,000 jobs in mining and power generation.74 Since the largest proportion of the coal consumed in Ukraine in 2021 was used in blast furnaces and coke plants for iron and steel production, a coal phase-out without a transitional plan would have knock-on effects well beyond the coal mining industry. Coal also makes up the second-largest share of Ukraine's electricity production (23.2%) after nuclear power.[75]

At the same time, employment in Ukraine's coal industry is precarious. Low Carbon Ukraine underlines that coal mines in Ukraine, in particular in the Donbas, are some of the most dangerous in the world, with one million tons of extracted coal being paid for by 2.5 miners' lives, on average. Due to complicated mining conditions and the fact that operations have an average depth of 900 meters, there are frequent methane explosions, coal dust explosions and rock bursts, placing some 75% of Ukrainian coal mines in the highest-risk group. Furthermore, infrastructure and equipment are outdated and lead to poor labor safety conditions. Since Ukraine's independence, up to 4000 Ukrainian miners have died in 40 major accidents.[76] Furthermore, energy production from coal in state-owned coal mines suffers losses of up to €230 per ton of coal extracted. Shutting down these mines would reduce the mine-related costs borne by the state by 35%, even when accounting for decommissioning costs and compensation for the workforce. In its study, Aurora Energy Research estimates that more than a billion euros

74 Probst et al., 'The Economic Implications of Phasing out Coal in Ukraine by 2030'.

75 State Statistic Service of Ukraine, 'Energy Balance of Ukraine'.

76 Zachmann and Unterschütz, 'Low Carbon Ukraine, Policy Advice on Low-Carbon Policies for Ukraine', 7.

would be necessary to sustain the state-owned coal mines in the coming 10 years.[77]

In June 2023, Ukraine's government committed to a coal phase out by 2035 (for state-owned plants) and 2040 (for the whole country). Earlier, during the COP26 in Glasgow, Ukraine had already joined the Powering Past Coal Alliance (PPCA), an international coalition that aims to secure government and private sector commitments for the coal phase out. Moreover, the country's largest private energy company, DTEK, joined PPCA with 2040 as its coal phase-out date.[78]

A successful coal phase-out will require that coal mines and plants that are shut down be offset by the generation of renewable electricity and heat. This will require a mix of renewable-energy sources (more information is available in section 1.2.1 Renewable Energy), which will in turn require the transmission and storage systems to be adjusted to decentralized, intermittent generation (this is discussed at greater length in sections 1.3 Electricity Transmission and Distribution and 2.4 Energy Storage).

1.2.5.1. Phase 1

Considering the plan to phase out coal in just over ten years, **reconstruction of damaged infrastructure related to coal extraction or coal-based energy generation should be kept to only the most efficient sites.** Efforts should focus scheduling the coal phase-out and on creating a comprehensive **just transition strategy** for coal mining regions as well as the manufacturing sectors and electricity generation that depend on coal.

A successful coal phase-out will need to be based on a thorough **assessment of all operational coal-based energy generation plants.** Their overall condition, economic viability, their ability to provide balancing for the electricity grid, and other factors will determine how long the plants will be kept operational. A comprehensive **decommission strategy** including dates for shutting down individual plants will provide stakeholders with a clear picture and help them prepare for the upcoming transition phase.

At the same time, the strategy should initiate **planning processes which aim to reduce coal consumption** in industries such as iron and steel production and electricity generation. These industries should explore alternative energy sources and technologies as part of their long-term strategies.

To support the coal-phase out, decision makers should draw on the expertise of experts, stakeholders, and representatives from the impacted communities. They should be members of a dedicated **just transition commission** responsible for drafting a comprehensive plan for the transition in regions and sectors affected by coal phase-out. This plan can include strategies for education, job retraining, and employment support tailored to the needs of affected regions and sectors as well as empowering local communities and industries to actively participate in and contribute to the transition.

To ensure the successful implementation of the coal phase-out, the government will need to allocate **sufficient funding** for education, employment, and economic development initiatives in the affected regions while also putting in place checks to prevent decisions that could lead to lock-in effects impeding the coal phase-out in the medium and long term.

77 Probst et al., 'The Economic Implications of Phasing out Coal in Ukraine by 2030'.

78 Powering Past Coal Alliance, 'Amid War, Ukraine Recommits to Phasing out Coal Power by 2035, Press Releases'.

1.2.5.2. Phase 2

In the pursuit of a successful and sustainable energy transformation, it is crucial to **uphold the established dates for the coal phase-out**. Maintaining these timelines or even accelerating them, where possible, is fundamental to reducing reliance on fossil fuel and reducing emissions.

To seamlessly transition away from coal, a **shift to renewable energy sources** is imperative. This transition involves substantial investments in renewable infrastructure and requires the **reconfiguration of transmission and distribution grids** to effectively integrate these new sources of energy into the existing systems. This process also needs to encompass a thorough **assessment of technologies capable of assuming the grid-related functions previously fulfilled by coal power plants**, e.g., advanced energy storage systems.

Moreover, it is vital to intertwine the coal phase-out with **increased production of hydrogen** or other clean energy-carriers that can replace coal in the production of steel and iron. To incentivize the decarbonization of industrial practices, establishing mechanisms that **promote a market for green steel and iron** is essential.

Incorporating these longer-term recommendations into the coal phase-out strategy positions Ukraine on the trajectory toward a greener and more sustainable energy future. This approach not only mitigates the environmental impact of coal but also establishes Ukraine as a frontrunner in renewable energy adoption and sustainable industrial practices.

1.3. Electricity Transmission and Distribution

Ukraine's grid is operated by the transmission system operator Ukrenergo. The electricity distribution systems consist of over 800,000 kilometers of overhead and cable lines with a voltage of 0.4-150 kV as well as some 200,000 6-150 kV transformer substations. The grids are operated by 32 distribution system operators. Until the full-scale Russian invasion in February 2022, Ukraine's national power grid had been part of the same wide area synchronous transmission grid as Russia (and much of the rest of the former Soviet Union).[79]

Ukraine had been working towards switching to the Continental European synchronous transmission grid since 2017 and was a year away from completing the necessary work when Russia invaded in February 2022. Ukrenergo redoubled its efforts and managed to complete the connection in March 2022.[80] By the summer of 2022, it had established interconnector capacity of around 2,300 MW per hour and was exporting some 500 MW of power per hour to European Union countries.[81]

According to Ukrenergo, from October 2022 to February 2023 Russia launched almost 200 missiles and 46 drones at Ukraine's electricity grid, knocking out 10 GW of generation capacity and 43% of the high-voltage transmission grid. Ukrenergo had to impose rolling blackouts, with up to 12 million people without power at any given moment.[82] From 11 October 2022, Ukraine ceased power exports to Europe due to these attacks and had to import electricity in small volumes from January 2023.[83]

On the large-scale transmission level, by early 2023 Russia had destroyed (or damaged to the point that they had to be disconnected) over 40 overhead lines and over 20 substations with a voltage of 220–750 kV; altogether 40% of controlled transmission substations have been put out of commission. At the distribution level, by early 2023 Russian attacks had resulted in the destruction or inactivation of more than a thousand overhead lines (6-150 kV) and more than eight thousand transformers (6-150 kV); this excludes the electrical infrastructure that was disconnected, usually temporarily, due to emergencies. At the same date, 12% of transmission substations were located in territories occupied by Russia.[84]

By February, Russia had exhausted much of its stock of missiles, while Ukraine had managed to keep its grid functional – by April, it was back to exporting electricity again. This was achieved through what appears to have been careful forward planning involving the preparation of replacement equipment and operational redundancies. Ukrenergo prepared emergency plans for every region in the country together with distribution system operators and deployed sandbags for defense against attacks.[85]

Equally important was the herculean repair effort, with services reportedly restored three to four times faster than under normal circumstances despite the scale of the damage. Finally, techniques to preserve system balance despite local failures appear to have been put in place, including procedures that allow the grid to function as a number

79 Cooperation for Restoring the Ukrainian Energy Infrastructure, 'Ukrainian Energy Sector Evaluation and Damage Assessment IV'.

80 Walton, 'After Months of Russian Attacks, Ukraine's Grid Resumes Electricity Exports to EU'.

81 Cooperation for Restoring the Ukrainian Energy Infrastructure, 'Ukrainian Energy Sector Evaluation and Damage Assessment IV'.

82 Walton, 'After Months of Russian Attacks, Ukraine's Grid Resumes Electricity Exports to EU'.

83 Cooperation for Restoring the Ukrainian Energy Infrastructure, 'Ukrainian Energy Sector Evaluation and Damage Assessment IV'.

84 Cooperation for Restoring the Ukrainian Energy Infrastructure.

85 Walton, 'After Months of Russian Attacks, Ukraine's Grid Resumes Electricity Exports to EU'.

of independent islands, preventing collapse if one island is knocked out.[86]

Before the full-scale Russian attack, Ukraine had 17.7 million consumers of electricity, of which 500,000 were commercial customers. By early 2023, electricity production had decreased by a quarter while demand had dropped by 30-35% and shifted massively due to the displacement of people from the east of the country to the west, as well as the disappearance or shutdown of economic activity. Hundreds of settlements and more than half a million people remain without electricity, and millions more have only partial access or are on capacity-limiting schedules, in early 2023.[87]

1.3.5.1. Phase 1

Once the hostilities cease, Ukraine will need to immediately shore up and reinforce the **basic physical power transmission and distribution infrastructure.** No major refurbishments or investments should be made, however, until it is clear which parts of the grid will no longer be needed as the power system evolves toward a greater share of renewable energy in the medium term. This assessment should also include an analysis of the **potential of a smart and decentralized grids** (e.g., to boost resilience) and should lead to a strategy that will guide Ukraine towards building a better transmission infrastructure.

1.3.5.2. Phase 2

Based on the initial assessment from Phase 1, Ukraine should start to plan and build its **future transmission infrastructure.** These plans should be developed in parallel with the broader strategies for the coming expansion of – mostly intermittent – renewables. Measures including ramping up digitization and **advanced grid management**, creating **demand-side flexibility**, integrating **energy storage** (see section 2.4) as well as taking steps towards more **interconnectivity** and regional grid integration will be essential to ensure grid reliability, maximize energy utilization, and support the integration of renewable energy sources into the energy mix. Where higher capacities for new power plants or new interconnections with neighboring states are required, existing lines can be **reconductored** to increase their capacity, or new ones can be built with advanced **high-performance new materials**. Another major cross-cutting priority for the planning and development of grids should be **energy efficiency** (see section 2.5).

86 Walton.

87 Cooperation for Restoring the Ukrainian Energy Infrastructure, 'Ukrainian Energy Sector Evaluation and Damage Assessment IV'.

1.4. Energy Markets, Imports and Exports

This section looks at the main energy markets – electricity, oil, and gas – in Ukraine, a broad topic which is also partly covered in other parts of this study. Ukraine's energy transformation will require a market that can attract capital, foster healthy competition with other countries and enable a massive buildout of renewable energy, among other things by facilitating trade and storage to manage intermittent generation (see also the findings from the expert survey in the annex under Obstacles in the Deployment of Renewable Energy Sources). The fact that electricity can be difficult to store and transport (especially in the case of non-physical energy carriers), and that production must correspond to consumption in any given time unless large-scale storage or trade channels are available, often leads to substantial and rapid fluctuations in price. This is reflected in the relative complexity of energy trading, and substantial unpredictability, especially between current and future prices. These issues are raised in the expert survey as well, and analyzed in the relevant section of this study.

1.4.1. Electricity Market

A series of reforms were completed by mid-2019 to meet Ukraine's Association Agreement commitment to implement the EU Third Energy Package, and the country successfully switched to a competitive power market structure with bilateral contracts, day-ahead, intraday, balancing and ancillary services markets at that time. Most thermal power plants had undergone some degree of privatization since the 1990s (although, illustrating the halting and incomplete nature of the process, a single private company – DTEK – now controls most of the market). Most distribution system operators and electricity supply companies today are privately owned by domestic or foreign investors. Nuclear power plants remain under state ownership through the company Ukrenergoatom, however, and Ukraine's state-owned national electricity company Ukrenergo still owns and operates the UnitedEnergy System of Ukraine (UES), including transmission networks and interconnections with neighboring countries.[88]

The more competitive market structure adopted in July 2019 still maintains certain trading restrictions and price caps which clash with the European legal requirements for a fully free market (see the relevant section in the preliminary legal study). The electricity market also remains highly concentrated on both the supply and demand sides, leading to manipulations and inefficiencies. Remedying this, adopting the relevant acquis communautaire, and coupling with the European market would give Ukraine access to a reliable electricity supply and enable it to take a further step towards EU membership. The Ukrainian electric system has been synchronized with the synchronous grid of Continental Europe since February 2022 and the country is now an observer in ENTSO-E; it can become a full member once it switches to a European model.[89]

As of 2019, Ukraine's power market is divided into the following four segments: a bilateral contract market, a day-ahead market, an intraday market, and a balancing market. Since February 2022, the entire non-occupied area of the country is a single bidding zone.[90] Ukraine imports and exports relatively little electricity, with exports and imports in 2021 standing at USD 241 million and $218 million, respectively.[91]

The transition from the Soviet economic system and the Russian invasion have had profound and unique effects on Ukraine's electricity consumption patterns. Grid losses are substantially higher than in the EU (see also chapter 2.5 Energy Efficien-

88 Cahill and Dawes, 'Developing Renewable Energy in Ukraine'.

89 Cahill and Dawes.

90 Cahill and Dawes.

91 Observatory of Economic Complexity, 'Ukraine Profile'.

cy), and import and export are lower, proportionately. There is also a higher resource concentration, with nuclear and coal representing comparatively high shares of electricity production. For at least a decade starting in 2009, Ukraine experienced a swift expansion of renewable electricity production driven by the adoption of a guaranteed buyer model with a very generous feed-in tariff. This expansion of intermittent renewable power has been balanced by coal-fired plants rather than nuclear (which is less flexible), leading to a "green-coal" paradox. In 2020, intermittent renewable power generation capacity was more or less equal to dispatchable capacity, implying difficulties for future balancing of renewables.[92]

A number of trends contrary to those seen in the rest of Europe are taking place in Ukraine and causing higher electricity prices: energy efficiency is decreasing due to physical wear and tear on conventional power plants, while the share of co-generation is dropping due to the ageing of combined heat and power plants and reduction in demand for district heating and industrial heat.[93]

In its annual report for 2021, the Energy Community noted both improvements and stagnation in Ukraine's progress in the implementation of a European electricity market model. The main problems identified were:[94]

- frequent regulatory interventions
- restrictive price caps and regulated prices set by state-owned companies
- trading restrictions on market players and special bilateral auctions for some consumers
- non-compliant public service obligations and the absence of defining vulnerability criteria
- high debts in the balancing market

In the coming years, Ukraine will continue to bring its electricity market in line with European norms and legislation. Ideally this will be inspired by practices found in other national electricity markets in the EU. The Ukrainian electricity market is likely to be integrated into ENTSO-E, potentially fostering more cross-border electricity flows.

1.4.1.1. Phase 1 and 2

Substantial efforts should be directed towards rebuilding and **strengthening critical institutions and infrastructures** after the war. This involves modernizing and reinforcing the electrical grid, enhancing transmission and distribution capacities, and empowering regulatory entities to ensure a robust and resilient electricity market. Parallel to reconstruction, Ukraine should create a **future-proof market scheme** aligned with EU regulations that also incentivizes the integration of renewables, the dissemination of energy storage solutions and demand-side flexibility measures as well as the pursuit of energy efficiency. Please refer to the corresponding legal report for further information and a comprehensive set of recommendations.

92 Cahill and Dawes, 'Developing Renewable Energy in Ukraine'.

93 Cahill and Dawes.

94 Energy Community Secretariat, 'Annual Implementation Report 2021'.

1.4.2. Gas Market

As with most other types of energy, the level of gas consumption has been falling in Ukraine throughout the post-Soviet period. This has been due to economic transformation and increases in energy efficiency, as well as repeated attacks from Russia. While industrial production is again likely to expand in the coming years, the other two factors mean that a major net increase in the demand for gas is unlikely, unless the government puts in place a strategy to promote the deployment of gas to balance increases in intermittent renewable generation capacity.[95]

In 2021, Ukraine exported USD 49.1 million and imported $2,390 million of natural gas in gaseous state. This was the country's second most important import after refined petroleum products. In the same year, the country exported $79.1 million and imported $3,260 million of petroleum gas, its third most important import. Both products officially originated mainly in Switzerland and Hungary.[96] In practice, imports consist almost entirely of Russian gas brought in through reverse flow from western neighbors.[97] Better connections with neighbors – mostly to the west, but also to the Trans-Balkan pipeline through Moldova and Romania – have facilitated reverse flows and helped integrate Ukraine's large gas storage capacities into the European market. At the same time, the country's transit business is in steep decline. In the first nine months of 2020, the state-owned company in charge of transit moved 39.5 billion cubic meters of Russian gas to Europe, 40% down on 2019. This is due both to the slump in European demand and Gazprom avoiding using Ukraine as a transit route unless completely necessary.[98]

Ukraine has the largest underground gas storage capacity in Europe, with 13 sites providing a working capacity of 30.9 billion cubic meters. Much of this can be marketed to governments and traders in the rest of Europe. The United States government has already provided political risk insurance to certain private players to use these facilities. Underground gas storage is having a renaissance since the gas crisis in 2022, which made it clear that spot gas and liquid natural gas could not always respond quickly to large swings in demand.[99]

In the two-three years before Russia's all-out assault in February 2022, Ukraine implemented market reforms that were leading to a deeper, more liquid wholesale market, with prices increasingly correlated to European ones. Sales to households and sales to the heating sectors (which account for half the gas consumed in Ukraine) are no longer covered by a public service obligation. The government will need to take strong action to foster and encourage energy efficiency measures such as building insulation and electrical alternatives for household heat.[100]

Between 2014 and 2019, Ukraine implemented reforms to bring its gas market in line with the European Union's third energy package. As with the electricity grid, the gas system was unbundled, separating transmission from supply, and new rules were introduced to liberalize gas prices for households and industry and to enable third parties to take part in transmission, storage and distribution. The state-owned company Naftogaz underwent its own liberal reforms increasing transparency. These reforms, which went into force in 2020, were partly reversed after the 2022 invasion. The Secretariat of the Energy Community proposed in its 2022 implementation report that the most vulnerable gas consumers could be protected while the bulk of the reforms was implemented once more.

95 Pirani, 'The Ukrainian Gas Sector to 2030'.

96 Observatory of Economic Complexity, 'Ukraine Profile'.

97 Pirani, 'The Ukrainian Gas Sector to 2030'.

98 Pirani.

99 Cahill and Palti-Guzman, 'The Role of Gas in Ukraine's Energy Future'.

100 Pirani, 'The Ukrainian Gas Sector to 2030'.

1.4.2.1. Phase 1 and 2

Similar to the measures recommended for the electricity market, Ukraine should pursue an integrated strategy for its gas market. Modernizing and gas transmission and distribution networks, along with empowering regulatory bodies, should be a priority. Furthermore, Ukraine should design a **market scheme** that adheres to EU regulations and that encourages energy efficiency as well as the overall integration of renewable energy sources and innovative energy carriers such as hydrogen.

1.4.3. Oil Market

As with other energetic resources, Ukraine has substantial oil reserves and a long tradition of oil production but has historically been an oil importer. In early 2022, the country was still receiving most of its oil from Russia and has had to switch to other sources very quickly, without the required infrastructure being in place. This initially led to a substantial jump in price for consumers.[101]

The largest oil-producing company, Ukrnafta (taken over by the government under wartime law), appears to be planning to redevelop 20 mature oil brownfields which have been out of operation but still have viable reserves. This is meant to cover more of the country's oil needs and substitute for imports. The large-scale capital investment required (around a billion US dollars per year) would mostly or entirely need to be covered by international investors.[102]

In 2021, Ukraine exported USD 191 million and imported $5,630 million of refined petroleum products (of which $3,370 million directly from Russia and Belarus). This made refined petroleum the country's largest import. Ukraine also exported $27.6 million and imported $547 million of crude petroleum in 2021, with Azerbaijan, Libya and the United Kingdom as the largest sources.[103]

1.4.3.1. Phase 1 and 2

For its oil market, Ukraine should adopt a dual approach that aims to secure a stable energy supply while paving the way for transformation. **Maintaining the operational capability** of existing oil infrastructure and institutions should be accompanied with comprehensive efforts to **transition towards alternative energy carriers**, such as hydrogen-based fuels and biofuels, as these will require a similar set of institutions and infrastructure in the future. By striking this balance between sustaining current operations and fostering innovation, Ukraine can safeguard its energy security and contribute to a cleaner and more diversified energy landscape.

101 McCormick, 'Naftogaz Held Talks with Big US Oil Groups about Ukraine Energy Projects'.

102 McCormick.

103 Observatory of Economic Complexity, 'Ukraine Profile'.

2. The Future Pillars of Ukraine's Energy System

This section provides an overview of the pillars of Ukraine's future energy market, including technologies involved in producing renewable energy and renewable energy carriers such as hydrogen, energy transmission and storage, and energy efficiency.

Ukraine's current total installed power generation capacity is around 60 GW, of which 6.5 GW is renewable (see Figure 6). Some 3-4 GW of energy could be exported today if power infrastructure were in a normal state.[104] The carbon dioxide intensity of electricity production in Ukraine in 2021 was 240.18 grams of carbon dioxide equivalent (gCO_2e) per kWh. The equivalent figure for the EU's electricity production was 277.33 gCO_2e/kWh.[105]

Ukraine's power system is characterized by a low level of flexibility and has been called one of the most inflexible national power systems in the world.106 This is due to the significant share of basic capacities that have not been designed for frequent and rapid changes in operating modes. The existing capacities to balance the system (mainly thermal power plants) have already exhausted their park capacity.107 A map of the power plants in Ukraine is shown in Figure 15.

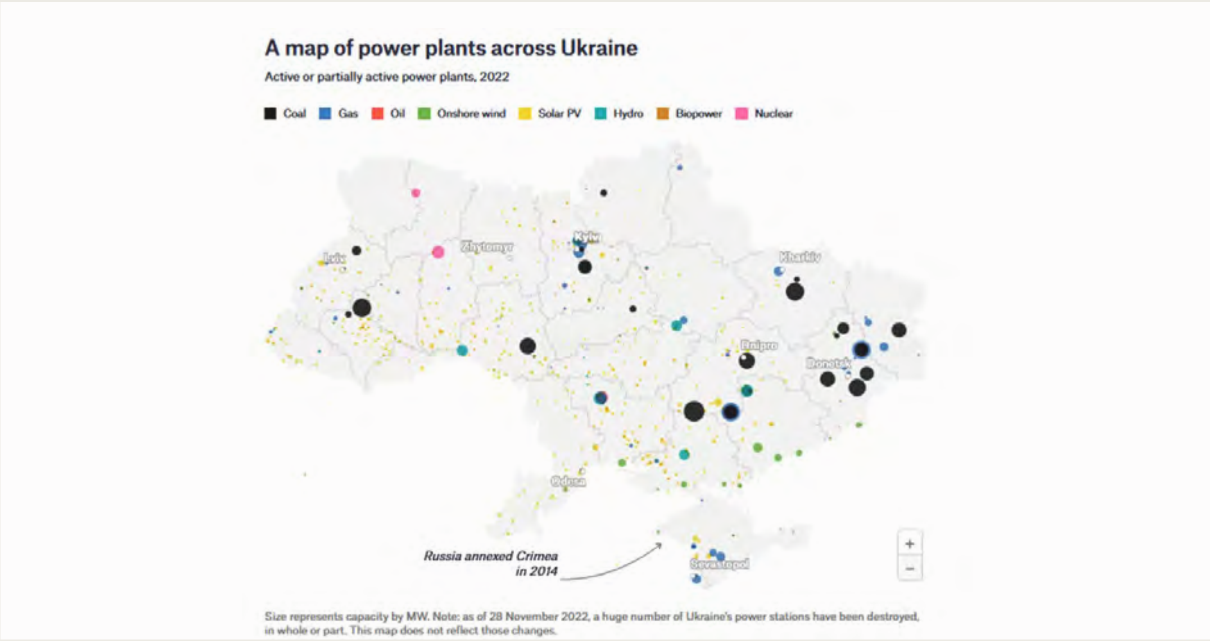

Figure 15: Power plants throughout Ukraine
Source: Keating, 'Can Solar Power Ukraine's Recovery?'

104 Timchenko, 'Help Ukraine Now, and It Could Power Europe Later'.

105 Ember, 'A Green Recovery Can Place Ukraine at the Forefront of the Clean Power Transition'.

106 Wärtsilä Energy Solutions, 'Flexibility to Future-Proof the Ukrainian Power System: Solving the Ukrainian Green-Coal Paradox'.

107 Konechenkov et al., 'Вітроенергетичний Сектор України 2021'.

2.1. Renewable Electricity

The development of the renewable electricity sector is crucial for any activity that aims to decarbonize Ukraine's economy. As mentioned above, Ukraine's renewable electricity sector has been developing rapidly, with the share of renewable sources in electricity supply increasing from 1.7% in 2007 to 6.6% in 2020, or around 5.7 million tons of oil equivalent.[108] At the beginning of 2022, total installed renewable capacity connected to the grid amounted to 9.5 GW (excluding 0.6 GW of capacity in areas occupied by Russia before February 2022). In February 2023, the Ukrainian Energy Minister Herman Galushchenko announced that 90% of electricity should come from carbon-free sources (including nuclear energy) by 2050.[109] According to some sources, Ukraine's potential renewable energy generation capacity is as high as 874 GW (see Figure 16).[110]

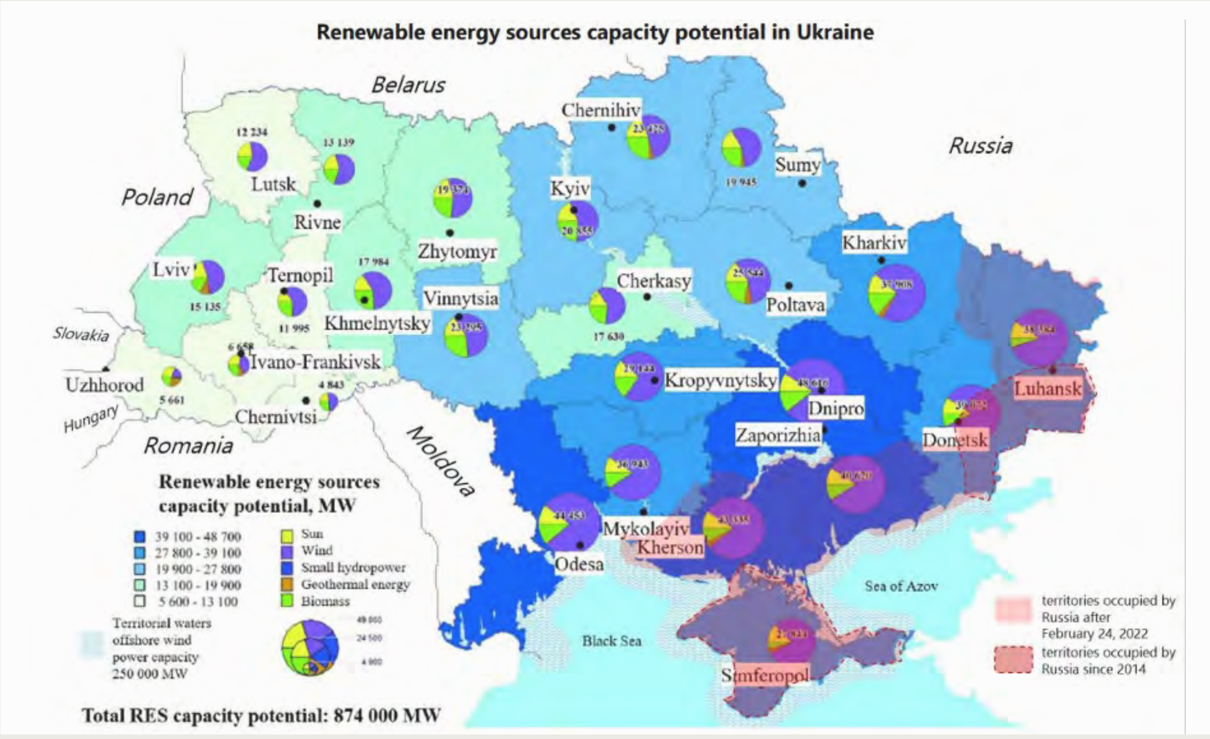

Figure 16: Renewable energy potential in Ukraine sorted by source in 2022
Source: Cooperation for Restoring the Ukrainian Energy Infrastructure Project Task Force, 'Ukrainian Energy Sector Evaluation and Damage Assessment II'.

Before the war, Ukraine planned to have 25% of renewable energy in the energy mix by 2035.[111] About USD 12 billion has been invested in the Ukrainian renewables sector during 2009-2021. Since 2009, the government has provided support through a guaranteed feed-in-tariff. This system

108 State Statistics Service of Ukraine, 'Energy Consumption from Renewable Sources for 2007-2021'.

109 Belousova, 'Міністр Енергетики Заявив, Що Україна До 2050-Го Вироблятиме 90% "Чистої" Енергії'.

110 Popov, 'How Ukraine Could Be Key to EU Clean Energy Ambitions'.

111 Cahill and Dawes, 'Developing Renewable Energy in Ukraine'.

did not work well and led to a great deal of debt, leading to reforms in 2019.[112]

The geography of renewable energy facilities in Ukraine is varied and corresponds to the natural potential of various regions. Wind power plants are located mainly in the southern and south-eastern regions, with about 85% on the coast of the Black and Azov Seas; solar generation is more evenly distributed, but about 60% of industrial solar power plants are also located in the country's south and southeast.[113] As of mid-2023, 35% of renewable power generation capacity is located in the occupied territories and 4% is inoperable.[114]

2.1.3.1. Phase 1 and 2

To expand overall renewable energy adoption, Ukraine will need to pursue a multi-faceted approach. **Streamlining legislation** by creating a clear and consistent regulatory and planning framework is essential for fostering renewable energy development. **Robust financing schemes**, including incentives, subsidies, and attractive financing options, will be needed to encourage private investment, and reducing financial barriers. **Improving coordination** of all stakeholders to initiate renewable energy projects and improve implementation speed will be equally important. This last issue can by addressed by creating a Ukrainian Energy Agency for Renewables, coupled with regional agencies that can accelerate the planning and approval process for new renewable plants.

More detailed insights and specific recommendations can be found in the following sections dedicated to individual renewable-energy sources as well as the preliminary financial and legal studies published in conjunction with this report.

2.1.1. Onshore Wind

In 2021, wind power in Ukraine had a capacity of 358.8 MWp and produced 30.6% of total green electricity. It is the second biggest source of renewable energy after solar.[115] Before the full-scale Russian invasion, the country counted 34 wind farms, mainly in the south and southeast, with around 85% situated on the Black and Azov Sea coasts (see Figure 17).[116] Wind power produced 3,866 GWh of green electricity, which is enough to meet the annual electricity consumption of around 650,000 households with a monthly consumption of about 500 kWh.[117] At the beginning of 2022, Ukraine's total installed capacity of wind power plants, mostly located in the Kherson and Zaporizhzhia regions, was 1.6 GW; this excludes the 0.2 GW located in territories already occupied by Russia at that time.[118]

As shown in Figure 16, wind is a highly promising source of renewable energy in the mix for Ukraine. According to a study by the Centre for European Policy Studies, the country's territory has capacity for as much as 320 GW of onshore wind energy.[119] (This is over five times the current 60 GW of power generation built in Ukraine.) The regions with the highest wind energy potential are Dnipro, Kherson, Zaporizhzhia, Odesa, Crimea, Mykolaiv and Luhansk. Steppe zones are best suited because of

112 Stiewe and Spiekermann, 'Analyse: Die Förderung erneuerbarer Energien in der Ukraine'.

113 Razumkov Centre, 'Сектор Відновлюваної Енергетики України До, Під Час Та Після Війни'.

114 Omelchenko, 'Ukraine's Renewable Energy Sector before, during and after the War'.

115 Omelchenko.

116 Omelchenko.

117 Konechenkov et al., 'Вітроенергетичний Сектор України 2021'.

118 Cooperation for Restoring the Ukrainian Energy Infrastructure Project Task Force, 'Ukrainian Energy Sector Evalua-tion and Damage Assessment X'.

119 Kustova and Egenhofer, 'How Black Sea Offshore Wind Power Can Deliver a Green Deal for This EU Region'.

strong winds in both cold and warm seasons, and compensating local winds in between. Furthermore, these areas in Ukraine already have good infrastructure for logistics, because of existing harbors and freeways. Mountain terrain and woods are less suitable for wind parks, because they are logistically harder to reach and the wind currents can be distorted.[120]

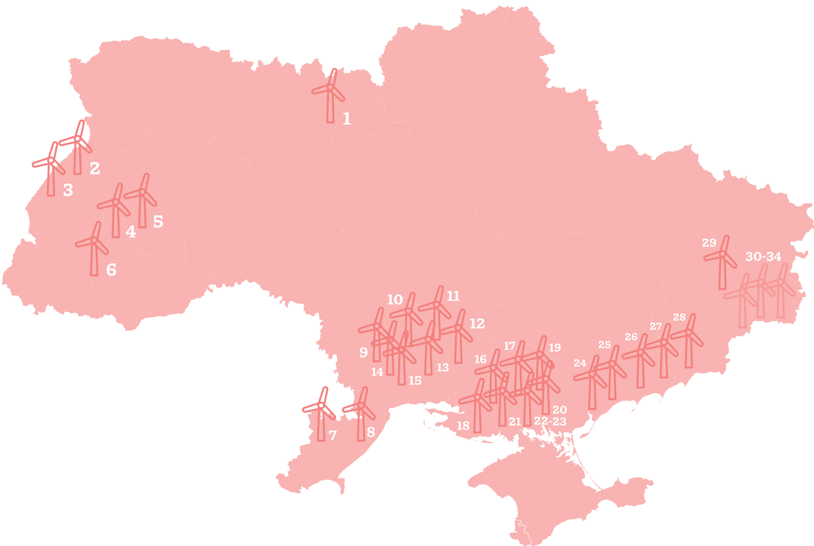

Figure 17: Wind turbines and wind parks located in Ukraine in 2021
Source: Razumkov Centre, 'Сектор Відновлюваної Енергетики України До, Під Час Та Після Війни'.

Russia's attack has had a disastrous impact on Ukraine's wind energy sector. The Ukrainian Wind Energy Association reports that 75% of the total installed wind capacity was offline and at least 10 wind turbines are damaged (the exact number is unclear since most wind farms are located in occupied territories). It is assumed that direct losses due to destroyed and stolen equipment are more than €50 million and there is an additional indirect shortfall of €500 million due to plants in the occupied territories being inoperative. The war also negatively affected the development and construction of wind projects which would otherwise have added a capacity of around 300 MW.[121]

120 Kudria, Атлас Енергетичного Потенціалу Відновлюваних Джерел Енергії України.

121 Ukrainian Wind Energy Association, 'News'.

2.1.1.1. Phase 1

Ukraine has an opportunity to foster the development of onshore wind power through a series of strategic measures. An essential step is conducting a **comprehensive assessment of onshore wind energy potential** across every region. This assessment will pinpoint areas with optimal conditions for rapid onshore wind energy deployment for the purpose of accelerated permitting and planning, often referred to as "go-to areas." Identifying and prioritizing such regions can streamline future development efforts.

To further bolster onshore wind energy generation, Ukraine should consider the development of instruments that **facilitate project development**. These may include the creation of a publicly accessible wind atlas – a comprehensive handbook offering information on suitable areas, wind conditions, and power generation potential. Accessible data of this nature can facilitate informed decision-making for investors and developers, catalyzing the growth of the wind energy sector. (The development of wind power should of course not be contingent on the existence of such a handbook, which is merely meant to facilitate.)

Another critical factor is the **evaluation of permitting procedures and administrative workflows** to expedite project development. Simplifying and streamlining these processes can reduce project lead times and attract more investments into the onshore wind industry. The preliminary legal study contains more information on this topic and a full set of recommendations.

Moreover, Ukraine can expedite wind energy growth by **initiating onshore wind projects on state-owned land**. Leveraging these resources can serve as a fast-track approach to boosting wind energy generation and overall capacity.

In parallel, it is essential to consider measures that **enhance local acceptance** of onshore wind projects. Drawing inspiration from successful practices in EU countries, Ukraine could explore the creation of schemes for local buy-in, such as energy cooperatives. Additionally, the implementation of local taxes or other benefits for affected municipalities, such as reduced energy costs, can foster goodwill and cooperation, aligning community interests with the expansion of onshore wind power. These collective efforts hold the potential to drive significant progress in Ukraine's onshore wind energy sector.

2.1.1.2. Phase 2

To enhance the integration and expansion of onshore wind energy after the reconstruction phase, Ukraine should follow a comprehensive approach. Firstly, it will be critical to conduct a thorough assessment of the impacts of increased renewable energy generation on the transmission system at an early stage. This assessment should serve as a basis for creating a **national grid development plan**, outlining the needs of the transmission system.

In parallel, it is imperative to establish clear and **effective guidelines for environmental protection measures** (many of which can be copied as best practices from other countries) linked to the installation of new wind turbines. Adhering to EU standards while maintaining speed in permitting procedures is crucial. Learning from successful models, such as the German or Spanish approaches, can provide valuable insights for the development and adoption of these guidelines.

Facilitating a **conducive regulatory and financial framework** is equally vital to ensure a swift, efficient, and cost-effective expansion of wind energy. Streamlining regulatory processes and providing financial incentives can significantly accelerate the growth of the wind energy sector, attracting investments and fostering a sustainable energy landscape.

Moreover, Ukraine should assess the supply chain for wind turbine production to find out, which components can be produced within Ukraine itself. Based on these findings, a comprehensive strategy should be formulated to establish a **Ukraine-based industry for renewable power plants and related services**. This strategic move can contribute to the growth of the local economy and the creation of a self-sufficient renewable energy sector.

2.1.2. Offshore Wind

The main advantage of offshore wind turbines is higher and more constant wind speeds at sea, which results in a more efficient and therefore higher-yield electricity production. They also have less impact on people and landscapes and thus have higher acceptance among populations. Turbine foundations can also be used as artificial reefs with a positive impact on marine biodiversity. On the flipside, wind turbines are more expensive to build offshore than onshore, as they are exposed to strong forces like storms, waves, and salt water, which makes offshore wind parks more maintenance intensive. Furthermore, accessibility for construction and maintenance is particularly difficult and dangerous and therefore more expensive than for onshore wind power plants.[122] Even so, global costs for offshore wind generation have decreased massively in the last decade: according to the data company BloombergNEF, the levelized cost of electricity for offshore wind in Europe in 2022 was USD 0.099-0.175 per kilowatt-hour, well above other renewable energy sources but clearly competitive with nuclear, gas, and, especially, coal.[123]
There are currently no offshore wind farms in Ukraine, but the country has great offshore wind power potential, thanks to the shallow waters of the Azov and Black Seas, the Dnipro cascade, the Dnister reservoir, Sivash Bay, and other water areas that allow for economically viable installation of offshore turbines.[124] According to the World Bank, the country may have some 251 GW of potential capacity in offshore wind, of which 183 GW fixed and 68 GW floating.[125] (Ukraine's total installed power generation capacity today, renewable and fossil, is some 60 GW.)[126] The Ukrainian Wind Energy Association envisions a significant boost in wind power capacity by 2030, including a contribution of 1 TWh in electricity production through offshore wind farms, which should have an installed capacity of 300 MW in that year.[127]

2.1.2.1. Phase 1 and 2

To unlock Ukraine's considerable offshore wind potential, a series of recommendations – most of which are similar to the recommendations for onshore wind (see previous section) – should be considered.

The key differences between onshore and offshore wind projects lie in the implementation, which is notably more technically demanding for the latter due to the necessity for high-capacity subsea cables and connections leading to onshore landing points. Ukraine's existing expertise in maritime operations, particularly in offshore oil and gas, offers a strong foundation upon which Ukraine can **build an offshore wind industry**. To support this process, Ukraine should conduct a strategic assessment of the existing know-how and infrastructure, the needs of manufacturers and other stakeholders, and it should facilitate joint ventures with companies from EU countries.

Considering the unique challenges posed by the marine environment, environmental protection measures must be robust. Ukraine should adhere to EU standards and regulations while concurrently streamlining permitting procedures. Exploring the possibility of implementing a **maritime planning procedure** specific to wind energy in the Ukrainian

122 Lee, 'Offshore Wind Power Price Plunges by a Third in a Year: BNEF'.

123 BloombergNEF, 'New Energy Outlook 2022'.

124 Yevstihnieieva, Saviytskyi, and Moroziuk, 'Investing in Ukraine's Renewable Energy: The Key to Future Energy Security'.

125 World Bank, 'Offshore Wind Technical Potential in Ukraine'.

126 Chepeliev et al., 'Can Ukraine Go "Green" on the Post-War Recovery Path?'

127 Yevstihnieieva, Saviytskyi, and Moroziuk, 'Investing in Ukraine's Renewable Energy: The Key to Future Energy Security'.

part of the Black Sea can help align environmental considerations with rapid project development.

In addition to domestic efforts, Ukraine should actively assess opportunities for offshore wind generation in **collaboration with neighbouring EU countries** Romania and Bulgaria as well as Moldova and Turkey. Developing a long-term strategy for a meshed-grid approach for the Black Sea, mirroring successful concepts in the North and Baltic Seas, can enhance regional energy security and cooperation.

Lastly, Ukraine should explore the potential for **offshore hydrogen production**, taking inspiration from similar plans from EU countries. Engaging in cooperative ventures with these countries can facilitate knowledge exchange and joint projects, ultimately advancing Ukraine's offshore wind and renewable energy objectives.

2.1.3. Solar Power

The solar sector had the highest growth rate among renewable energy sources in Ukraine during 2019-2021, ranking the country seventh in Europe for expansion of solar generation.[128] At the beginning of 2022, total installed PV capacity reached 7.6 GW or 80% of the total renewable installed capacity in Ukraine; this excludes 0.4 GW located in the territories occupied by Russia before February 2022 and includes 45,000 prosumer installations with a total capacity of 1.2 GW.

From a geographical perspective, Ukraine has a high potential for the production of solar electricity. The average annual amount of total solar radiation ranges from 1070 kWh per square meter in the northern part of the country to 1400 kWh per square meter in the south (see Figure 18). The overall potential of solar electricity production is estimated to be 82,768 MW, with an annual potential of 100 TWh.[129]

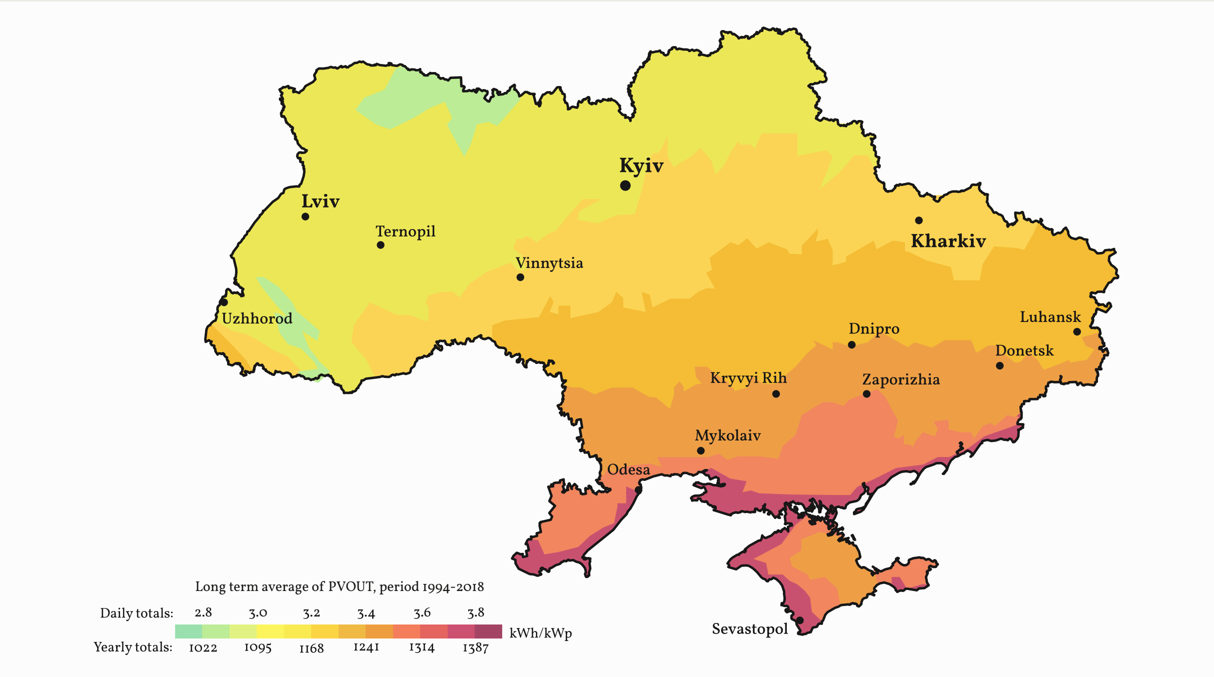

Figure 18: Solar power potential in Ukraine
Source: Solargis, 'Photovoltaic Power Potential Ukraine'.

128 International Renewable Energy Agency, 'Renewable Energy Statistics 2022'.

129 Kudria, Атлас Енергетичного Потенціалу Відновлюваних Джерел Енергії України.

From 2014 to 2020, the production of energy from solar plants has been increasing constantly, and the number of solar plants in operation has been growing from 2017 to 2020. According to Ukraine's State Agency for Energy Efficiency and Energy Saving (SAEE), on 1 April 2020 there were 991 industrial solar plants and 24,139 solar power plants operated by private households. Industrially operated solar plants had an installed capacity of 5,576 MW, while household solar plants accounted for 618 MW. However, the latter increased more significantly, growing 12-fold from 51 MW since 2017 (see Figure 19 and Figure 20).[130]

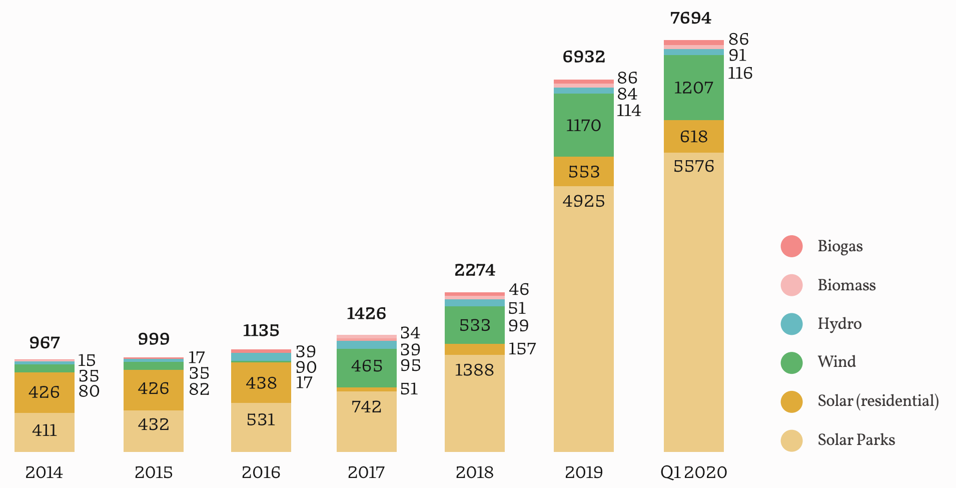

Figure 19: Installed capacity of renewable electricity facilities operating under the "green" tariff in megawatts on 1 April 2020
Source: Own Illustration based on State Agency for Energy Efficiency and Energy Saving of Ukraine, 'Report on the Promotion and Use of Energy from Renewable Sources in Ukraine in 2019–2020'.

130 State Agency for Energy Efficiency and Energy Saving of Ukraine, 'Report on the Promotion and Use of Energy from Renewable Sources in Ukraine in 2019–2020'.

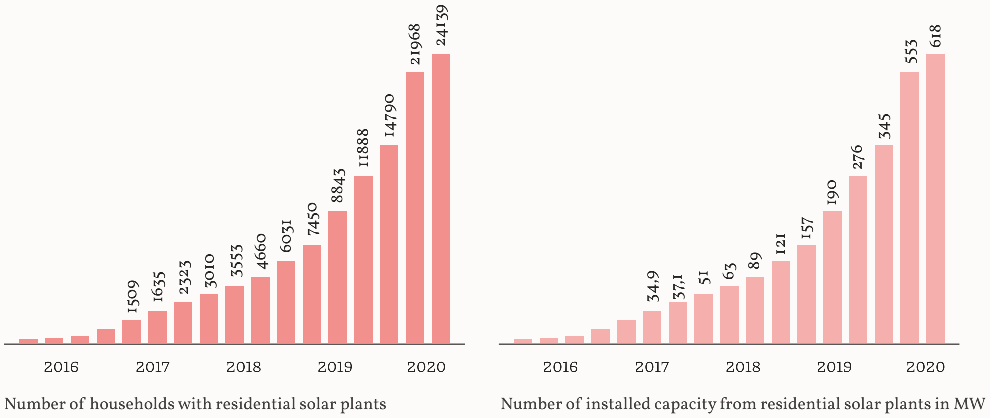

Figure 20: Dynamics of residential solar panels from 2016 to 2020
Source: State Agency for Energy Efficiency and Energy Saving of Ukraine.

The Russian war of aggression has given solar energy pride of place in terms of securing Ukraine's electricity supply. Solar electricity generation helps prevent power outages and protect critical infrastructures such as hospitals, improving resilience.[131] It is not war-proof, however: according to the Ukrainian Association for Renewable Energy (UARE), from March 2022 renewable energy plants have also been at high risk of total or partial destruction. In March 2022, 37% of ground and 35% of roof/facade solar power facilities were located in areas where active hostilities are taking place.[132]

There are a number of solar panel manufacturers in Ukraine. In 2020 the product range covered everything from portable 10 W solar panels up to 390 W modules for solar power plants, as well as other materials, components, and equipment, like batteries, monocrystalline silicon ingots, silicon wafers, solar modules, and sapphire monocrystals. Some of the production is exported to other countries such as the United States, Japan, Germany or China.[133]

131 pv magazine, 'Der Krieg Erhöht Den Einsatz von Solarenergie in Der Ukraine'.

132 UARE, 'Half of Ukraine's Renewable Energy Sector Is Threatened with Destruction Due to Russia's Military Aggression'.

133 Solar Panel Today, 'The Best Ukrainian-Made Solar Panels 2020'; KNESS, 'KNESS PV Will Be Updated for the Solar Modules Production Using the Most Advanced Technologies'; Prolog Semicor LTD, 'Materials and Components for Solar Application'; Kvazar-7, 'Ідеальні Сонячні Рішення'.

2.1.3.1. Phase 1

In Phase 1, Ukraine can embark on a series of strategic measures to advance its solar energy capacity, aligning with the Energy Strategy of Ukraine until 2050, which envisions an eventual increase in installed solar capacity to (a so far perhaps unambitious) 17.5 GW.[134]

During reconstruction, public authorities can set an example and increase renewable generation by **supplying public buildings with solar panels.** Concurrently, providing residents with small solar and storage systems to meet basic energy needs can empower communities and promote decentralized energy production. Adapting the regulatory framework to stipulate requirements for reconstructed buildings to host solar panels is pivotal in creating an environment conducive to solar integration.

Moreover, it is advisable to **maintain the basic structure of the current market design** to continue promoting solar and residential solar plants. Simultaneously, **improving permitting procedures** and creating additional **regulatory incentives** will be essential to expediting solar project development. This phase offers an ideal juncture to **explore innovative concepts like floating** solar on hydropower lakes and combining solar energy with agricultural land use, energy storage, or hydrogen generation. The development of a **handbook for greenfield solar projects** can serve as an additional resource for project developers, streamlining project implementation.

To ensure sustained progress, Ukraine should conduct a comprehensive **assessment of financial and regulatory obstacles** hindering solar energy expansion. Subsequently, measures should be taken to address these challenges, ensuring a conducive environment for solar investments. Leveraging the existing solar industry is critical, and an assessment of local producers' needs can inform a **strategy to bolster local solar panel production**, fostering economic growth and energy self-sufficiency.

2.1.3.2. Phase 2

In Phase 2, Ukraine should build upon these foundations by **adapting regulations to facilitate the construction of medium and large-scale solar parks**, possibly in conjunction with other renewable energy generation sources. This approach optimizes the use of available space and minimizes connection costs.

Additionally, providing regulatory and financial **support for local solar manufacturers**, in compliance with EU legislation, can bolster domestic production capabilities. **Funding research** to improve solar power technology can support the long-term advancement of Ukraine's solar industry.

Developing a robust concept for an **optimal grid integration** of increased solar power capacity is crucial. Measures for managing generation peaks, such as integrating energy storage or power-to-gas technologies into larger-scale solar parks, can enhance grid stability and maximize the benefits of solar energy.

Ensuring **compliance with the EU Taxonomy** and other sustainability standards is paramount for the integrity of solar projects. Furthermore, integrating solar panels and related infrastructure into the circular economy enhances resource and energy efficiency, aligning with sustainability goals.

134 Ukraine's Cabinet of Ministers, 'Energy Strategy of Ukraine until 2050'.

2.1.4. Hydropower

According to the International Hydropower Association, Ukraine had a total installed hydro capacity of 6,317 MW in 2021. A 324 MW unit added to the Dnister pumped-storage plant in 2021 raised the plant's total installed capacity to 1,296 MW and 1,684 MW in pumping mode, but the Kakhovka Dam, with a capacity of 334.8 MW, was destroyed on 6 June 2023.[135] Since 1985, the proportion of electricity produced with hydropower plants in Ukraine has fluctuated between 3 and 10%.[136] According to Andritz, an international technology group which supplies systems, equipment, and services for hydropower, some 60% of the installed hydropower base was built in the 1960s and today requires renovation and rehabilitation.[137]

Given Ukraine's ambitious plans to decarbonize its electricity sector through massive expansion of intermittent renewables, existing hydropower plants are likely to play a major part in keeping power supply stably matched to demand with frequency response ancillary services. Responding to this realization, from 2023 the World Bank is financing a project to equip four existing hydroelectric power plants with new high-power and fast-discharge battery energy storage systems with a capacity of 197 MW. This is planned to be built in combination with 35.9 MW of photovoltaic generation capacity to ensure backup power when water levels are low and to serve auxiliary power systems during normal operation. The tender also envisages a further 15 MW of long-duration energy storage and 28 MW of solar at a fifth hydropower site for use in electric vehicle charging infrastructure as well as electricity production for the grid.[138]

In theory, the country's total hydropower capacity could be more than doubled, adding more than 4 GW and there are in fact a number of projects in the planning or feasibility study phases.[139] In 2016, the Ukrainian government approved a program for hydropower development which aims to increase hydropower generation capacity by 3.3 GW and to boost its share in overall electricity production to 15.5% by 2026.[140] Current plans to expand the Dnister hydropower complex, for instance, are expected to increase its capacity from 1,296 MW to 2,268 MW.[141]

Hydropower has many advantages, not least its reliability, dispatchability and lack of emissions during generation. In 2021, it was estimated by the International Renewable Energy Agency to have a global weighted average levelized cost of generation equivalent to photovoltaic facilities (this applies for new utility-scale plants) and around 11% lower than the cheapest fossil sources.[142] At the same time, dams are not always as green as they may seem – the reservoirs that form behind the dams of hydro plants flood vegetation and other organic matter, which can release greenhouse gases like carbon dioxide and methane as it decays over time.

While there are a number of promising new technologies under development that can minimize these effects, they have not yet been tested on a large scale.

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135 International Hydropower Association, '2022 Hydropower Status Report'; Kyrylenko, 'Flooded South: The Consequences of Blowing up the Kakhovka Dam'.

136 Our World in Data, 'Share of Electricity Production from Hydropower'.

137 Andritz Hydro, 'Ukraine - Big Plans for Hydro'.

138 Colthorpe, 'Ukraine Tender Would Pair Hydroelectric Plants with Large-Scale Battery Storage'.

139 Andritz Hydro, 'Ukraine - Big Plans for Hydro'.

140 International Energy Agency, 'Market Design: Ukraine Energy Profile Analysis'.

141 International Hydropower Association, '2022 Hydropower Status Report'.

142 International Renewable Energy Agency, 'Renewable Power Generation Costs in 2021'.

Phase 1 and 2

After the end of hostilities, Ukraine's primary focus should be to thoroughly evaluate, stabilize, and, whenever feasible, undertake **renovation or reconstruction efforts** for its existing hydroelectric plants. These initiatives will aim to ensure the security, functionality and longevity of these hydro plants which will play an important role in Ukraine's renewable energy supply. Ukraine should also develop a **strategy for refurbishment and modernization** of its hydro power infrastructure, which should be implemented after the reconstruction phase. This strategy should also explore potentials for symbiosis with other modes of renewable power generation, e.g., floating solar, the use of hydro power lakes as means to store energy, or the integration of hydrogen generation.

To ensure the compliance of any new hydro projects with EU regulations, careful **environmental impact assessments** considering the effects of large new dams on ecosystems and livelihoods along the affected rivers should begin in the immediate afterwar period. These assessments should inform a comprehensive **cost-benefit analysis** for these projects. Considering the long planning and construction times as well as the (environmental) costs of large dams, Ukraine's priority for additional renewable energy should be on renewable sources of energy such as solar, wind, and biomass, with new hydropower plants.

Periods of water scarcity and flooding are likely to increase because of climate change. While this may negatively affect the profitability of power generation in hydroelectric dams, these facilities will still be needed for water management. Ukraine should conduct a comprehensive assessment of the hydrological outlook for its territory to inform a **water management strategy** addressing both the needs of power generation and water supply for citizens, industry, and agriculture.

2.1.5. Bioenergy

Bioenergy, or energy carriers derived from biomass, come in many forms. Practically any of the most common physical energy carriers today can be produced with biomass – this applies both to carbon-based fuels, such as biomethane, bioethanol or biodiesel, and to carbon-free fuels such as biohydrogen or bioammonia. They are produced through a variety of processes which require different feedstocks, levels of energy input, equipment, and expertise.

As a country with one of the largest agricultural sectors in the world, Ukraine has no shortage of biomass. Biomass can be both combusted for heat production or turned into biogas – a mixture of methane and carbon dioxide – for electricity production or indirect heat production. Biogas can in turn be refined into biomethane, which is almost identical to natural gas.[143] In 2022, there were 73 biogas plants in Ukraine producing some 260 million cubic meters of biogas per year.[144] Biogas plants produce direct thermal energy as well as digestate (fermented mass) which can be used as a fertilizer or soil improver. In 2021, biomass accounted for 9% of Ukraine's total heat production (almost all of it in industrial processes), substituting imports of around 4 billion cubic meters of natural gas a year.[145] Biogas is also used to produce electricity, with capacity in Ukraine increasing from less than 5 MW to 60 MW between 2017 and early 2020.[146]

The Ukrainian government passed Law No. 1820-IX on the development of biomethane production in October 2021 to define biomethane and make it possible to feed into the pipeline system.[147] According to the European Bank of Reconstruction and Development's (EBRD) bioenergy program in Ukraine, with a high enough level of investment (some USD 2 billion), the country could realistically develop an annual production capacity of five to six billion cubic meters of biomethane.[148] The lobbying organization UABio, which encourages sustainable bioenergy development in Ukraine, reckons that the country's total annual production potential for biomethane is currently at least 7.8 billion cubic meters.[149]

In 2021, Ukraine consumed some 30 billion cubic meters of natural gas, of which two thirds were covered by domestic production. The remainder was imported indirectly from Russia for billions of dollars a year – in other words, sustainable biomethane, which can replace natural gas in all applications, could potentially contribute greatly to the country's energy security, as well as its national accounts, economic activity and employment.[150] Among the benefits of biomethane is the fact that a great deal of infrastructure already exists in Ukraine in the form of well-developed existing gas grids.

Natural gas in Ukraine today is used for industrial purposes or heating, which accounts for around one fifth of all gas consumption. Municipal district heating companies use gas-fired boilers or combined heat and power plants, consuming around 6 billion cubic meters per year. They are particularly well-placed to use biogas instead. If 50% of the natural gas used by district heating companies (a realistic medium-term goal) could be substituted by biomass, Ukraine could reduce its consumption

143 Prince and Solonyna, 'As Gas Prices Surge, Bioenergy Could Help Heat Ukraine'.

144 Gerit Schulze, 'Biomethan als neuer Exportschlager der Ukraine'.

145 Prince and Solonyna, 'As Gas Prices Surge, Bioenergy Could Help Heat Ukraine'.

146 Sustainable Agribusiness Forum Ukraine, 'Biogas Projects in Ukraine 2020'.

147 Gerit Schulze, 'Biomethan als neuer Exportschlager der Ukraine'.

148 Prince and Solonyna, 'As Gas Prices Surge, Bioenergy Could Help Heat Ukraine'.

149 UABio, 'Біогаз Та Біометан в Україні'.

150 Prince and Solonyna, 'As Gas Prices Surge, Bioenergy Could Help Heat Ukraine'.

of natural gas by 3 billion cubic meters a year, or a third of its imports.[151] The biomass currently used for heat production in Ukraine mainly comes from wood chips produced in lumber operations. Agricultural waste is not yet used on a large scale, despite great potential, especially from the country's abundant sunflower and wheat production.[152]

There are several issues standing in the way of an expansion in bioenergy production and deployment, however, including lack of connections from producers to district heating, low conversion efficiency (and therefore higher prices), lack of appropriate legislation or other state support such as certification programs and insufficient supplier guarantees.[153] Moreover, natural gas is sold by the government to district heating companies at a steep discount, creating little incentive to invest in alternative sources (or increase efficiency) – in late 2021, they were paying around USD 280 for 1000 cubic meters of natural gas when spot market prices were around $1,100. Domestic heating tariffs are set by local governments at below-market prices, leaving the companies cash-strapped and unable to invest in any new technology. At the same time, they function as monopolies and can deny market access to private companies.[154]

2.1.5.1. Phase 1 and 2

Once the war ends, Ukraine's priority should be to reintegrate the bioenergy production in previously occupied territories into its supply chains and distribution grids. The country should also start to lay the groundwork for a multifaceted expansion and deployment of bioenergy.

Based on this assessment, Ukraine should develop and implement a medium to long-term **strategy to expand the production and use of bioenergy**. This strategy should include measures increasing production of all domestic energy carriers based on biomass, including raw biomass and biogas, favoring production of more refined types of energy carriers, such as bioethanol, biodiesel, biomethane or biohydrogen, for domestic use as well as export, and creating the regulatory and physical infrastructure needed to deploy more bioenergy across all sectors.

To **encourage private sector investments** in biomass energy, Ukraine should establish a clear and stable regulatory framework that provides long-term predictability for investors. A major building block could be the reintroduction of a feed-in tariff both for electricity generation and gas production. There was a feed-in tariff in place for operations that started before January 2023, but it was set too low and only helped large-scale operations reach profitability by assessing the overall **biomass potential and infrastructure requirements** for every region. Within a reasonable timeframe. Since January 2023, bioenergy enterprises have to take part in auctions, which also favors large-scale operations. Another effective incentive could be to continue to **offer loan guarantees**, such as those currently provided in Ukraine by the German state investment and development bank KfW. Additionally, costly or labor-intensive legal obligations, such as the requirement to sterilize livestock waste under pressure, could be repealed.[155]

151 Prince and Solonyna.

152 Prince and Solonyna.

153 Gerit Schulze, 'Biomethan als neuer Exportschlager der Ukraine'.

154 Prince and Solonyna, 'As Gas Prices Surge, Bioenergy Could Help Heat Ukraine'.

155 Trypolska et al., 'Economic Feasibility of Agricultural Biogas Production by Farms in Ukraine'.

It is important to recognize that many farming and forestry enterprises in Ukraine may simply lack the scale necessary to profitably market heat and/or electricity produced through biomass under reasonable and realistic conditions.[156] Ukraine could **incentivize smaller operations** by providing information for navigating the relevant regulatory, economic, and technical environments, e.g., by dedicated government agencies or private development companies. Ukraine should also consider setting up specific financial support schemes or programs for setting up **regional or local biomass cooperatives** for clusters of individual farms.

2.2. Energy Efficiency

Energy efficiency is an important pillar of the green energy transition, and has the potential to improve energy security and reconstruction costs by decreasing reliance on fossil fuel imports, reducing long-term costs, and improving the comfort and health of residents.[157] The Energy Strategy of Ukraine until 2050 mentions the importance of energy efficiency, pointing out that improving energy efficiency is directly linked to cost savings and minimizing the environmental impact of the energy sector by reducing emissions of pollutants and greenhouse gases, decreasing the use of national resources, and reducing waste.

It should be underlined that efficiency measures need to be interlinked with measures to avoid a rebound effect. For example: if private car transport becomes less expensive thanks to improved efficiency, individuals may choose to maintain their transport consumption and budget unchanged by simply acquiring a larger vehicle. Similarly, if residential heating costs are decreased though efficiency measures, residents can afford larger living spaces, nullifying the energy savings in absolute terms.[158] The Energy Strategy of Ukraine until 2050 also recognizes the need for energy sufficiency and sets the following strategic goals:

- renewal and modernization of energy infrastructure according to the best international standards, and
- self-sufficiency and consumption efficiency.

Absolute final energy consumption can be seen as a general indicator for the progress of energy efficiency. As shown in Figure 2 in section 1 Energy in Ukraine today, Ukraine's final energy consumption decreased from around 86 million tons of oil equivalent (mtoe) in 2007 to almost 48 mtoe in 2020 (the original target for 2020 in Ukraine's National Energy Efficiency Action Plan (NEEAP) had been 55.5 mtoe).[159] While this is a significant overperformance, it should be noted that Ukraine underwent two significant recessions in 2009 and 2013-14, as well as loss of control over Crimea and a portion of the Donbas region, resulting in a huge decrease in total final consumption of 29.6% between the reference average of 2005-2009 and 2015. The reduction in final energy consumption is due more to structural shifts and a general decline in activity than to energy efficiency measures.[160]

A better way to measure efficiency and sufficiency is to look at the energy intensity per unit of GDP. According to the Energy Strategy of Ukraine until 2050, this should be almost halved between 2023 and 2050. Figure 39 shows Ukraine's and the EU's energy intensity levels from 2000 to 2020. Ukraine's economy is much less efficient than the EU's, demonstrating substantial potential for improvement.

156 Trypolska et al.

157 International Energy Agency, 'Multiple Benefits of Energy Efficiency'.

158 Umweltbundesamt, 'Rebound-Effekte'.

159 Energy Community Secretariat, 'Annual Implementation Report 2021', 13; State Statistics Service of Ukraine, 'Final Energy Consumption for 2007-2021'.

160 International Energy Agency, 'Energy Security – Ukraine Energy Profile'.

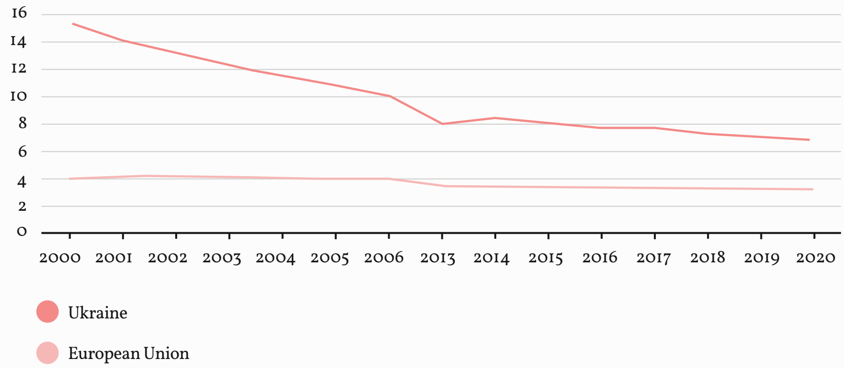

Figure 39: Comparison of the energy intensity level between Ukraine and EU in megajoules per US dollar of GDP at purchasing power parity
Source: World Bank, 'Energy Intensity Level of Primary Energy (MJ/$2017 PPP GDP) - Ukraine, European Union'.

Energy efficiency plays a role in every pillar of the energy system. This includes energy generation and energy transport & transmission, as well as energy consumption. The efficiency of energy generation is higher with state-of-the-art power plants – however, energy infrastructure is often outdated in Ukraine. This applies, among other things, to coal-fired power plants (see section 1.2.5 Coal and the Coal Phase Out for more information) as well as hydropower plants (see 2.1.4 Hydropower). In 2020, Ukraine's losses of energy linked to transportation and distribution were 3.6 mtoe (see Figure 40).

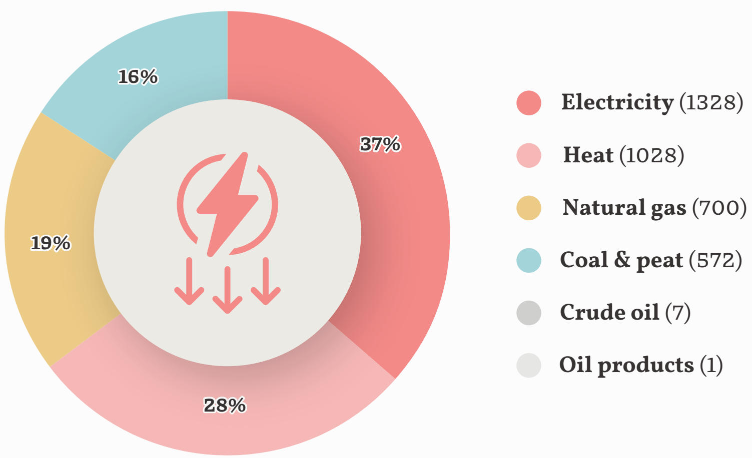

Figure 40: Energy losses in Ukraine in 2020 in thousand tons of oil equivalent
Source: Own illustration, based on State Statistic Service of Ukraine, 'Energy Balance of Ukraine'.

The Energy Strategy of Ukraine until 2050 specifically proposes investing in energy efficiency in the following fields:

- industrial enterprises,
- residential buildings,
- behavioral change,
- energy labelling,
- eco-design and efficiency of material use,
- energy management,
- full commercial metering of utilities, and
- reduction of losses in electricity transmission and distribution networks.

The most constructive and realistic measures differ depending on the sector, with the major ones outlined below.

2.2.1. Manufacturing

As the largest energy consumer, the industrial sector has the highest potential to save energy. According to the International Energy Agency (IEA), most of Ukraine's energy-intensive industries have introduced energy management systems compliant with the ISO 50001 standard. Experience on a global scale has demonstrated several crucial measures that hold the potential to enhance demand restraint and energy conservation within the industrial sector. These measures include the implementation of a comprehensive energy management system, coupled with an independently verifiable energy efficiency auditing framework. Such an approach can effectively pinpoint areas for energy efficiency improvements, fostering a continuous cycle of progress in industrial energy efficiency.[161]

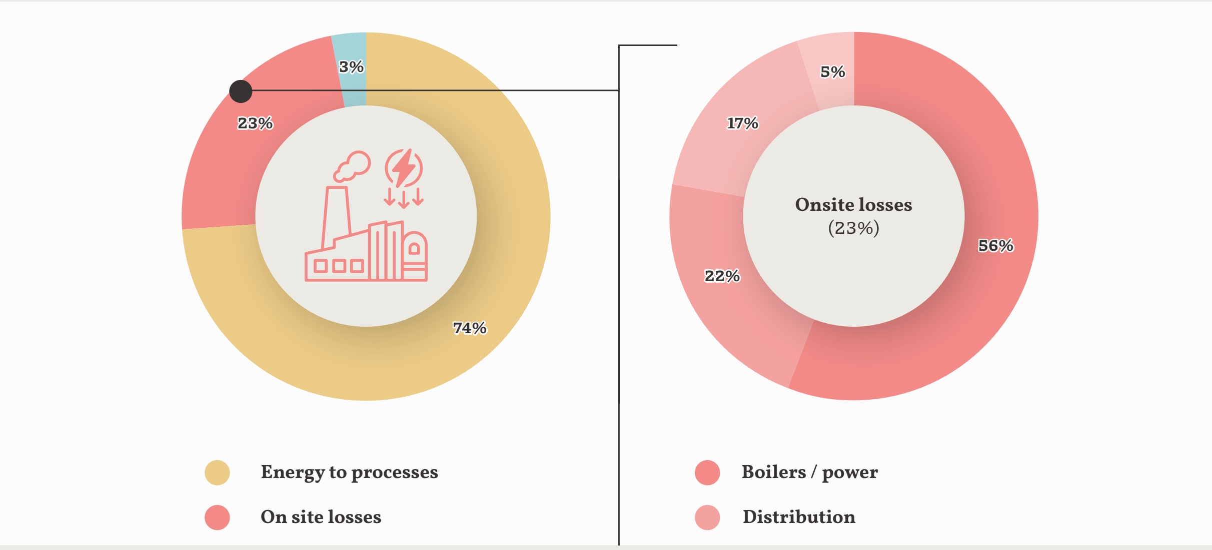

Figure 41: Onsite energy loss profile for the iron and steel industry
Source: Own Illustration, based on Worrell et al., 'Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry'.

161 International Energy Agency, 'Harnessing Energy Demand Restraint in Ukraine: A Roadmap'.

Iron and steel production are the most energy consuming part of the manufacturing sector in Ukraine. This may also be where the lowest-hanging fruit in terms of efficiency is to be found. Some 23% of the energy entering the average steel mill is lost before it can be used in process units. Losses occur primarily in equipment and distribution systems which supply process operations with energy or convert energy to usable work (see Figure 41).

Another opportunity to reduce the waste of energy in the iron and steel sector is to simply make the sector smaller by consuming less iron and steel products and replacing them with sustainable materials, such as wood in the building (see section 1.1.2 Residential Sector for more information). Energy can also be saved by producing steel from steel scrap, which requires only an eighth of the energy used in iron ore-based production.[162] Further efficiency gains can be achieved during the retrofitting of steel production plants when switching to the use of green hydrogen.

2.2.2. Residential Sector

The second-largest energy consumer is the residential sector, where space heating is a significant share and holds the potential to provide the most significant energy efficiency measures (see also sections 1.1.2 Residential Sector and 2.4 Renewable Heating). Energy consumption can be reduced, and decarbonization and efficiency fostered, through efficient modern heating systems.

The thermal insulation of buildings is also relevant. This includes windows as well as wall insulation and additional measures to improve the thermal envelope of buildings, such as better metering for heating and hot water or heating regulators. Table 2 summarizes the energy saving potential of such measures.

Type of measure	Energy savings
Wall insulation and additional insulation measures	21 %
Windows exchange	65-75 %
Heating meters	5-20 %

Table 2: Energy saving measures and their saving potential in Ukraine
Source: Kiva, 'Energy Efficiency in the Residential Sector in the Ukraine', June 2009, 37.

Behavioral differences concerning energy use and attitude toward energy saving, and thus the rebound effect, can differ between countries and regions. Rebound effects can also depend on the income and education level of different groups of society. They are therefore difficult to measure and predict. For Ukraine, it is estimated that energy efficiency savings in this field lead to a rebound effect that increases heating energy consumption by 10-30% for space heating, 10-40% for water heating, and 5-20% for lighting.[163] This issue should be addressed in Ukraine's overarching long-term energy strategies.

162 ABB, 'Energieeffizienz in Der Eisen- Und Stahlproduktion'.

163 Kiva, 'Energy Efficiency in the Residential Sector in the Ukraine', June 2009.

2.2.3. Transport

As the third largest energy consumer in Ukraine (see Figure 1), transport is another important topic in energy efficiency (see also section 1.1.3 Transport Sector). In addition to more efficiency in the design of vehicles, the transport sector can also benefit from more energy sufficiency. This includes traffic planning that prioritizes energy-efficient traffic methods such as public transport, electric train traffic and pedestrian & bicycle traffic. Residential and transport planning should be interlinked to enable sustainable urban and regional planning. The Energy Strategy of Ukraine until 2050 provides for no measures in the sense of fostering a transport sector with more sufficiency as well as efficiency.

There are essentially four options for decarbonizing road transport: battery electric vehicles (BEVs), fuel cell vehicles (FCEVs), vehicles with hydrogen combustion engines and conventional combustion engines that use synthetic fuels – so-called e-fuels. There are major differences between these applications in terms of efficiency (see Figure 42).

	$[kWh_{el}]$	**Drive Technology** [%: Utilisation rate]			**Drive energy** [kWh]
Battery electric vehicle (BEV)	1	Battery charge 95%	Battery discharge 90%	E-motor 90%	0.75
Fuel cell electric vehicle (FCEV)	1	Electrolysis 65%	Fuel cell 55% el.	E-motor 90%	0.3
Vehicle with H_2 combustion engine	1	Electrolysis 65%	Internal combustion engine 30%		0.2
Diesel vehicle with eFuels	1	Electrolysis 65%	Fischer-Tropsch synthesis 56%	Internal combustion engine 40%	0.15

● Power ● Hydrogen ● eFuel

Figure 42: Comparison of the average utilization rates of propulsion technologies
Source: Heikel and Becker, 'Pkw-Antriebe Im Überblick - Vergangenheit, Gegenwart Und Zukunft'; Wilms et al., 'Heutige Einsatzgebiete Für Power Fuels - Factsheets Zur Anwendung von Klimafreundlich Erzeugten Synthetischen Energieträgern'.

The use of BEVs is usually recommended for passenger cars, but they are impractical for long-distance truck traffic, which carries heavy payloads across long distances, requiring batteries to be very large and heavy, or recharging stops to be very many. Ukraine has a relatively low density of population and high distance between economic centers, which would make this impractical. For instance, Kyiv is 481 km from the second largest city of Kharkiv and 475 km from the third largest city Odesa. To classify the relevant distances, Figure 43 shows the range of selected trucks from different manufacturers.

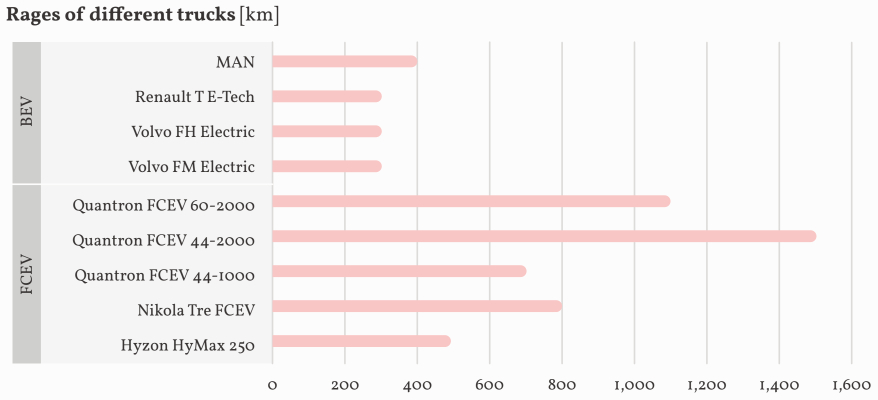

Figure 43: Ranges of selected trucks
Source: Market research by BBH Consulting in May 2023.

The distances between Kyiv, Kharkiv and Odesa cannot be covered with today's BEV trucks without a charging stop, and exports, for instance, would have correspondingly larger distances to go. It should be noted here that the charging processes for FCEVs are roughly the same as for conventional vehicles, but significantly shorter (depending on the available charging infrastructure).

The extent to which future advances in battery technology will make up for these disadvantages is difficult to foresee. It is equally hard to predict whether fuel cell vehicles or conventional trucks with synthetic fuel drives will prevail in the future. The benefits of FCEVs are that they produce no local emissions of polluting nitrogen oxides (NOx) or carbon dioxide, and are less noisy, while enjoying lower fuel costs and less maintenance, as electric motors have fewer moving parts than internal combustion engines. The advantages of conventional trucks are the broad availability of refueling and maintenance infrastructure, and lower upfront purchase costs. The future cost and availability of synthetic fuels future are as yet uncertain, however. Hydrogen can be expected to have some role in the decarbonization of road transport, but the precise extent cannot be conclusively predicted at present.

Developing hydrogen and biofuels technologies and incorporating them into transportation can nevertheless present an opportunity for Ukraine as these technologies have the potential to become integral components of the supply chain for the trucks of the future. By investing in the research, development, and implementation of hydrogen and biofuel technologies, Ukraine can position itself as a key player in this evolving part of transport industry.

2.2.4. Recommendations for Energy Efficiency

2.2.4.1. Phase 1

Phase 1 should see short-term rebuilding and restoration carried out with energy efficiency in mind. This should include:

- evaluation of **efficiency strategies** in manufacturing, the residential sector and transportation to evaluate the most effective measures, such as:
  - the modernization of the heating system and thermal insulation,
  - thermal pipe insulation and upgrades to variable-speed electric motors in industrial applications,
  - the renovation and reconstruction of buildings,
  - efficiency measures in the iron and steel industry,
  - the use of waste heat, or
  - expansion of public transport;
- update to the Energy Strategy for 2050 based on these findings;
- development of instruments to implement the most effective measures;
- assessment of the sectors in which the embedded consumption of energy can be avoided or reduced, for instance by:
  - using sustainable materials instead of steel or
  - preserving living spaces at a reasonable size;
- ensuring that **reconstruction planning** incorporates energy efficiency measures, especially in terms of transmission and distribution systems.

2.2.4.2. Phase 2

In Phase 2, all reconstruction and new constructions should involve efficiency measures. In addition, efforts should be made to **modernize** existing buildings, industrial processes, energy plants, energy infrastructure, and so on. It makes sense to **start with the largest** energy consumers. Energy sufficiency should also be considered, not least so as to minimize the rebound effect. Specific recommendations include:

- implementing measures developed in Phase 1,
- **renovating** existing transmission system to reduce energy losses,
- **modernizing** existing buildings,
- **transitioning** towards carbon neutral systems for district heating in conjunction with the coal phase-out, and
- setting **standards** for sustainable urban and regional planning.

2.3. Hydrogen and its Derivatives

In a longer perspective, hydrogen and its derivatives will be essential in the future energy mix required to achieve a climate-neutral economic system. This section looks at the production of hydrogen and hydrogen derivatives and their fields of application. It considers economic potential wherever possible, but it should be noted that there is great uncertainty in terms of the costs of nuclear power, biogas/biomethane and natural gas as partial basis for the production of hydrogen, due to market mechanisms.

2.3.1. Hydrogen

A major goal in Europe's energy transition is the large-scale production and use of renewable or climate-neutral hydrogen. The EU defines this as hydrogen produced using electrolysis powered by renewable solar, wind or hydro energy.[164] Under EU regulations, so-called low-carbon hydrogen can be produced and used as a bridging technology in a transition phase to accelerate the hydrogen ramp-up. This path has not yet been defined in a legally binding way for the European Union, although, as a rule of thumb, low-carbon technologies are meant to have a greenhouse gas reduction potential of at least 70%. Logically, this would include blue hydrogen (obtained from fossil energy sources by steam reforming but with the application of carbon capture) and pink hydrogen (produced through electrolysis with nuclear power). It is not yet clear how hydrogen obtained via the steam reforming of biogas/biomethane will be classified. These categories are crucial for Ukraine because it will need to comply with European regulations as a future Member State, as well as to trade with the EU. Their costs and benefits are explored below.

2.3.1.1. Renewable hydrogen

Renewable hydrogen, produced via electrolysis from renewable electricity, is the gold standard with the largest future applications and the highest potential for decarbonizing the economy. Since the market for hydrogen electrolyzers is global, the related investment costs are the same in Ukraine as anywhere else – in other words, the decisive factor in estimating production cost are the operating expenses, essentially the price of electricity.

Determining these for Ukraine involves calculating the price of the most common renewable energy sources in the country. Since the investment costs for these technologies also do not greatly differ globally and the marginal cost of renewable energy sources is close to zero, the decisive factor is the yield potential or energy density of each energy source.

Figure 21 shows the average specific solar power yields in Ukraine compared to selected countries which have major hydrogen export ambitions or are large consumers. The right section of the diagram shows the regions with the highest solar yields in Ukraine. This shows that Ukraine has average solar yields, and no specific comparative advantage.

164 The EU has defined specific requirements in a Delegated Act to Art. 27 of European Union, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). See also European Commission, 'Production of Renewable Transport Fuels – Share of Renewable Electricity (Requirements)'.

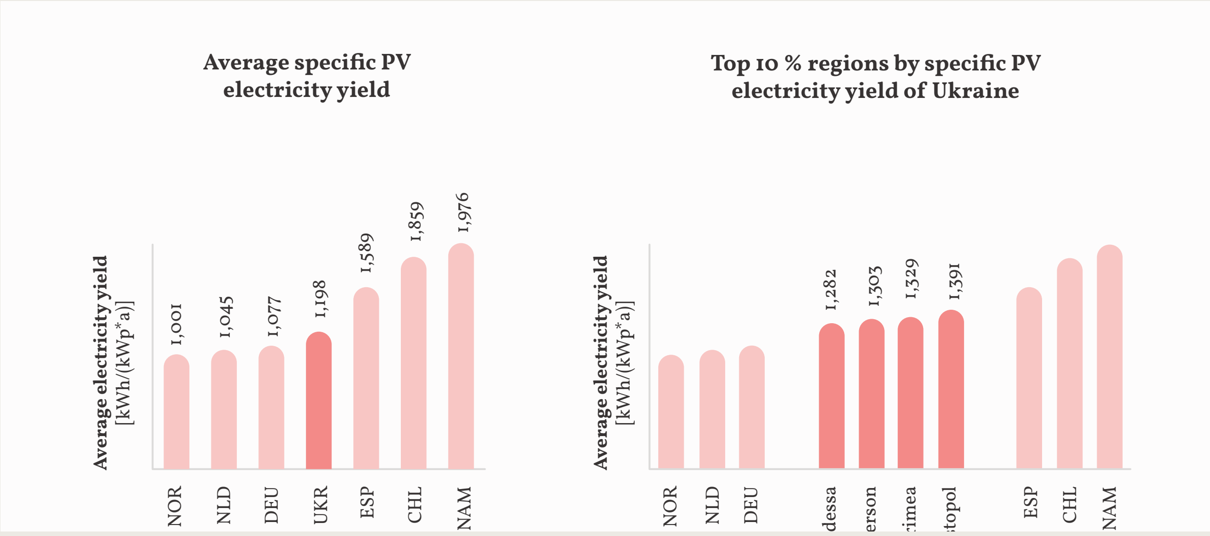

Figure 21: Solar power in Ukraine and select other countries
Source: 'Global Solar Atlas'. Abbreviations: NOR: Norway, NLD: Netherlands, DEU: Germany, UKR: Ukraine, ESP: Spain, CHL: Chile, NAM: Namibia.

Figure 22 shows the potential of onshore wind in different countries, again showing average or low values for Ukraine compared to other countries.Here, too, there is no global comparative advantage for Ukraine.

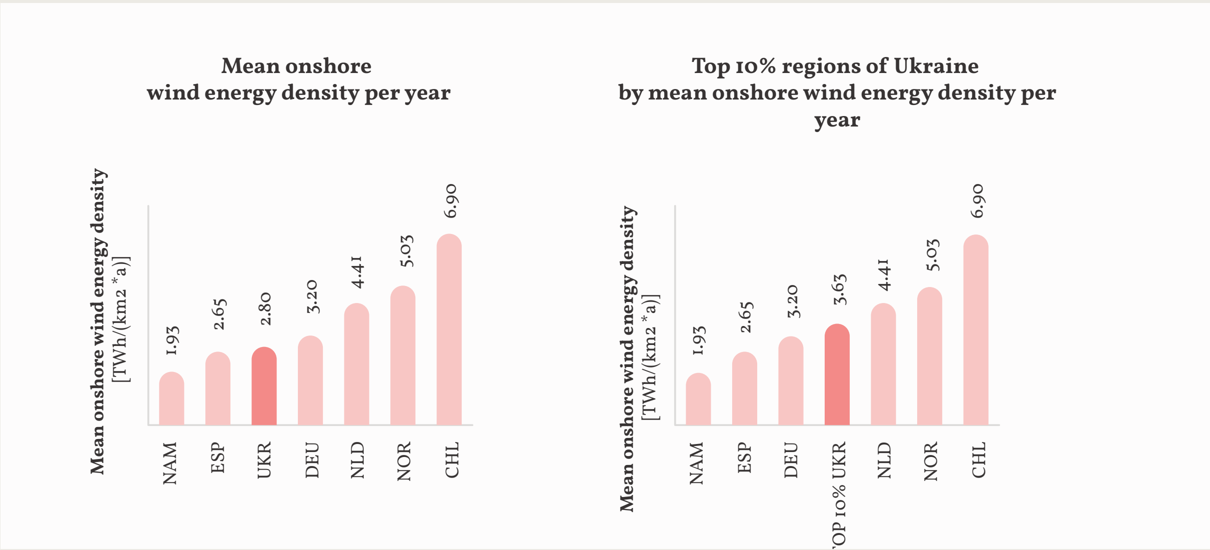

Figure 22: Average onshore wind energy potential in Ukraine and select other countries.
Source: 'Global Wind Atlas'. Based on an altitude of 100 m. Abbreviations: NOR: Norway, NLD: Netherlands, DEU: Germany, UKR: Ukraine, ESP: Spain, CHL: Chile, NAM: Namibia.

A comparable situation holds for offshore wind power, where Ukraine has a significantly lower potential than the most promising countries such as Chile and Namibia (see Figure 23).

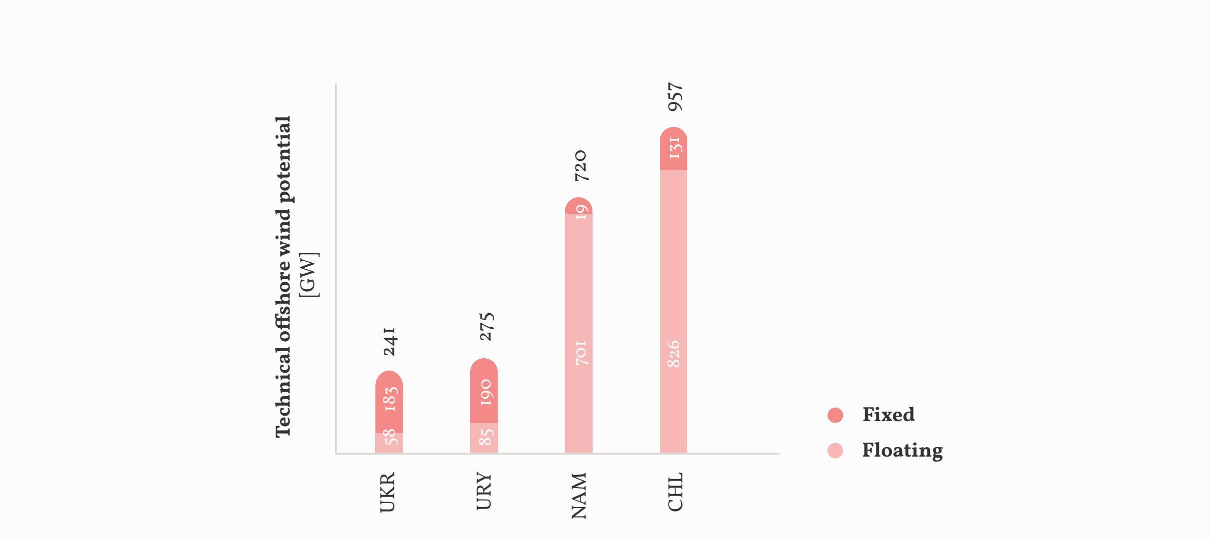

Figure 23: Technical potential of offshore wind power in Ukraine and select other countries
Source: 'Global Wind Atlas'. Based on a distance of 200 km from the coastline, Abbreviations: URY: Uruguay, NAM: Namibia, and CHL: Chile.

A realistic assessment of how much electricity could be generated in each country at reasonable prices, which takes into account only the most promising areas, paints a similar picture (see Figure 24; note that these values are somewhat subjective and imprecise).

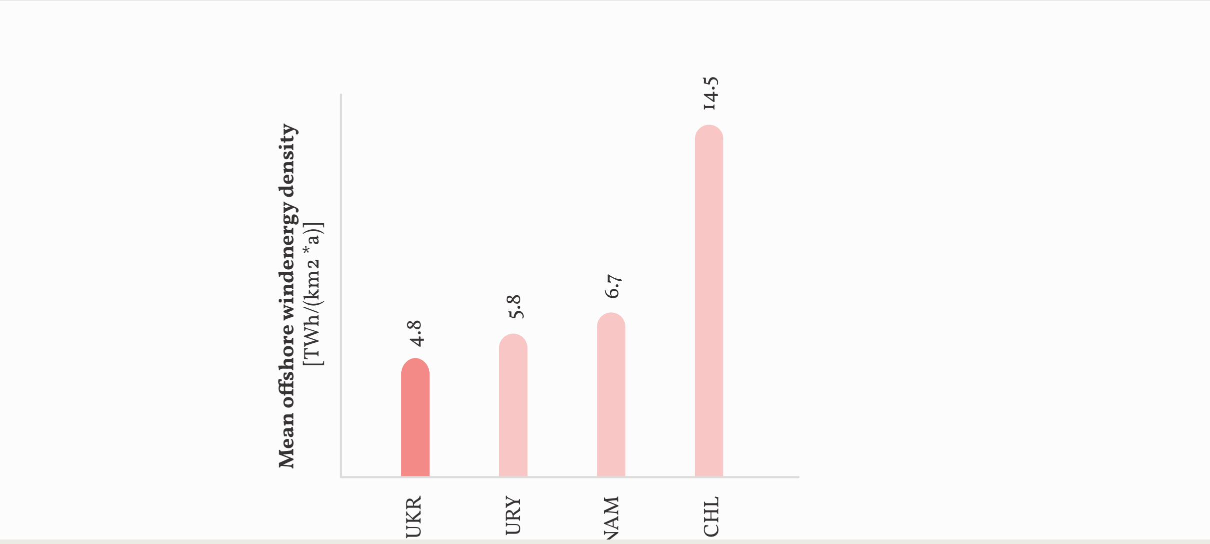

Figure 24: Average offshore wind energy potential in Ukraine and select other countries
Source: Own illustration, based on 'Global Wind Atlas'.

Another possibility for hydrogen production are hydropower plants, which are suitable for electrolysis thanks to their usually high full-load hours and consistent electricity production. In the years 2011 to 2020, Ukrainian hydropower plants (excluding pumped storage plants) only had average full-load hours of 1,907, which is significantly below the international average (see Figure 25).

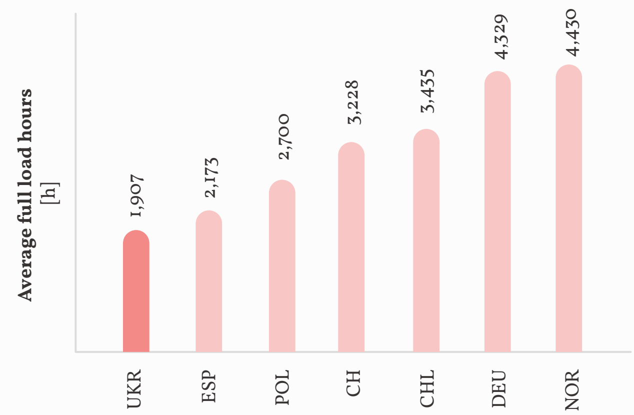

Figure 25: Average full load hours of hydropower plants in Ukraine and select other countries
Source: International Energy Agency, 'Hydropower Data Explorer'.

Figure 26 shows that the technical potential of hydropower in Ukraine – at 21.5 TWh per year – is comparatively low. In summary, production of renewable hydrogen in Ukraine is likely to be more expensive than in several other countries with export ambitions.

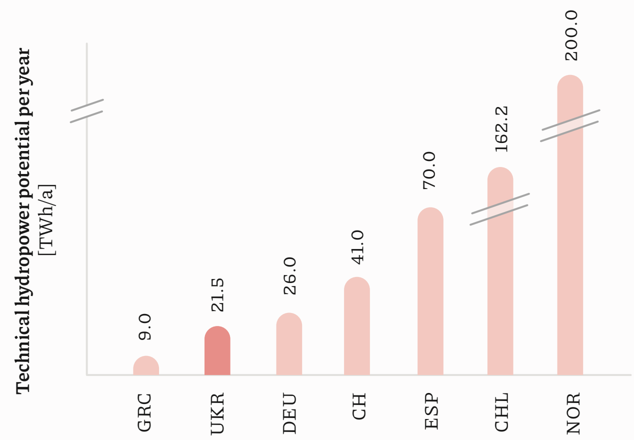

Figure 26: Average technical hydropower potential in Ukraine in international comparison
Source: Andritz Hydro, 'Ukraine - Big Plans for Hydro'; Horlacher, 'WBGU, Globale Potenziale Der Wasserkraft'.

2.3.1.2. Pink Hydrogen

Pink hydrogen is produced through electrolysis fueled by nuclear power. As described in section 1.2.2, nuclear power generation is a cornerstone of Ukraine's energy supply. The extent to which electricity from these power plants will be available for hydrogen production will depend heavily on future electricity demand, which is difficult to estimate, and the generation infrastructure available for this purpose.

As nuclear power generation is substantially more expensive than renewables, it would make little sense to expand nuclear generation instead of solar or wind for the sole purpose of producing hydrogen. Nevertheless, excess capacity in existing nuclear power plants could be used to keep electrolyzers running when general demand for electricity is low or when excess renewable electricity generation is scarce. Increasing the operating hours of electrolyzers this way could help increase their profitability and kickstart hydrogen production, which in turn can be gradually switched to renewable energy sources when the expansion of wind and solar power in Ukraine moves forward.

2.3.1.3. Blue Hydrogen

Blue hydrogen is produced through steam reforming of natural gas, with a substantial degree of carbon capture. For the European market, only Norway and the Netherlands, who make use of their local natural gas supplies and the availability of underground storage capacity for the captured carbon dioxide, produce significant amounts of blue hydrogen. As there is a high demand for hydrogen in the European market, it makes sense for Ukraine to assess whether local production and subsequent export of blue hydrogen is feasible.
While Ukraine does have reserves that can be developed, including shale gas deposits, the country is a major net importer of natural gas (see section 1.2.3 for more details). Possible production costs for blue hydrogen and thus its economic potential depend on gas prices. How high these will be in a post-war period and what competitiveness will result accordingly cannot be predicted for the near or medium term.

Developing new natural gas resources or using imported gas for hydrogen production might not only have economic limitations but may also be difficult to square with a commitment to climate neutrality. It is also not clear for how long the EU will tolerate blue hydrogen as a transition fuel.

2.3.1.4. Hydrogen from Steam Reforming of Biogas/Biomethane

If biogas or biomethane are used for steam reforming to produce hydrogen, the carbon produced during the process theoretically does not have to be captured for the process to be climate neutral. (If the carbon is captured, the process could conceivably lead to net removal of carbon from the atmosphere.)

As explained in greater detail in section 2.1.5, Ukraine has some of the world's greatest potential in agricultural feedstocks and by-products such as straw and other residues, making it potentially highly suitable for biomethane production.[165] Possible production costs would depend on natural gas prices, carbon taxes, and any green premiums for bioenergy. The exact numbers in the near and medium term cannot currently be predicted with any precision.

Future European regulations related to the sustainable status of bioenergy and hydrogen produced from bioenergy are also not entirely clear at present. Nevertheless, current EU regulation and political discourse point out that bioenergy should, wherever possible, be used directly as substitute for natural gas instead of transforming it to hydrogen – biomethane will be needed to decarbonize industrial processes or older gas power plants.

165 Yevstihnieieva, Saviytskyi, and Moroziuk, 'Investing in Ukraine's Renewable Energy: The Key to Future Energy Security'.

2.3.1.5. White Hydrogen

White (or natural or geological) is molecular hydrogen occurs naturally in the earth (that is, it's not produced through an industrial process). While it is not extracted on a large scale today, white hydrogen has several benefits: it can be extracted with little pollution and may allow for lower cost operation compared to industrial hydrogen. One of the processes through which it is formed in the earth's subsurface is an oxidation-reduction reaction known as serpentinization. This continuously produces substantial amounts of hydrogen, which is then stored in geological formations.[166] There are studies which suggest that this process may replenish up to 23 megatons per year (in the order of 30% of today's global annual hydrogen demand), making this type of hydrogen a potentially sustainable and renewable resource as well. A bore hole can theoretically provide constant production forever, without the need for redrilling or declining yields.[167] While is not currently clear whether substantial deposits of white hydrogen can be found in Ukraine, this is surely worth investigating.

2.3.2. Hydrogen derivatives

The price of hydrogen derivatives like ammonia on synthetic methane depends partly on the cost of hydrogen. The above analysis therefore applies for each of them as well. Additionally, their production requires other chemical elements, namely carbon and nitrogen, which need to be sourced through specific processes at additional cost.

2.3.2.1. Carbon availability

Synthetic carbon-based fuels like methane require carbon in addition to hydrogen. To ensure climate neutrality, the carbon must come from sources other than fossil fuels. There are three potential sources:

- Direct air capture extracts carbon directly from the atmosphere. The availability of carbon dioxide in the atmosphere is practically unlimited, but technology readiness is quite low. Moreover, the process is extremely energy-intensive: depending on the technology, direct air capture consumes between 222 and 638 kWh per ton of carbon dioxide extracted in 2022 – to all intents and purposes, these costs are currently prohibitive.[168]
- Carbon capture from large point sources such as power generation or industrial facilities that run on fossil fuels or biomass. There are around 35 commercial facilities worldwide capturing the carbon from industrial processes, fuel transformation and power generation. Ukraine has a great deal of industrial facilities and power plants, and thus substantial theoretical potential for carbon capture.[169]
- Carbon capture from biogas during its upgrading to biomethane. There are a wide range of market-ready technologies for this process, and Ukraine has substantial biogas potential.

Considering the availability of large amounts of biomass and bearing in mind that some coal power plants will need to remain operational for the next decade, Ukraine should undertake a comprehensive assessment of its carbon sources and look for pathways to make use of this potential – either for the production of hydrogen derivatives, other material utilization or carbon capture.

166 Koloma, 'About Us'.

167 Zgonnik, 'The Occurrence and Geoscience of Natural Hydrogen'.

168 International Energy Agency, 'Direct Air Capture'.

169 International Energy Agency, 'Carbon Capture, Utilisation and Storage'.

2.3.2.2. Nitrogen availability

The nitrogen needed to produce ammonia is abundant in nature and can be extracted from many sources, not least air (of which it forms more than 75%). There are a range of processes for this, which are quite energy intensive, but can be powered by renewable energy. Given Ukraine's substantial agricultural sector, it is advisable to assess the feasibility of expanding domestic nitrogen extraction and ammonia production based on renewable energies. As ammonia is a crucial component in fertilizer production, an increased production aligns with the nation's need for a stable and accessible source of fertilizers while also boosting its potential for use in other sectors, e.g., maritime transportation.

2.3.3. Fields of Application of Hydrogen and its Derivatives

Hydrogen and derived energy carriers can be deployed wherever direct electrification is not practical or economical. The largest final energy consumers in Ukraine (see Figure 27) are, in order, the residential sector, iron and steel production, road transport, commercial and public services, and raw materials for manufacturing (non-energy use). These sectors are analyzed below with regard to the potential deployment of hydrogen.

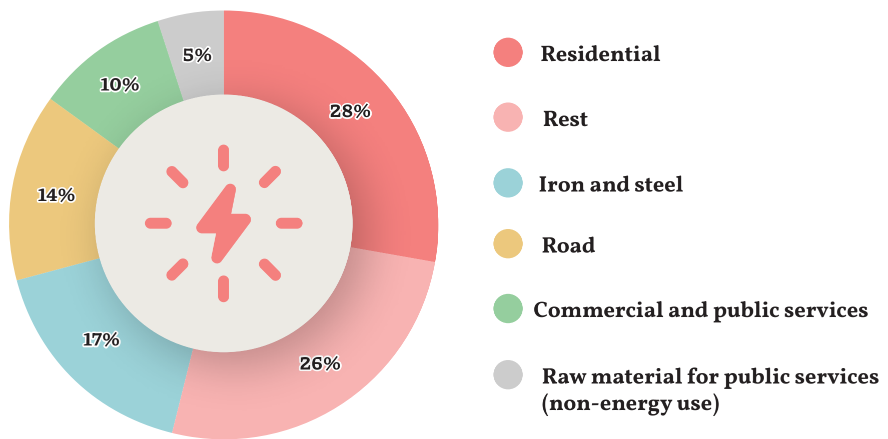

Figure 27: End energy use by sector in 2020
Source: Own illustration, based on State Statistic Service of Ukraine, 'Енергетичні Потоки, Тис'.

2.3.3.1. Hydrogen in the Residential Sector and Commercial & Public Services

Residential services and commercial & public services consume energy primarily for heating. For reasons of efficiency and climate policy, these systems should first and foremost be electrified through the use of heat pumps running on sustainable electricity; it does not normally make sense to replace them with hydrogen-fueled solutions (see Figure 28 for details). Electric heat pumps obtain around 2.6-4.6 kWh of thermal energy from 1 kWh of electricity, while all other technologies have an efficiency lower than 100% due to conversion losses.

	[kWh_{el}]	Heat supply technology [%: Utilisation rate]			Heat [kWh]
Electric heat pump	1	Heat pump & ambient heat (260 - 460 %)*			2.6 - 4.6
Electrical boiler	1	E-boiler 95%			0.95
H_2-Fuel cell	1	Electrolysis 65%	Fuel cell 40% (power), 45% (heat)		0.3 (0.26 kWh electricity)
H_2-condensing boiler	1	Electrolysis 65%	Boiler 95%		0.62
PtG condensing boiler	1	Electrolysis 65%	Methanisation 80%	Boiler 95%	0.49

Power
Heat
Hydrogen
Methane

*Depending on building, heat source and heating temperature.

Figure 28: Comparison of average utilization rates of heating technologies
Source: Heikel and Becker, 'Pkw-Antriebe Im Überblick - Vergangenheit, Gegenwart Und Zukunft'; Wilms et al., 'Heutige Einsatzgebiete Für Power Fuels - Factsheets Zur Anwendung von Klimafreundlich Erzeugten Synthetischen Energieträgern'.

In exceptional cases, such as buildings that cannot be renovated, heating via hydrogen may make sense under certain circumstances. However, even then other technologies such as solar thermal energy or biogas combustion may be more suitable and economically feasible than hydrogen.

The right answer depends on local conditions and individual situations. In areas with hydrogen production facilities and industrial demand for hydrogen, existing or future hydrogen supply and infrastructure might also be used to heat residential, commercial, and public buildings. This approach can optimize resource and energy efficiency, create additional synergies for all hydrogen users in these clusters, and mirrors the concept of "Hydrogen Valleys." This concept is part of the EU Strategy on hydrogen and can offer a framework to Ukraine for implementing regional hydrogen-based solutions across various sectors.[170]

170 European Commission, 'Hydrogen Valleys'.

2.3.3.2. Hydrogen in the Iron and Steel Industry

Metal processing is the second largest industry in Ukraine, accounting for 20% of exports.[171] In 2020, iron and steel production accounted for 17% of Ukraine's total final energy consumption. The country was the world's 14th largest and Europe's 3rd largest producer of crude steel in 2021.172 While direct electrification of steel production is not an option given the state of the art today and in the foreseeable future, steel production can be decarbonized through the deployment of direct reduction, which uses hydrogen (as opposed to the conventional blast furnace method, which consumes coke instead). This requires enormous quantities of hydrogen: a typical blast furnace deploying the direct reduction process requires around 2,000 tons of hydrogen per year – the equivalent of 2,250 fuel cell trucks. If Ukraine's steel industry were decarbonized, it would require correspondingly large amounts of hydrogen.

Before Ukraine joins the EU, it will be subject to the Carbon Border Adjustment Mechanism (CBAM), a border tax proportionate to the climate impact of a given product. This will represent a financial incentive for Ukrainian steel exports to the EU to decarbonize. Once the country becomes a Member State, it will be covered by the EU's emissions trading system (ETS), which obliges individual industries, including the steel sector, to buy certificates for the greenhouse gases they emit. While many certificates are initially issued free of charge, this will cease to apply by the mid-2030s. Accordingly, the production of steel containing carbon dioxide will gradually become more expensive, making a switch to direct reduction more lucrative. Several EU countries, not least Germany, are considering introducing so-called green lead markets. This would result in increased demand for green products such as green steel within the EU. That demand and associated willingness to pay more for green steel would also represent an incentive for Ukrainian producers to become more sustainable. The economic importance and high energy consumption of steel, and the lack of alternatives to direct reduction using hydrogen, mean that the deployment of hydrogen in Ukraine's steel industry should be a cornerstone of the country's decarbonization efforts.

Ukraine stands to gain significant advantages by exploring the establishment and development of a green steel sector. Beyond the immediate benefits to its industrial landscape, the proximity of the steel industry to energy production facilities (traditionally coal power plants) creates a unique opportunity for regional development. Leveraging the existing infrastructure of these areas for the expansion of renewable energy generation and hydrogen production not only contributes to the decarbonization of the steel sector but also fosters a sustainable and integrated energy ecosystem. This approach also mirrors strategies adopted by several coal phase-out regions in the EU. By following these examples, Ukraine can harness the full potential of its industrial and energy sectors, promoting environmental responsibility and long-term economic growth.

171 The New York Times, 'Ukraine's Steel Plants'.

172 World Steel Association AISBL, 'World Steel in Figures 2022'.

2.3.3.3. Ammonia Production

Agriculture, forestry and fisheries accounted for 9.3% of Ukraine's GDP and 17.1% of employment in 2020.[173] This involves fertilizer, which comprises large amounts of ammonia; and ammonia production is a major source of carbon dioxide emissions, being solely responsible for 2% of worldwide emissions.[174] With disproportionately large production volumes (see Figure 29), Ukraine is a major player in the ammonia market, leading to substantial decarbonization potential.

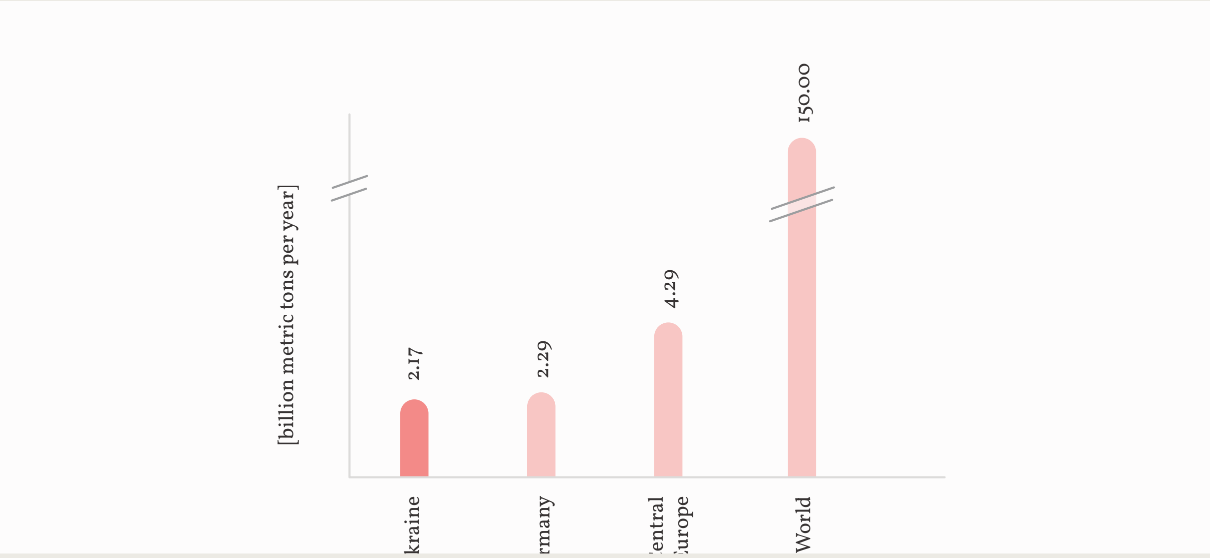

Figure 29: Ammonia production volumes in Ukraine and select other countries in 2021
Sources: U.S. Department of the Interior and U.S. Geological Survey, 'Mineral Commodity Summaries 2023'.and Statista, 'Production of Ammonia Worldwide in 2021, by Region'.

Ammonia can be produced in a climate-neutral way if hydrogen is used instead of natural gas. This involves fairly straightforward adaptations to the Haber-Bosch process. Alternatives include the use of biomethane or maintaining the current process or using natural gas with downstream capture of carbon dioxide. The choice of technology for ammonia production in Ukraine's future energy landscape will depend on various factors, particularly the evolving costs of hydrogen, natural gas, and the feasibility of carbon dioxide storage and transport solutions.

It is important to note that the EU has already initiated and funded numerous projects which aim to explore and advance the potential of sustainable ammonia production technologies. Ukraine should actively engage and collaborate with these ongoing initiatives, aligning its efforts with the broader EU strategies for sustainable energy transition.

173 Nemitz, 'Ukrainische Wirtschaft Durchläuft Große Umbrüche'.

174 International Energy Agency, 'Ammonia Technology Roadmap'.

2.3.4. Hydrogen Transmission

According to the draft roadmap for production and use of hydrogen in Ukraine by the United Nations Economic Commission for Europe (UNECE), the "extensive system of mainstream gas pipelines and gas distribution network in Ukraine has a significant potential for […] hydrogen both in the national market and for export […]." UNECE underlines its prediction with findings from the Regional Gas Company (RGC), which controls approximately 70% of gas distribution networks in Ukraine, and carried out experiments that allowed it to conclude that natural gas with an admixture of 10-15% of hydrogen can be transmitted through existing infrastructure. Moreover, the current pipelines could be refurbished to enable the transport of pure hydrogen.[175]

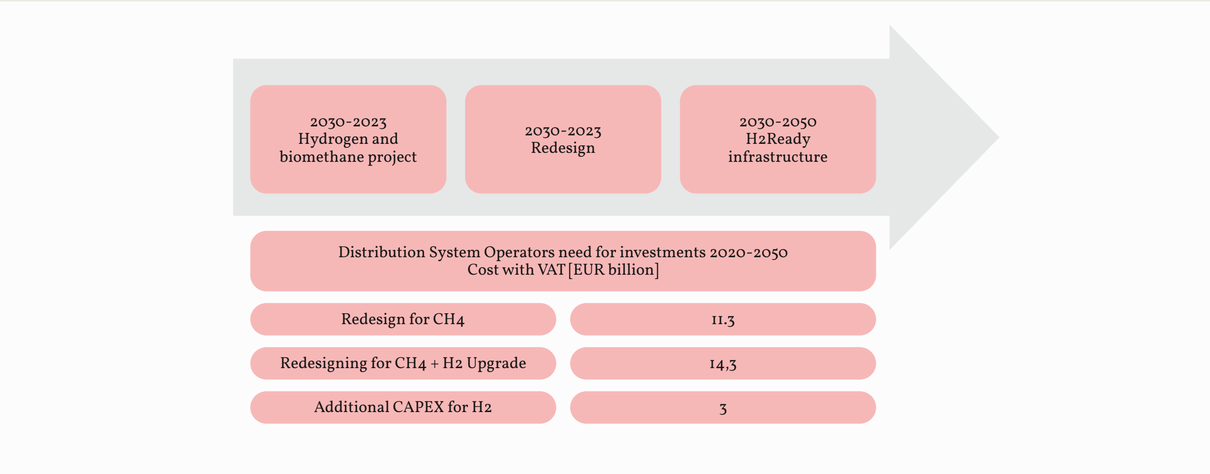

Figure 30: Steps and investments needed to provide a hydrogen-ready gas infrastructure
Source: RGC, 'Ukrainian Natural Gas Distribution Network Renovation'.

RCG developed a strategy, time schedule and cost forecasts for a redesign of the distribution system that would make the grid hydrogen ready (see Figure 30). RCG expects that Ukraine will not have sufficient funds to carry out the renovation itself and points out that the participation of international institutional and private investors will be necessary.

In addition to the purely economic perspective explored above, geopolitical factors can be decisive for establishing a hydrogen export infrastructure. One argument in favor of this is the presence of good transport infrastructure in the form of existing natural gas transport pipelines (see section 1.2.3). These geopolitical possibilities need to be examined in more detail and weighed against the cost disadvantages in production. In the meantime, Ukraine should actively engage in European initiatives, such as the "Hydrogen Backbone," which im to facilitate efficient hydrogen transport network across Europe.[176]

175 United Nations Economic Commission for Europe, 'Draft Roadmap for Production and Use of Hydrogen in Ukraine'.

176 Rik van Rossum et al., 'European Hydrogen Backbone – a European Hydrogen Infrastructure Vision Covering 28 Countries'.

2.3.5. Bringing together Potential and Purpose

Given that large-scale hydrogen production and export are still evolving technologies, it is important to carefully prepare the regulatory and technological conditions for their future implementation. By embracing a forward-thinking, long-term perspective and establishing an adaptable framework for hydrogen, Ukraine can position itself at the forefront of this technology. A strategic approach will help to ensure Ukraine's competitiveness by allowing it to leapfrog other countries in the development and integration of hydrogen solutions.

2.3.5.1. Phase 1

No large-scale hydrogen production projects can come on stream within the first few years after the war in Ukraine. However – as with other types of renewable energy – it is important that **no path dependencies** be created during this time that might prevent later deployment and decarbonization by 2050. An example of this is the steel industry: **the lifetime of a blast furnace**, that is, the period until its refractory lining needs to be completely renewed, is approximately **15 to 20 years.**[177] Other plant components can have significantly longer lifetimes.

At the same time, it is important for Ukraine to **design projects and establish partnerships** between domestic hydrogen producers and buyers as well as between domestic hydrogen producers and international buyers – a global market for hydrogen does not yet exist but is emerging (see Figure 31). This applies to political agreements as well as concrete partnerships and projects at company level. Declarations of intent should gradually be backed up with concrete project approaches in Phase 1 so as to build a project pipeline.

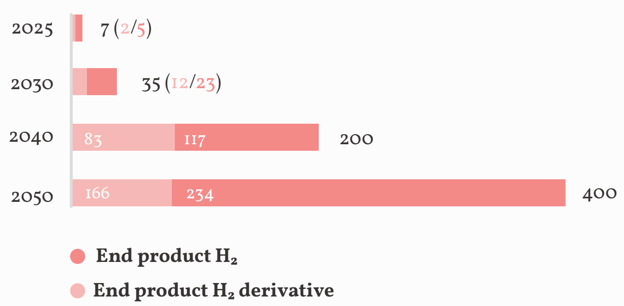

Figure 31: Global hydrogen trade over time
Source: Hydrogen Council and McKinsey & Company, 'Global Hydrogen Flows: Hydrogen Trade as a Key Enabler for Efficient Decarbonization'.

177 Stahlinstitut VDEh, 'Kohlenstoffbasierte Stahlerzeugung'.

In addition, **renewable energy generation** must be developed, as this is the main bottleneck of hydrogen production. First pilot projects involving the production and application of hydrogen should be carried out to build up expertise. Above all, Ukraine's **long-standing expertise in European gas transport** can be of benefit for possible export ambitions. It is crucial to continuously be guided by European requirements, ensuring that products are qualified for export to the EU. Some specific measures for Phase 1 can include:

- elaborating **realistic plans** for the production and export of hydrogen that can help in avoiding lock-in effects in terms of unnecessary repairs and new construction of fossil-fuel installations;
- starting to **adapt regulations and incentives** to foster eventual innovation and investments into hydrogen infrastructure;
- connecting with European TSOs and **fostering knowledge transfer**;
- determining which **pipelines can be made hydrogen ready** and can be part of a hydrogen backbone;
- carrying out **cost-benefit analyses and cost forecasts** for making gas infrastructure hydrogen ready;
- developing **strategies for the upgrade** of fossil fuel infrastructure to hydrogen;
- ensuring that sufficient **feedstocks, especially critical raw materials**, will be available in the medium and long term.

2.3.5.2. Phase 2

In Phase 2, Ukraine should concretize and start implementing the projects prepared in Phase 1. Since – as described above – the availability of renewable electricity is the main bottleneck for hydrogen projects, it is important to **build up as many renewable energy sources as possible** and as quickly as possible. Given electrification needs, the risk of stranded investments is likely to be negligible.

The first blast furnaces should be converted to **direct reduction with hydrogen**, helping avoid lock-in effects and creating know-how that can be transferred to other plants. Partnerships between hydrogen producers and the steel industry should be intensified and binding contracts concluded. In **road transport**, too, the use of hydrogen or its derivatives should be ramped up where there is no other green alternative. This is particularly important because road transport is determined by many actors, possibly requiring a long and erratic decarbonization process.

In decarbonizing the ammonia industry, a two-part approach seems advisable: plants for ammonia production in which investments were made after the end of the war, for example, and which continue to be operated with natural gas, should increasingly be expanded to include **plants for carbon capture**. Plants that are due for major replacement investments in Phase 2 should consider the production of ammonia using hydrogen in addition to carbon capture, based on a sound cost analysis. This renewable ammonia will almost certainly be more attractive in the European market.

To prepare or start the **export of hydrogen**, partnerships concluded should be consolidated in long-term supply contracts. Since – as described above – hydrogen production in Ukraine is more expensive than in a number of other countries, it will probably also be important to involve the EU and implement an appropriate support regime.

In parallel, **licensing authorities** should be prepared for new technologies at an early stage, allowing them to implement appropriate processes and train employees. Since Ukraine is some years behind its partners, it is important that such processes be carried out quickly and yet in accordance with the relevant requirements so as to make up for lost time. In addition to this preparatory work, projects should gradually go into concrete operation.

2.4. Renewable Heating

The third pillar of Ukraine's green future will be renewable heating applications. The generation and transmission of heat come in many forms and are often more complicated to decarbonize than electricity. The specificities and opportunities of major sources of heat and the related technologies are explored in this section.

2.4.1. Geothermal Energy

For the purpose of this study, geothermal energy is understood to mean the direct transmission of thermal energy from the Earth's crust to the surface for use in heating processes. Geothermal energy is generally sustainable and renewable, although fluid extracted from the ground during the initial drilling can contain toxic chemicals and greenhouse gases, depending on the location. Moreover, most underground waters suitable for geothermal heat transfer are highly mineralized and can therefore not be discharged to surface water bodies after cooling due to environmental concerns. The only suitable option in most cases are thus open geothermal well systems where underground water is pumped to the surface for heat transfer and subsequently reinjected underground after cooling. This also boosts the efficiency of the heat transfer, as it makes the most of underground rock heat as well as groundwater heat. Ukraine has legal tools to allow the risks of these activities to be assessed and protective measures to be adopted, not least in the Law on Environmental Impact Assessment.[178]

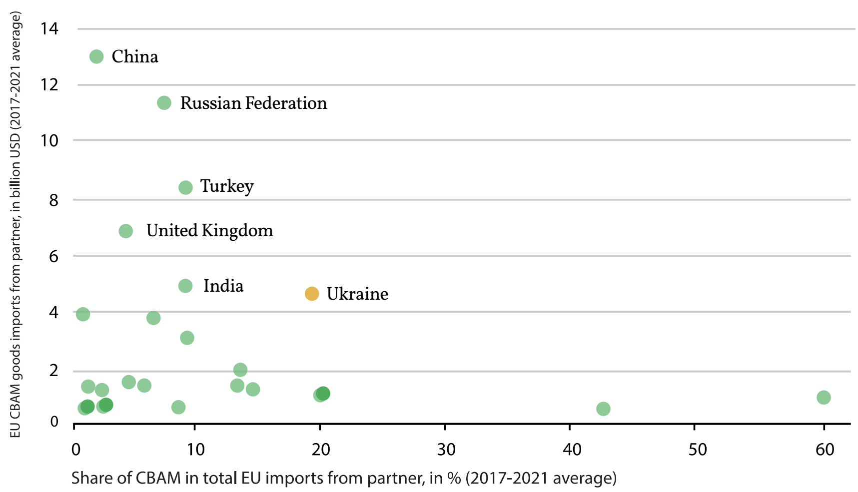

Figure 32: Modified Lindal Diagram Showing Applications for Geothermal Fluids
Source: Rudakov and Inkin, 'An Assessment of Technical and Economic Feasibility to Install Geothermal Well Systems across Ukraine', 3 July 2019, 37.3 July 2019, 37.

178 Rudakov and Inkin, 'An Assessment of Technical and Economic Feasibility to Install Geothermal Well Systems across Ukraine', 3 July 2019.

Applications for geothermal energy are often in the field of space heating, warm water supply or industrial low-grade heat. Examples are shown in Figure 33. Ukraine has substantial untapped geothermal energy potential. The map below shows the potential thermal output of geothermal plants across the country.[179] The Institute of Renewable Energy of the National Academy of Sciences of Ukraine calculates that the total geothermal potential for the whole country is 10.81 GW, or 80,494 GWh, with substantial opportunities especially in the regions Crimea and Kherson in the south, Chernihiv in the north, Zakarpattia and Lviv in the west, and Poltava and Kharkiv in the center-east (see Figure 33).[180] In theory, 80,000 GWh of geothermal energy could replace almost 9 billion cubic meters of gas.[181]

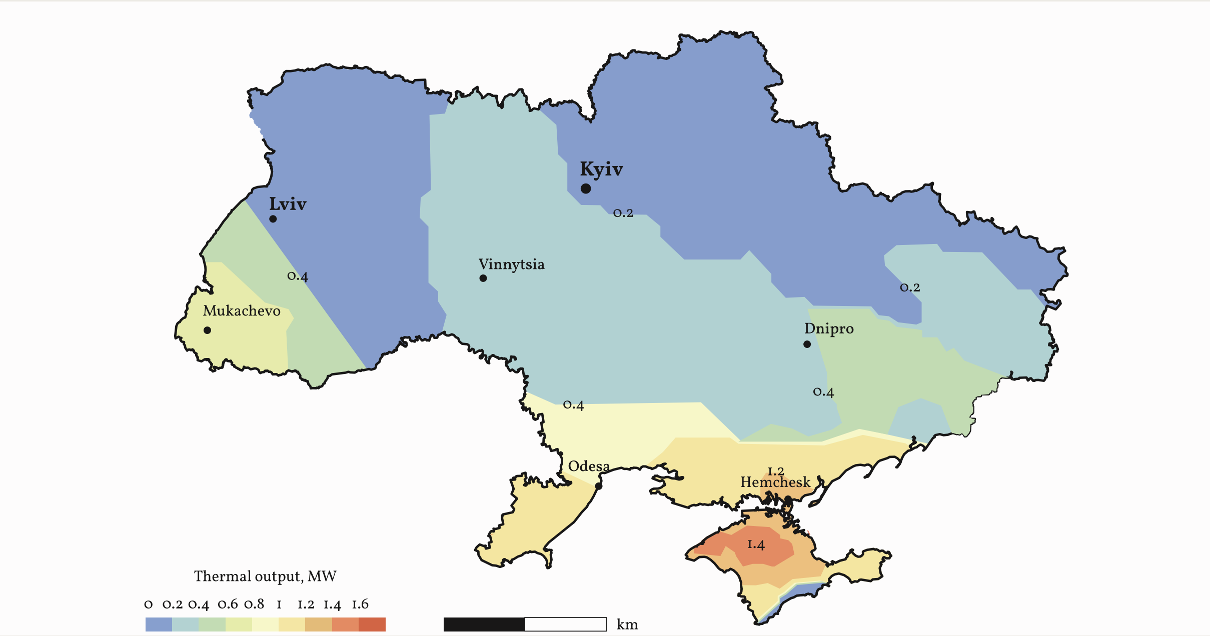

Figure 33: Distribution of expected thermal output across Ukraine
Source: Shogenov, 'Geothermal Prospects in Ukraine'.

Very little of this potential is currently harnessed in Ukraine (or elsewhere), due to high upfront investment costs, environmental issues, and the need for advanced technological knowhow. The need for special anti-corrosion materials and equipment for the capture and disposal of noxious gases also means that fixed maintenance costs are quite high, and half of a plant's total output is typically used to power process maintenance.[182]

179 Rudakov and Inkin, 'An Assessment of Technical and Economic Feasibility to Install Geothermal Well Systems across Ukraine', 3 July 2019.

180 Kudria, Institute of Renewable Energy, National Academy of Sciences of Ukraine.

181 Shogenov, 'Geothermal Prospects in Ukraine'.

182 Shogenov.

2.4.1.1. Phase 1 and 2

As with other types of renewable energy, the Ukrainian government needs to continue supporting geothermal energy by **facilitating investment and distribution.** This includes loan guarantees, incentives attracting investment and the accompanying expertise from allied countries, and openness to new, non-centralized and bottom-up methods and idea.

Initially, geothermal energy can be used for direct heating of buildings and low-intensity industrial heat applications in places where it is easiest to harness. Eventually, once large-scale investments are safe and realistic, deeper wells may be used for higher-intensity industrial processes or the production of electricity or other green energy carriers such as hydrogen or ammonia. Particularly in the east of the country, geothermal energy may partly fire the industry which is currently powered by coal.

At an early stage, Ukraine should **actively engage with its partners** and aim to attract a small number of international consortia willing to initiate such geothermal projects with local companies. This strategic collaboration can contribute to **capacity building** within the country which can, in the long run, facilitate the implementation of more geothermal energy initiatives.

2.4.2. Combined Heat and Power

Combined heat and power (CHP) is a technical process which allows electricity and thermal energy to be produced simultaneously from a single fuel source. It is a highly efficient type of energy conversion that can save some 40% of primary energy compared to the separate purchase of electricity from the national electricity grid and operating a gas boiler for on-site heating.[183]

CHP plants are available on many scales, ranging from small applications for domestic use to large-scale plants for industrial sites or district heating grids. Micro-scale CHPs for domestic use can have a capacity of up to 50 kW. Small-scale CHPs appliances for larger buildings and local heating grids range from 50 kW to 1000 kW. And medium and large-scale CHPs used on industrial sites or in district heating grids can have capacities as high as 540 MW for electric power and up to 1,650 MW for heating.[184]

In 2020, CHP plants in Ukraine consumed 4% of the country's total primary energy supply (see Figure 34). In the same year, CHP plants generated 1.417 million tons of oil equivalent of electricity and 2.902 million tons of oil equivalent of heat. At the beginning of 2022, the total installed power capacity of CHPs was 6.1 GW. This number excludes the plants located in the territories occupied by Russia before 24 February 2022.[185]

183 MAN Energy Solutions, 'MAN CHP, Engine Combined Heat & Power Plants'.

184 PJSC «Kharkiv CHPP-5», 'Equipment Characteristics'.

185 Cooperation for Restoring the Ukrainian Energy Infrastructure Project Task Force, 'Ukrainian Energy Sector Evaluation and Damage Assessment X'.

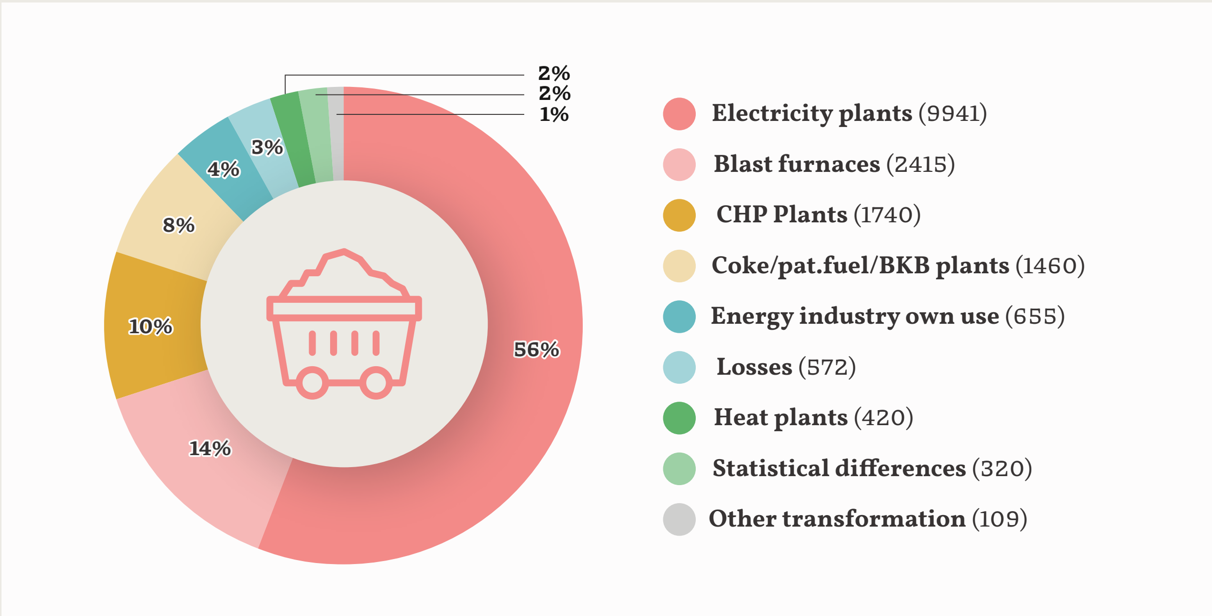

Figure 34: Total primary energy supply in Ukraine in 2020
Source: Own illustration, based on State Statistic Service of Ukraine, 'Energy Balance of Ukraine'.

In March 2023, approximately 8% of the installed CHP capacity was under Russian occupation. Furthermore, 48% of installed capacity was either destroyed or damaged. This includes two-thirds of CHP plant capacities used for balancing the power system. According to Energy Charta, five CHP plants located near the frontline were destroyed, while eight CHPs in the regions of Kharkiv, Sumy, Mykolaiv, and Kyiv were damaged.[186] In addition, the rising costs of gas has been raising constraints for entire domestic generation, pushing many CPH plants to shut down operations.[187]

District heating plays a major role in Ukraine's residential sector, where 60% of heating originates in heat-only boilers and 40% in CHP plants.[188] (More information on this topic can be found in the next section, which focuses on district heating section of this report.) CHP Plants are also used in the industrial sector for heat production.

As shown in Figure 35, in 2020, most CHP plants operated with natural gas, followed by coal and peat. Biofuels and waste together accounted for no more than 3% of the energy resources used in CHP plants.[189] CHP plants offer several advantages, thanks primarily to their high efficiency. They can deploy renewable energy, although this can be less efficient, for instance if the fuel used is hydrogen. Even so, CHP plants can gainfully use hydrogen during shortages of other types of renewable energy to ensure continuous power generation and grid stability.

186 Cooperation for Restoring the Ukrainian Energy Infrastructure Project Task Force, 'Ukrainian Energy Sector Evaluation and Damage Assessment X'.

187 mind, 'Харківська ТЕЦ-5 Зупиняє Діяльність Та Консервує Обладнання Через Зростання Ціни На Газ'.

188 Energy Community Secretariat, 'Annual Implementation Report 2022'.

189 State Statistic Service of Ukraine, 'Energy Balance of Ukraine'.

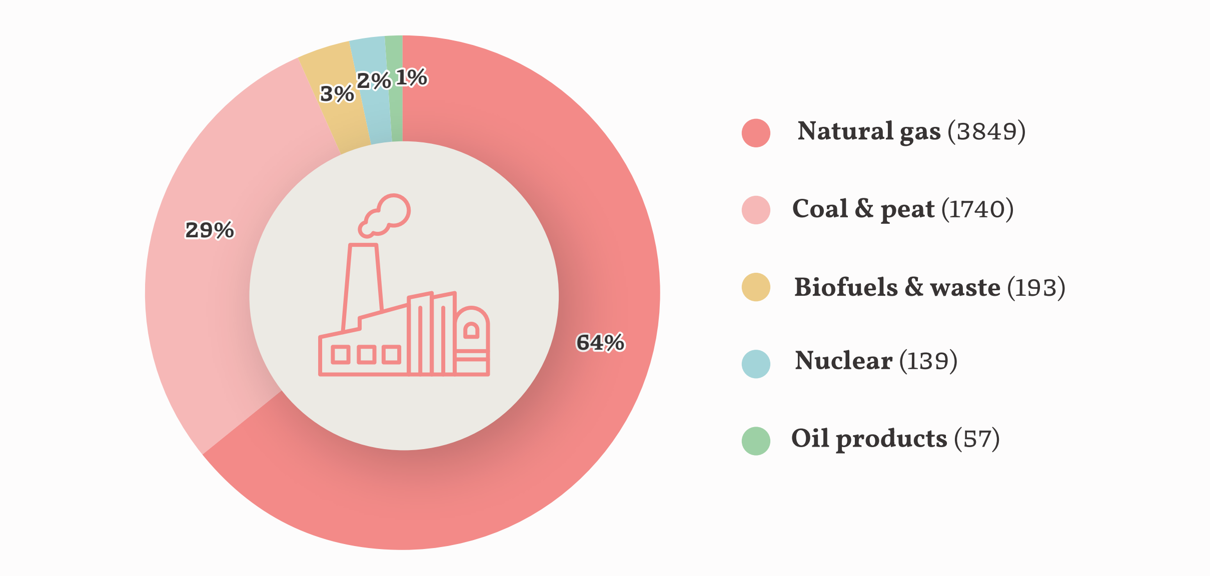

Figure 35: Resources/fuels used in 2020 to operate CHP plants in Ukraine in 2020, in thousands of tons of oil equivalent
Source: Own illustration, based on State Statistics Service of Ukraine, 'Energy Balance of Ukraine'.

The benefits of bioenergy in CHP plants also have their limits. For one thing, the production of certain types of bioenergy is not necessarily much more sustainable than the use of fossil fuels. Waste and residual material can be deployed in CHP plants to benefit sustainability, however, there are issues of availability that make this solution complex on a very large scale. For these reasons, CHP plants should play a role in the future Ukrainian energy system for the purpose of providing grid stability during wind or solar shortages, but the focus should stay firmly on the production of renewable energy through wind and solar.[190]

The Ukrainian government has also acknowledged this fact. CHP plants are a component of the Energy Strategy of Ukraine until 2050, which notes that electricity generation from intermittent wind and solar power requires balancing of the grid from quickly dispatchable sources as well as energy storage. The government plans to achieve this balancing and reserve capacity through a range of measures, of which CHP plants are one. They are likely to be operated with natural gas, biomethane and biofuels derived from sources like solid household waste, agricultural waste and wood. CHP plants are also included in the Energy Strategy of Ukraine until 2050 for the replacement of coal-fired generation. By 2050, the available capacity provided by biofuel-powered CHP plants is projected to reach 4%. There is more information on these topics in the sections 2.1.5 Bioenergy and 2.4 Energy Storage of this study.

According to EU regulations, newly constructed CHP facilities are typically required to be "hydrogen ready," i.e., prepared to accommodate hydrogen as an energy source. It is advisable for Ukraine to consider implementing similar measures to future-proof any new CHP installations and to facilitate its energy market's integration into the European Union.

190 Huber et al., 'Kraft-Wärme-Kopplung, Von Der foKraft-Wärme-Kopplung. Von Der Fossilen Effizienztechnologie Zu Einer Neuen Rolle in Der Wärmewende. Policy Paper Der Scientist for Future.'

2.4.2.1. Phase 1

In Phase 1 of Ukraine's green recovery, combined heat and power (CHP) plants should be included in the technological feasibility analysis mentioned in the Energy Strategy of Ukraine until 2050, and considered in the relevant cost-benefit analyses, especially as a grid balancing solution. The government should also see to it that:

- Instruments are implemented to ensure that the CHP plants which are installed can operate with **renewable energy** carriers.
- CHP plants are **hydrogen ready** or can carry hydrogen derivatives as a measure to balance the grid system or during capacity shortages.
- Regulations are implemented to support the use of **sustainable bioenergy** only (originating in residual materials and waste).
- CHP plants are able to function at a high level of efficiency. If energy is generated from bioenergy sources, CHP plants should be the **prioritized** technology.
- Targets are developed for the use of CHP which interlink with other measures so as to **secure grid stability**.

2.4.2.2. Phase 2

In the second phase of the green transition, Ukraine should:

- **expand** the use of CHP for grid stability, in combination with storage and an increase of renewable energy capacities and transmission capacities according to the targets developed in phase 1;
- **retrofit** existing CHP plants for the use of renewable energy carriers;
- **monitor and adjust** the measures and regulations required to achieve the targets; and
- deploy biogas only if it meets strict sustainability criteria, for example by using only biomass from waste and residual materials.

2.4.3. District Heating

District heating – a centralized network of pipes that distributes heat to homes, business and public services – is particularly prevalent in the former Soviet Union and parts of Central Europe, for historic, economic and cultural reasons. In Ukraine, 53% of urban households still relied on it in 2021. The size, age and dispatchability requirements of these systems mean that they were built for, and are currently almost exclusively powered by, fossil fuels. However, relying on large-scale centralized heating sources, they can theoretically be adapted for use with more sustainable fuels much more easily than the small-scale distributed heating systems that are more common in Western European residential buildings.[191]

The fuel can come from biomass or waste heat from sewage systems, industrial processes or even data centers. The complexes can be combined with electric power generation in combined heat and power plants. (More information on these topics can be found in the sections 2.1.5 Bioenergy, 2.3.2 Combined Heat and Power and 2.3.4 Heat Pumps of this report.) In Ukraine, there have been a number of projects funded by foreign donors to retrofit old and dilapidated district heating systems in cities including Kyiv, Zhytomyr and Kremenchuk.[192]

191 Nugent, 'Soviet-Era Centralized Heating Systems Were Ukraine's Secret Weapon for Cutting Emissions. Now They're a Vulnerability'.

192 Nugent.

According to a report prepared under the Horizon 2020 project KeepWarm, heat generation efficiency by boiler houses in Ukraine is 89% on average, but 40% of boilers, and substantial numbers of auxiliary equipment such as pumps, needed to be modernized or replaced already in 2018. Most of the pipelines are made of black steel and therefore poorly insulated, while being older than 25 years.[193] At the same time, the level of investment in modernization projects has been far below what is required. The poor state of the equipment and sometimes high natural gas prices keep companies' operational expenses at a substantial level, while tariffs for heat are set by politicians at a level that does not allow for investments, or indeed even cover the expenses. Subsidies fill the gap, but generally only partly.[194]

In the years preceding the war, significant progress was achieved in switching from lump-sum billing (per size of residence) to consumption-based billing, and the share of buildings benefiting from district heating and equipped with heat meters expanded from 40% in 2014 to near full coverage. Even so, this generally still only means heat metering at the level of individual buildings, with the intensity of heat adjusted at the generation source. This makes it difficult for end users to control their consumption and reduces the impetus for energy efficiency improvements. It has led to individual heating units (mostly electrical resistance systems) being installed at many residential and public buildings in Ukraine to top up the heat supply in a way that consumers can fine-tune.[195] Between 1995 and 2018, the share of urban households in Ukraine benefiting from district heating decreased from 89% to 55%. The solutions which have replaced it have led to reduced efficiency and increased pollution, while burdening other infrastructure, including electricity and gas supply, unduly. In some cases, individual boilers can be of poor quality or fitted in buildings not designed with proper ventilation from individual apartments, leading to health and safety risks. These can in turn be worsened by insufficient maintenance.[196]

It is important to note that it doesn't necessarily make sense to simply replace old equipment with new equivalents, since district heating systems in Ukraine currently have far too much capacity, partly because they were built in the Soviet era when there was far more demand from industry, partly thanks to improved insulation and energy efficiency among consumers, and partly because so many individual (mostly electrical) heating systems have been installed in households and other buildings, leading to a fall in demand for hot water especially. This leads to operational inefficiency.[197]

2.4.3.1. Phase 1

A major priority for central and local governments, public authorities, and utilities after the war ends should be to escape the "**vicious circle of district heating**" as defined in a recent report for USAID (see Figure 36).[198] The many institutions involved in planning and operating district heating must come together to enable **consistent policymaking**, perhaps through a specific overarching coordination mechanism. The first step should be to ensure **financial stability** for district heating operators by seeing that tariffs allow costs to be recuperated, regulations are conducive to efficient operations, and end users pay on time and in full (More information on financial instruments and recommendations can be found in the preliminary financial study published in parallel with this report).

In parallel, there should be an analysis of the state of existing large-scale centralized district heating systems throughout Ukraine and a thorough

193 KT-Energy LLC, 'District Heating in Ukraine'.

194 Tetra Tech ES, 'White Paper on Transforming District Heating in Ukraine'.

195 KT-Energy LLC, 'District Heating in Ukraine'.

196 Tetra Tech ES, 'White Paper on Transforming District Heating in Ukraine'.

197 Tetra Tech ES.

198 Tetra Tech ES.

cost-benefit review for a range of future options. These should include:
- **reconstruction and refurbishing** of existing systems;
- **decentralization** to smaller units (on the level of residential or factory blocks, for instance); and
- **installation of individual** heating systems in residences and offices.

The analysis should be **comprehensive**, taking into account:
- the complexity of the required investments;
- the practical availability of the equipment necessary and the time and cost required for its installation and maintenance; and
- the net value added for consumers and municipalities as well as suppliers and investors.

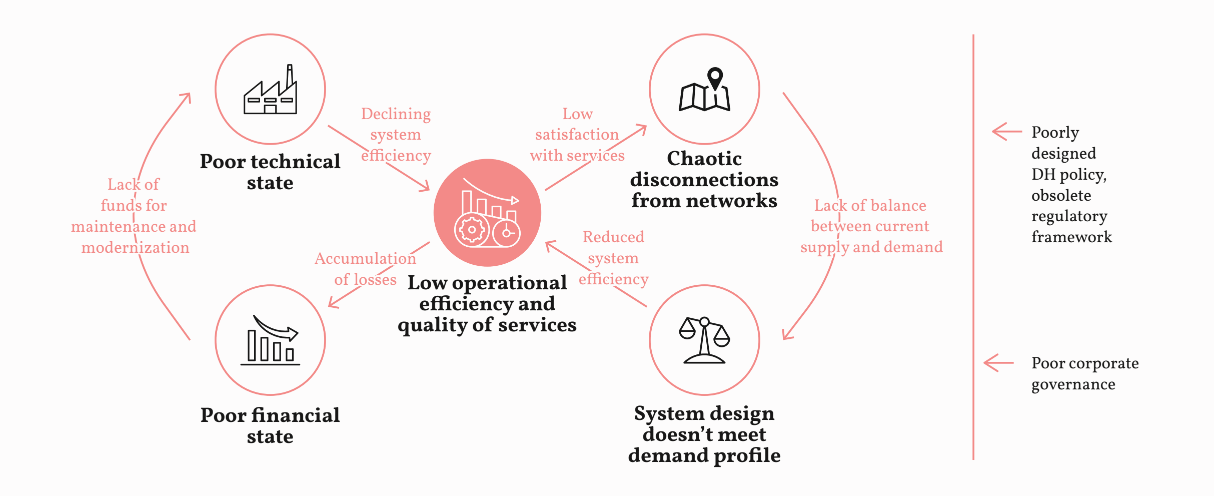

Figure 36: The vicious circle of district heating
Source: Tetra Tech ES, 'White Paper on Transforming District Heating in Ukraine'.

Before a comprehensive approach is defined, individuals and institutions should be discouraged from installing multiple smaller systems, which are likely to run on fossil fuels and may end up being comparatively harder to convert to sustainable operation given that they will be more recent and decentralized.

Another step should be to define a framework allowing for **more competition** in the district heating sector. The Ukrainian Law on Natural Monopolies recognizes that the transportation of heat is a natural monopoly, leaving the generation and supply of heat as potentially competitive markets.[199] In practice, however, the three activities are still carried out by the same companies, minimizing market incentives for better quality and prices.[200] Potential reforms could include expanding the competences of regulatory bodies, amongst other things, making them responsible for determining grid fees.

Ukraine should prepare a **comprehensive strategy**, a district-heating transition plan, to prepare the long-term transformation and decarbonization of its district-heating systems and to inform the necessary steps for the next phase.

199 Bulletin of the Verkhovna Rada of Ukraine, Закон України про природні монополії.

200 KT-Energy LLC, 'District Heating in Ukraine'.

2.4.3.2. Phase 2

The longer term can provide an opportunity for Ukraine to become a true climate leader in terms of district heating, as long as **proper planning and sufficient investments** of funds and expertise are available. This will include repairs and upgrades of major equipment, an expanded role for **climate-neutral and sustainable fuels** such as biomass, a streamlining of the district heating system to better respond to demand, improved **energy efficiency** and insulation, and a more competitive market.

The full **implementation of EU regulations** governing the heating of buildings is of paramount importance. These regulations provide a comprehensive framework for enhancing the energy efficiency and sustainability of heating systems in buildings. By aligning with these EU standards, Ukraine can create a favorable environment for foreign investors and set the groundwork for its future EU membership. (More information on this topic is available in the preliminary legal study.)

A lack of **competition** contributes to inefficiencies in the sector and discourages market entry by new players as well as investment, especially foreign investment. As with other types of economic activity, and energy-related ones in particular, the state has a major role to play in streamlining the legal system for quick and fast contract enforcement and dispute resolution. Investment can also be boosted by **targeted loan guarantees**.

Human resources are another long-term priority. The deployment of modern heat generation and transmission equipment will require new skills and ideally regular trainings and education. Salaries should reflect market conditions and encourage the recruitment of the staff required to implement the sector transformation.

To facilitate these efforts, it is imperative to **enhance the financial stability** of the district heating systems. This can be achieved, in part, through the implementation of more precise and non-competition-distorting tariff structures, coupled with the widespread adoption of individual **metering systems**. In the future, it will also be essential to consider the social effects of rising energy prices for tenants using district heating. Ensuring overall affordability and fairness will be crucial for a successful transition.

2.4.4. Heat Pumps

In buildings and industries, heat pumps offer a highly efficient solution for decarbonizing the provision of sanitary hot water, space heating, and low-temperature process heat. By predominantly extracting heat and cooling from ambient energy sources like the air, ground, or ground water, heat pumps considerably outperform conventional heating technologies in terms of efficiency. The remaining energy required is usually supplied in the form of electricity, ideally sourced from renewable sources. Compared to natural gas boilers, heat pumps are three to five times more energy efficient. For instance, a typical household heat pump has a coefficient of performance of around 4, indicating that the energy output is four times greater than the electrical energy consumed to operate it.[201]

Electrification, with heat pumps at the forefront, is expected to contribute significantly to reducing direct carbon dioxide emissions in the buildings sector by around 50% by 2050. As the grid's share of renewable energy sources increases, the environmental benefits of existing heat pump systems also grow, making them a sustainable and future-proof choice for heating and cooling in the energy transition.[202] Compared to gas boilers, heat pumps using today's refrigerants reduce greenhouse gas emissions by at least 20%, even when running on electricity generated from emissions-intensive sourc-

201 International Energy Agency, 'How a Heat Pump Works'.

202 International Renewable Energy Agency, Renewable Solutions in End-Uses: Heat Pump Costs and Markets.

es. When the energy mix is cleaner, this reduction can be as significant as 80%.[203]

For instance, when comparing the emission values of natural gas combustion for producing thermal energy and electricity (0.202 tons of carbon dioxide equivalent per megawatt-hour) with emissions from electricity consumption in Ukraine (0.663 tons of carbon dioxide equivalent per megawatt-hour), there is a considerable 30.4% reduction in greenhouse gas emissions achieved with heat pumps.[204] Additionally, heat pumps offer the advantage of providing flexibility to the electricity system. By incorporating water storage, they can operate during periods of low electricity prices, storing energy as heated water for release when electricity demand and prices are higher. [205] This feature contributes to a more efficient and adaptable electricity system.

There are downsides to the heat pump technology as well, however. Firstly, heat pumps typically have high upfront investment costs. Even the most affordable air-to-water heat pump models, including modifications to existing radiator systems, remain two to four times more expensive upfront than natural gas boilers in most major heating markets. Secondly, an accelerated deployment of heat pumps would inevitably lead to an increase in electricity demand. For households that add a heat pump without improving efficiency at the same time, peak electricity demand during winter can nearly triple.[206] The high electricity demand for running heat pumps also contributes to relatively high operation costs. Electricity costs are generally higher than those of fossil fuels, as fossil fuels do not fully account for the real cost of their externalities (such as local and global pollutant costs) and often still receive subsidies.[207]

One way to address these challenges is through moderate to deep energy efficiency renovations. Such renovations can significantly improve the economics of heat pumps by reducing the required operating temperature (thus boosting efficiency) and decreasing the size of the heat pump needed. Older, poorly insulated buildings with existing hydronic heat distributing systems (like wall-mounted radiators) often require higher flow temperatures, which can reduce the efficiency of heat pumps, and necessitate larger peak capacities to meet the demand. Therefore, especially in countries where building sector policies prioritize energy efficiency and renewable requirements in new buildings, heat pump technologies can prove to be the most economical and sustainable solution.[208] There is more on this topic in the section 2.5 Energy Efficiency of this report.

Heat pump capacities for space and water heating needs in buildings range from a couple of kilowatts to systems with capacity in the megawatt range. The biggest single heat pumps today have a capacity of around 35 MW, but manufacturers such as BASF and MAN Energy Solutions have announced projects for heat pumps with a thermal output of up to 120 MW.[209]

Ukraine's 2023 Energy Strategy until 2050 outlines policy measures which aim to enhance energy efficiency, including a program to install micro boilers which use methane as fuel in apartment buildings and the fitting of heat pumps in private homes and larger district heating units. Ukraine has set ambitious targets for the share of alterna-

203 International Energy Agency, 'World Energy Outlook, Special Report: The Future of Heat Pumps'.

204 Banja and Oppelt, 'Market Study on Mitigation Potential for Heat Pump and Commercial Refrigeration Equipment in Ukraine'.

205 International Renewable Energy Agency, Renewable Solutions in End-Uses: Heat Pump Costs and Markets.

206 International Energy Agency, 'World Energy Outlook, Special Report: The Future of Heat Pumps'.

207 International Renewable Energy Agency, Renewable Solutions in End-Uses: Heat Pump Costs and Markets.

208 International Renewable Energy Agency.

209 Fabian, 'Joint News Release: BASF and MAN Energy Solutions Enter into Partnership for Construction of One of the World's Largest Heat Pumps in Ludwigshafen'.

tive energy sources in heat production by heat supply facilities. By 2025, the goal is to reach a share of 30%, and by 2035, the target is set at 40%.[210]

By some estimates, a large-scale buildout of heat pumps in Ukraine could allow a reduction of up to 12 million tons of carbon dioxide equivalent by 2030. Their usage today remains limited however, and progress has been slow. Currently, the heat produced from heat pumps in Ukraine accounts for only 0.05% of the gross final energy consumption, 1% of final renewable heat, and 0.8% of the final consumption of renewables.[211]

2.4.4.1. Phase 1

For the Ukrainian heat pump market to thrive, the period immediately following the end of the war in Ukraine should comprise a number of policy changes. The current focus on centralized heating, without adequate attention to the efficiency of heating and energy systems, needs to be addressed. The adoption of heat pump technologies should be supported and promoted through subsidies and grants, while implicit and explicit **subsidies for fossil fuels should be phased out**. And these programs should be revised continuously to encourage energy-efficient technologies, such as heat pumps, driving **greater uptake**.

To address the issue of grid stability, Ukraine could consider implementing a regulatory framework that grants grid operators the capability to remotely manage and control heat pump systems, enabling them to optimize energy consumption during peak periods. Furthermore, Ukraine can launch **comprehensive smart grid projects** that encompass various elements of energy management including the supply of heat pumps. These projects could identify best practices and inform decisions regarding heat pump deployment and grid adjustments.

2.4.4.2. Phase 2

Two years after the end of the war, the measures taken should become more large-scale and structural. There should be increased government support for research & development, and the introduction of heat pump technologies. Investing in **advancements like natural refrigerants** with low greenhouse gas potential, such as hydrocarbons, can improve the overall thermodynamic properties of heat pumps and further enhance the environmental sustainability of the technology.

210 Ukraine's Cabinet of Ministers, 'Energy Strategy of Ukraine until 2050'.

211 Banja and Oppelt, 'Market Study on Mitigation Potential for Heat Pump and Commercial Refrigeration Equipment in Ukraine'.

2.5. Energy Storage

Energy storage plays a major role in the system integration and decentralization of the energy market. This includes grid-scale energy storage feeding into the electrical grid, storage of electricity for direct use, electrification of the transport sector through the deployment of batteries, and heat storage.[212]

The damage to Ukraine's electrical grid infrastructure caused by the war has resulted in recurring power outages, prompting hospitals, government institutions, businesses, and individuals to seek alternative power solutions. In this context, portable battery energy storage systems and solar panels have the potential providing backup electricity, albeit for a limited duration. A relatively low-power portable 700 W and 220 V battery energy storage system can meet the power requirements of a typical family living in a small apartment.

In addition, grid-scale storage technologies can provide significant system services in a decentralized and decarbonized energy system, including short-term balancing and operating reserves, ancillary services for grid stability and deferment of investment in new transmission and distribution lines, to long-term energy storage and restoring grid operations following a blackout.[213] The Energy Strategy of Ukraine until 2050 aims to increase the capacity of energy storage facilities, including long-term (seasonal) storage devices that use power-to-X technologies, to help balance the power grid. As Figure 37 shows, there has been a major increase in annual additions to grid-scale battery storage from 2015 to 2021 worldwide. There are a number of technologies that allow the storage of electric as well as heat energy.

2.5.1. Pumped-Storage Hydropower

According to the International Energy Agency, pumped-storage hydropower is the most widely deployed grid-scale storage technology worldwide, with total installed capacity of around 160 GW in 2021. Global capability was around 8,500 GWh in 2020, accounting for over 90% of total global electricity storage.[214] In 2021 Ukraine had a total installed pumped-storage hydro capacity of 6,317 MW. This has undergone some changes lately: a 324 MW unit added to the Dnister pumped-storage plant in 2021 raised the plant's total installed capacity to 1,296 MW and 1,684 MW in pumping mode, but the Kakhovka Dam, with a capacity of 334.8 MW, was destroyed on 6 June 2023 (see section 2.1.4 Hydropower for more information).[215]

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212 International Energy Agency, 'Energy Storage'.

213 International Energy Agency.

214 International Energy Agency, 'Grid-Scaled Storage'.

215 International Hydropower Association, '2022 Hydropower Status Report'; Kyrylenko, 'Flooded South: The Consequences of Blowing up the Kakhovka Dam'.

2.5.2. Lithium-Ion Batteries

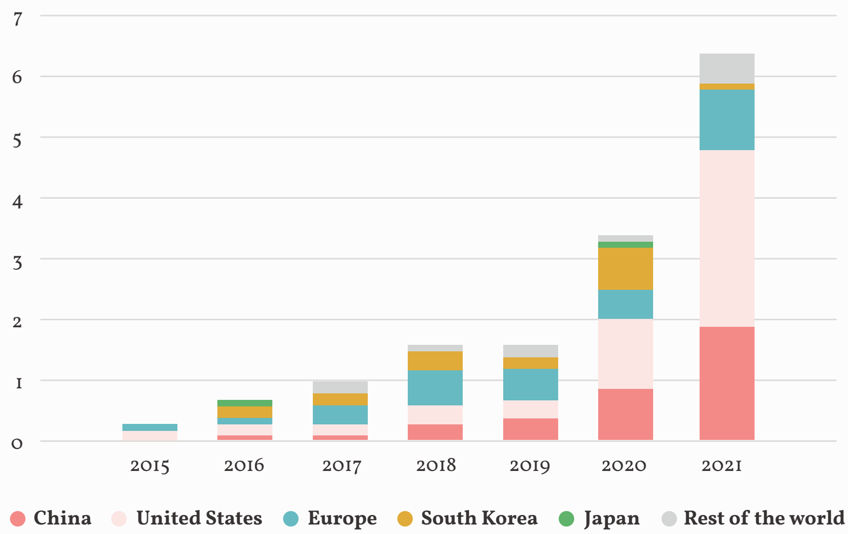

Figure 37: Annual grid-scale battery storage additions, 2016-2021
Source: International Energy Agency, 'Annual Grid-Scale Battery Storage Additions, 2016-2021'.

Lithium-ion batteries are another very common form of electricity storage. They can be used as portable energy storage systems (such as batteries in cars) as well as for grid-scale storage. The largest energy storage project in Europe is currently BigBattery Lausitz in Germany, with 8,840 lithium-ion battery modules with a usable capacity of 53 MWh.[216] Lithium-ion batteries do, however, require a large amount of resources such as lithium, nickel, cobalt, graphite, manganese, aluminum, tantalum, magnesium, and vanadium. As shown in Table 3 below, Ukraine has the potential to mine all of these minerals and is in fact already exploiting some of them.

Lithium-ion-batteries face certain obstacles, particularly problems linked to environmental impact and the supply chain. The estimated carbon emissions of lithium mining are estimated to be above 1.3 million tons per year, with each ton of lithium mined corresponding to the release of 15 tons of carbon dioxide into the atmosphere. These mining operations can also cause toxic metals to leach into water sources, posing a threat to human populations as well as animal biodiversity.[217]

Waste recovery and recycling are other important aspects of the production and use of lithium-ion batteries. Ukraine has generally had significant difficulties in the waste recovery and recycling of batteries and has accumulated thousands of tons of used batteries over the past decades. In the best-case scenarios, these batteries are stored in warehouses, but, more frequently, they are disposed of in landfills or, alarmingly, even find their way into the Black Sea. Storing old batteries in landfills is a wasted opportunity: recycling processes allow the critical resources to instead be reused. So far, Ukraine has no industrial facilities that would enable this type of recycling, however. This will have

216 „et"-Redaktion, 'Sicherheit Für Die Energiewende – Das Größte Batterie- Speicherprojekt Europas Arbeitet in Der Lausitz'.

217 Earth.org, 'The Environmental Impacts of Lithium and Cobalt Mining'.

to change, especially given the likely increase in demand in the future (see Figure 38).[218] It should also be mentioned that batteries that are no longer useful for cars can still be used to help stabilize the grid, reducing their environmental impact and the consumption of resources.

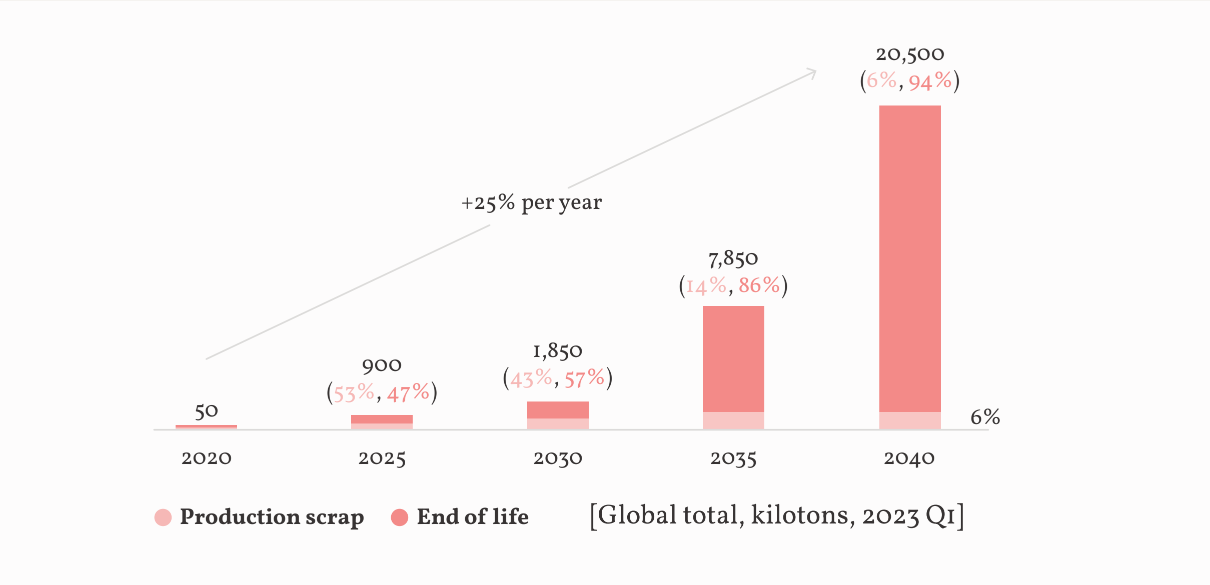

Figure 38: The global supply of batteries for recycling, global total in kilotons
Source: McKinsey & Company, 'Battery Recycling Takes the Driver's Seat'.

2.5.3. Other Long-Duration Energy Storage

While pumped-storage hydropower and lithium-ion batteries are the most commonly considered types of energy storage – for instance by the experts surveyed in the framework of this study (see section 4 Expert Survey of Innovative and Clean Technologies for more details) – there is a wide range of available storage technologies to consider for implementation in Ukraine's future energy landscape. Energy storage systems can be divided into electrochemical, thermal, mechanical, and chemical.[219]

Concerning electrochemical storage systems, the experts in the survey assign **redox flow batteries** a high likelihood of complying with European strategic energy priorities. Furthermore, they are noted as having potential in the fields of supply security impact and contribution to net zero. Thanks to the low internal energy consumption of the system and efficient electrochemical reaction, the overall efficiency of redox flow batteries is up to 75%.[220] They have several advantages such as scalability of performance and capacity, safety, recyclability and a long service life of 15 to 20 years. The largest redox flow battery storage system so far, located in Dalian in China, has a capacity of 100 MW and will eventually be scaled up to 200 MW.[221] There are many battery manufacturers in Ukraine, producing a wide range of electrochemical battery sys-

218 Gerasimov, 'Activists Sent First 100 Tons of Batteries from Ukraine for Recycling Abroad: Why and How It Works'.

219 Future Cleantech Architects, 'Long Duration Energy Storage for the Power System'.

220 Kühne and Wenske, 'Redox-Flow-Batterie: Funktionsweise Und Typen| DiLiCo'.

221 Santos, 'China Connects World's Largest Redox Flow Battery System to Grid'.

tems, including lithium-ion batteries, lead-acid batteries, and alkaline accumulator batteries.[222]

Thermal energy storage systems are designed to capture and retain thermal energy for subsequent use. Depending on the application and technology used, this can be achieved with high-temperature heat or cryogenic cold while retaining (sensible heat) or changing (latent heat) the phase of the storage material. Technologies in this field include **molten salt** or **thermal oil systems**, already in extensive use to transport and store energy in solar power plants, phase change applications such as **liquefied air**, and power-to-heat applications based on large-scale heat pumps. Thermal energy storage offers high energy density, long-duration storage capabilities, efficiency in capturing and releasing energy, and synergies with other energy sectors, e.g., heat supply for buildings through district-heating. Drawbacks include relatively high costs, particularly for large-scale applications, due to the need for specialized materials and infrastructure as well as space requirements for some technologies.

Energy can also be stored **mechanically**. Apart from stored hydro described above, an additional example are **compressed-air energy storage systems**, a clean storage medium with a high lifetime scalability, low self-discharge, long discharge times, relatively low capital costs, and high durability. Its main disadvantages are its long response time, low depth of discharge, and low roundtrip efficiency.[223] There are no compressed-air energy storage systems in Ukraine yet. Other mechanical energy storage technologies include gravitational storage and flywheel energy storage.

Excess energy can be used to produce substances such as hydrogen and ammonia that can be used as chemical energy storage. Both offer high energy density, making them well-suited for long-duration and portable applications, and can be utilized for various energy vectors, including electricity and transportation fuels. However, they face challenges such as energy conversion losses during production and utilization, infrastructure requirements for transportation and storage, and safety concerns due to high flammability or toxicity. Please refer to (see section 2.2 Hydrogen and its Derivatives for further information.[224]

The energy storage technology sector is fast developing and there is a wide range of technologies that can be considered. Given the breadth of applications required, stakeholders in the Ukrainian energy system should assess all options, pursuing a technology-open approach.

2.5.4. Critical Raw Materials

Most grid-scale energy-storage systems require a substantial amount of raw materials, many of which have few other purposes, and many of which are quite rare.[225] The European Commission keeps and updates a list of critical raw materials of particular importance to Europe's economy. These materials are defined as contributing to the industrial base and being necessary for a wide range of goods, services, and technologies. Moreover, their availability is a concern, often for political reasons. In other words, the supply of critical raw materials is both important and risky.

Storage technologies such as batteries are a prime example of a field reliant upon critical raw materials. As mentioned above, Ukraine has access to a large number of such materials – for instance, all of those required to build lithium-ion batteries (see Table 3). This does not mean, however, that they are available in sufficient quantities for all applications – for instance, vanadium, which is used in many batteries, is imported into Ukraine mainly from Czechia (447 tons in 2019).[226] But Czechia itself imports 88% of its vanadium from Russia, which accounts for 21% of global vanadium oxides

222 EuroPages, 'Ukraine Manufacturer Producer Batteries - Europages'.

223 Rabi, Radulovic, and Buick, 'Comprehensive Review of Compressed Air Energy Storage (CAES) Technologies', 104.

224 Future Cleantech Architects, 'Long Duration Energy Storage for the Power System'.

225 The Economist, 'How to Avoid a Green-Metals Crunch'.

226 WITS, 'Ukraine Ferro-Alloys; Ferro-Vanadium Imports by Country in 2019'.

production and 25% of world vanadium oxides exports.[227] In other words, these are indirect imports from Russia to Ukraine, which should be avoided for obvious reasons.

Critical raw material	Potential to mine in Ukraine
lithium	• Close to 500,000 tons of lithium deposits are found in Proterozoic complexes • Promising areas such as Dobra and Kruta Balka, along with deposits like Shevchenkivske, Polokhivske, and Stankuvatske, have revealed substantial reserves of lithium
nickel	• Deposits of nickel are associated with silicate ores in the residual soil of ultrabasites, magnesium in potassium salt and brine are exploited in Ukraine • Nickel-bearing ore is already mined • High potential for copper-nickel mineralization in Volyn' gabbro-dolerites
cobalt	• Deposits of cobalt associated with silicate ores in residual soil of ultrabasites, magnesium in potassium salt and brine are exploited in Ukraine
graphite	• Ukraine has considerable graphite resources: its reserves comprise up to 6 million tons of proven resources and 2 billion tons of probable resources
manganese	• Ukraine has the world's biggest surveyed resources of manganese ore • It is a top producer of manganese ore and ferroalloy products • There are considerable resources in the Dnipro manganese-ore basin and the Velykyi Tokmak deposit • Total resources of ore comprise 2.26 billion tons, including oxidative, oxidative-carbonate and carbonate types
aluminum	• Deposits of aluminum have been found • There is ferrous bauxite in the Vysokopillia deposit in the Dnipro region, from which ferrosilicon and alumina are extracted • There are good prospects for the discovery of high-quality bauxites in Serednie Prydnistrovia • Zakarpattia alunites may be considered a potential aluminum raw material
tantalum	• There are proven deposits of tantalum in Ukraine • The most important deposit is in the Ukrainian shield, which has 22 rare-metal formations, including tantalum-niobium-zirconium ores in Mazurivka

Table 3: Potential to mine critical raw materials in Ukraine
Source: WDC-Ukraine, 'National Atlas of Ukraine, Mineral Resources'.

227 'The Supply of Critical Raw Materials Endangered by Russia's War on Ukraine'.

2.5.5. Recommendations

Recommendations for technologies related to energy storage in Ukraine after the war can be divided into two periods.

2.5.5.1. Phase 1

In the first years after the war, a crucial goal for Ukraine will be to ensure energy security. The use of storage systems as an integral part of the green transition will need to be increased, while the risks of environmental effects and human rights violations must be minimized. The following should take place in the first years after the war:

- The access of residents to **small-scale storage** systems connected with **solar power** generation should be facilitated.
- There should be an evaluation of where **grid-scale storage** capacity is needed and how grids should be expanded to accommodate it.
- A specific tailored solution is necessary for a wide range of applications, so **a range of different storage technologies** should be explored.
- A **technology-open** approach should be pursued.
- Regulations and monitoring based on **environmental EU law** should be introduced to ensure environmentally sound mining and recycling.
- Regulations supporting **second-life use** for batteries should be developed.

2.5.5.2. Phase 2

The second phase, which will involve large-scale increases in renewable energy, will require **much more storage** capacity. This should be accompanied by the following measures.

- **System integration** should be improved through the connection of car batteries to the grid.
- **Battery recycling** should be improved by establishing an elaborate recycling landscape for energy storage technologies and by removing old stockpiles of batteries from landfills.
- **Scaled storage** systems should be implemented.
- The **mining of raw materials** critical to battery production should be safeguarded and expanded where possible.

3. Cost-Benefit Analysis of Different Sources of Electricity

Given limited resources in terms of time, finance, raw materials and expertise, and the various externalities linked to different types of power production, it is important to be aware of the total net costs and benefits of a given installed capacity for each type of power generation technology. Many of these are financial, or can be reasonably expressed in financial terms, while others, such as the risk of accidents or military or terrorist attacks, or the value of flexible dispatchable power to counter the fluctuations of intermittent renewables, can be hard to quantify. The cost or benefit of these externalities can moreover fluctuate greatly depending on the circumstances – for instance, the value of dispatchability rises with the proportion of intermittent renewables in the energy mix. This section provides a reasonably comprehensive overview of all the relevant elements for each of the major power generation technologies currently present or considered in Ukraine.

Figure 44 below shows average levelized cost of electricity (LCOE) for a range of technologies, based on aggregated data originating in the Ukraine LCOE Calculator of the Clean Energy Lab. These numbers assume no carbon dioxide emissions tax and a single cost of capital for all projects of 12% (typically this rate is between 8 and 20% in Ukraine, well above equivalent values in much of the rest of Europe). The assumptions for each technology in terms of CAPEX, capacity factor and fuel cost are given in Table 4.[228]

According to this data, wind onshore wind (€0.06/kWh) is the cheapest ways to produce electricity, followed by utility-scale solar (€0.083/kWh), rooftop solar (€0.107/kWh) and nuclear power (€0.105/kWh). More expensive technologies are hard coal (€0.124/kWh), combined-cycle gas turbines (€0.126/kWh), household solar (€0.127/kWh) and open-cycle gas turbines (€0.289/kWh). Current technology trends imply that costs for renewable energy, especially solar power, are set to further decrease in the next years while all fossil fuels will experience cost increases due to carbon pricing.

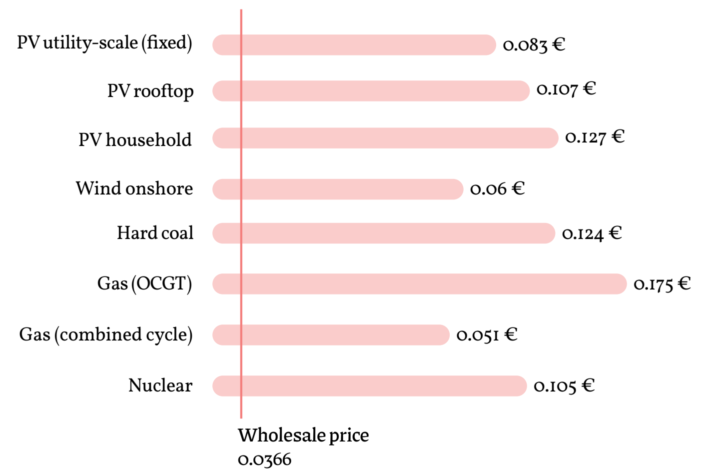

Figure 44: LCOE in Ukraine
Source: Clean Energy Lab, 'Ukraine LCOE Calculator'.

228 Clean Energy Lab, 'Ukraine LCOE Calculator'.

	CAPEX €	Capacity factor %	Fuel cost €/fuel unit
PV utility-scale (fixed)	700	15	0
PV rooftop	750	13	0
PV household	800	12	0
Wind onshore	1200	37	0
Hard coal	3500	55	46.99 / t
Gas (OCGT)	800	10	0.49 / cbm
Gas (combined cycle)	1000	55	0.49 / cmb
Nuclear	6000	92	47.62 / lb

Table 4: Assumptions underlying LCOE calculations for Ukraine
Source: Clean Energy Lab.

3.1. Nuclear Energy and Fossil Resources

Nuclear and fossil energy applications are reliable and well established. This does not mean they are static, however, as the latest plants and methods can have very different advantages and disadvantages compared to older facilities.

3.1.1. Nuclear Energy

As noted in the relevant section of this study, most nuclear power plants in Ukraine have technically already reached the end of their originally planned lifetime. In the summer of 2023, the largest is occupied by Russia. Their operation has been extended, however, which seems wise given that they produce cheap and reliable electricity once built. The country has also long been planning an expansion in the form of multiple small modular reactors.

As with other types of electricity production, nuclear has serious benefits and drawbacks. For one thing, building conventional nuclear reactors does not appear to be more cost-effective than renewables in any set of circumstances (of course, if sufficient funding and capacity can be found, it may not be necessary to choose between the two). The table above refers to existing reactors in Ukraine; building new ones is famously prone to massive delays and cost overruns. Small modular reactors (SMRs) are still a novel technology, with all-in costs in mid-2023 even higher than for conventional nuclear plants and well above renewables, gas or coal power generation. Being envisaged as modular, factory-assembled and scalable units, however, it is to be hoped that SMRs can avoid some of the pitfalls of larger facilities, notably being quicker to complete – three to five years compared with the 10 years – at best – needed to build a large conventional reactor.[229]

While it represents a greener option than fossil fuels, nuclear generation cannot normally be used to balance intermittent renewable production in the same way gas turbines or even coal plants can. As the dramatic events surrounding the Russian occupation of the Zaporizhzhia nuclear plant – or the travails of the French nuclear power plants over the summer of 2022 – show, they may also be vulnerable to attack and leave the electrical system in greater deficit in case of malfunction than decentralized wind farms.

At the same time, nuclear power is economical, reliable, and plentiful once the plants are completed, and not subject to major risks if managed properly. Existing plants should therefore be kept running for as long as possible, while any plans to expand nuclear energy should undergo a careful assessment that also considers the potential of nuclear power to provide balancing for the grid and possible synergies with hydrogen production.

3.1.2. Natural Gas

As shown above, there is a price argument to be made for power plants produced with natural gas, especially new combined-cycle gas turbines. This type of power is also eminently dispatchable, creating major balancing potential. Natural gas remains a fossil fuel (albeit less damaging to the climate than coal), however, and should ideally only be a transitional power source. Moreover, supplies and transport of gas are vulnerable to interference and attack by Russia and the price for gas is set to increase with the adoption of EU carbon pricing.

3.1.3. Oil

The share of oil in Ukraine's electricity mix has been negligible since the year 2000.[230] There is no economic or climate argument for its revival.

3.1.4. Coal

According to the International Energy Agency, the levelized cost of electricity produced in coal plants in Ukraine is roughly in line with the average for most other countries,[231] and coal will be one of the backbones of Ukraine's energy supply in the aftermath of the war. While it is true that, unlike nuclear (the other mainstay of Ukraine's power system), coal generation can be used to balance intermittent renewables, other options exist and should be explored.

Coal power generation in Ukraine is more expensive than all grid-scale renewables, sometimes dramatically so, adding to the arguments for its phasing out. Making use of existing energy infrastructure. the coal phase-out should be coupled with increased production of hydrogen or other clean energy-carriers. These can be used to replace coal previously employed in the production of steel and iron, and can help lead the way to a greener steel industry.

229 Brown, 'The Nuclear Option'.

230 World Bank, 'Electricity Production from Oil Sources (% of Total) - Ukraine'.

231 International Energy Agency and Organisation for Economic Cooperation and Development/Nuclear Energy Agency, 'Projected Costs of Generating Electricity'.

3.2. Renewable Energy

3.2.1. Onshore Wind and Photovoltaic

Onshore wind and photovoltaic solar are, together with combined cycle gas turbines, by far the cheapest electricity sources in Ukraine. They provide the best value for money and are the most climate-friendly type of electricity for the time being. As such, they should be prioritized at every turn until there is reason to think that marginal cost may come to exceed that of other energy sources. This should be established through regular analyses and recalculations, which should take into account externalities such as relative security risk facing a Russia which is likely to remain hostile for the foreseeable future, and climate and environmental costs throughout the supply chain. Merely taking into account a theoretical carbon price set by the EU or otherwise is not likely to capture the full negative externality of fossil fuels, and as such would not lead to the most efficient outcome. For instance, the Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine calculates the environmental and health costs (not counting the incalculable damage to the climate) of the pre-war, fossil-fuel-based economic system to be 0.7-1.3% of gross domestic product or USD1.1-2.1 billion per year, of which much is measured in human lives.[232]

3.2.2. Offshore Wind

There are currently no offshore wind farms in Ukraine. According to an analysis by the World Bank, the country has 251 GW of potential capacity in offshore wind, of which 183 GW fixed and 68 GW floating.[233] (The total installed power generation capacity of Ukraine today is some 60 GW.)[234] According to the data company BloombergNEF, levelized cost of electricity for offshore wind in Europe in 2022 was USD 0.099-0.175 per kilowatt-hour, well above other renewable energy sources but in many cases competitive with nuclear and, especially, coal.[235] Apart from a projected decline in costs due to continued technology development, cooperation with neighboring countries in the Black Sea promises potential for additional cost reductions.

3.2.3. Hydropower

BloombergNEF estimates the levelized cost of electricity (LCOE) for hydropower in Europe in 2022 to be USD 0.138-0.468 per kilowatt-hour, well above the LCOE for coal in Ukraine.[236] As other power generation options such as wind and solar continue to have much lower marginal costs and because of their environmental impact, it is not advisable to expand hydropower generation in Ukraine but to invest in retrofitting and modernizing existing plants. With periods of water scarcity and flooding likely to increase because of climate change, these dams might be needed for water management while also serving as a power supply (see section 2.1.4).

232 Chepeliev et al., 'Can Ukraine Go "Green" on the Post-War Recovery Path?'

233 World Bank, 'Offshore Wind Technical Potential in Ukraine'.

234 Chepeliev et al., 'Can Ukraine Go "Green" on the Post-War Recovery Path?'

235 BloombergNEF, 'New Energy Outlook 2022'.

236 BloombergNEF.

3.2.4. Bioenergy

According to BloombergNEF, the levelized cost of electricity (LCOE) produced from bioenergy in Europe in 2022 is USD 0.110-0.298 per kilowatt-hour, which is relatively high.[237] Thanks to its substantial agricultural production, Ukraine could be expected to achieve economies of scale that might place it at the lower end of the spectrum, but even so, bioenergy cannot obviously compete with intermittent renewables on its own merits. However, LCOE does not capture all the negative or positive externalities: a major advantage of bioenergy is its system utility and dispatchability, making it a rare energy source that can be truly renewable and still used for system balancing. It seems advisable for Ukraine to leverage its large biomass potential as a core part of a renewable energy supply.

3.3. Conclusions

While large sums have been promised to Ukraine for its recovery after the war, funding – whether from public or private sources – will not be unlimited, and the available workforce and regulatory capacity are likely to represent a limit on the amount of resources the economy will be able to absorb – certainly in the early stages after the war ends. Assuming a technology-open approach based on market principles, Ukraine will likely need to choose where to invest its resources. As mentioned above, this will require a transparent cost-benefit analysis that explicitly takes into account often overlooked externalities such as pollution or the value of dispatchability.

Research by the Institute for Economics and Forecasting at the National Academy of Sciences of Ukraine indicates that a green reconstruction of the Ukrainian economy after the war which prioritizes decarbonization would – under conservative assumptions – require just five percent more capital investment than a reconstruction of the fossil-fuel-based system.[238] Similarly, studies in Germany have shown that an electricity system comprised of 95% or 100% renewables would have an annual cost that is equal to or lower than today's electricity mix, especially if expected increases in the cost of fossil fuels are taken into account.[239]
Of course, cost is not the only consideration – a major issue with an electricity system based almost entirely on intermittent renewables is the load balancing they require. To take the example of a large country where the energy transition is quite advanced, the share of Germany's electricity originating in renewable energy sources is usually just shy of 50% – and on some days as high as 80%[240] – and already curtailment of renewable generation (mostly from wind power plants) amounts to 1% of the total power production per year.[241] The low-carbon power sources which can be used for this purpose include hydro power, of which Ukraine has a substantial capacity, but not nuclear, another mainstay of the country's electricity system. And since hydro power cannot by itself provide the necessary balancing, there is need for other green solutions.

237 BloombergNEF.

238 Chepeliev et al., 'Can Ukraine Go "Green" on the Post-War Recovery Path?'

239 Henning and Palzer, '100 % Erneuerbare Energien Für Strom Und Wärme in Deutschland'; Matthes, Heinemann, and Ludig, 'Renewables Versus Fossil Fuels – Comparing the Costs of Electricity Systems'.

240 Bauer et al., 'Energiemonitor: Die wichtigsten Daten zur Energieversorgung'.

241 Agentur für Erneuerbare Energien, 'Durch Einspeisemanagement Verlorene Stromerzeugung Aus Erneuerbaren Energien'.

There are three possible pathways to increase grid flexibility:

- Boosting storage capacity to make it possible to accumulate power reserves during periods of overproduction which can be drawn upon when generation is low – this can include grid-scale batteries as well as hydrogen and hydrogen derivatives, small batteries in electric vehicles and homes, or power-to-heat for district heating systems.
- Increasing interconnections with neighboring countries – to take another example from Germany, that country's weather service has calculated that a cold dark period (*Dunkelflaute* – defined as a period of 48 hours in which solar and wind power achieve less than 10% of their maximum output) occurs on average twice a year in Germany, but only once every five years in Europe as a whole.[242] (Having said that, weather patterns in adjacent regions do tend to be correlated).
- Adapting consumption to generation instead of vice versa – in the case of activities which do not have to take place at a given time of day, for instance – like automated industrial processes or for running heat pumps or charging electric vehicles.

According to a report by the consultancy Aurora Energy Research, a theoretical all-renewables power system with average demand of 100 GW would require some 5-10 GW (depending on how flexible demand could be made) of storage capacity, only needed in the rare periods (a few hours per year on average) when both solar and wind fail to cover demand, and the shortfall cannot be made up for by imports.[243]

Given these findings which underscore the economic viability of an energy system based on renewables, Ukraine stands to benefit from actively embracing a renewable energy approach, while remaining resolutely open to all types of technology which are clean and cost-effective. Further insights into the financial aspects of this transition can be found in the preliminary financial study published alongside this technical report.

242 German Meteorological Service, 'Wetterbedingte Risiken Der Stromproduktion Aus Erneuerbaren Energien Durch Kombinierten Einsatz von Windkraft Und Photovoltaik Reduzieren'.

243 Stycz et al., 'The Impact of Weather in a High Renewables Power System'.

4. Expert Survey of Innovative and Clean Technologies

The research conducted for this study was complemented by an expert survey on the energy market in Ukraine. The aim of this survey was to engage with stakeholders and foster discussions around the study's results and findings. This served as a valuable avenue for gathering input, perspectives, and feedback from key stakeholders, while also ensuring a comprehensive and inclusive approach to the topic at hand.

The expert survey involved 16 specialists in the field of energy systems in Ukraine and international energy markets.

They work in the following fields:
- policy think tanks and research networks,
- diplomatic representatives in the energy sector,
- the academic sector,
- energy industry, including Ukrainian state-owned enterprises,
- associations of energy market participants, and
- the international finance sector.

Nine participants preferred to stay anonymous. The remaining participants are listed below. The authors of this study would like to thank all the participants, without whom this survey would not have been possible.

dixi group
Viktoria Kovalenko
Consulting services organization manager in the sector of sustainable development providing

IKEM
Simon Schäfer-Stradowsky
Board Member

IKEM; RMS
Prof. Dr. Rainer M. Speh
Consultant

Johns Hopkins University
Dr. Daniel Hamilton
Senior Fellow,
Foreign Policy Institute

PJSC UkrHydroEnergo
Kucher Serhii Vladyslavovych
Head of realization on the innovative policies

Ukrainian Energy Exchange
Oleksandr Kovalenko
CEO

Ukrainian Wind Energy Association
Dr. Andriy Konechenkov
Chairman of the Board

The central research question guiding the survey was: "What are the main obstacles in the Ukrainian energy market for green technologies, how should they be overcome, and what is the potential of various renewable technologies for the Ukrainian energy system?" The overall implication of the survey answers is that energy supply should rely on a wide range of diverse systems, and that Ukraine's greatest potential is in wind and solar energy, combined with efficient transmission. Such an energy system could lay the groundwork for extensive energy exports to the EU and pave the way for Ukraine to become an essential and valued member of the European energy market.

The participants felt that the most significant **obstacles to implementing more renewable energy** solutions would likely be financial first and foremost, followed by issues of public administration, infrastructure, supply chains, and legislation. The main problem with financing is that there is too little of it. As for public administration, the primary issue identified is the lack of effective communication among various stakeholders, including government bodies and local authorities. The infrastructure needs to be modernized and made fit for purpose in a world of decentralized electricity generation and storage. Supply chains may have to be strengthened, especially when it comes to materials required for new efficient buildings and components such as batteries. And legislation in many ways ties all these topics together, having the capacity to facilitate or obstruct green reform and reconstruction.

The second part of the survey evaluated the **centralization of the energy market** and found that the experts were particularly keen on building-level photovoltaic generation, decentralized storage, district power systems and local distribution grid reinforcement. The respondents highlighted the importance of a roadmap or energy strategy (possibly for each region). They insisted on the need for clear objectives and time schedules, as well as seeking support and collaboration from national and international stakeholders.

The final part of the survey looked at the **potential of specific technologies and processes** to foster the energy transition. The participants were asked about eight such pathways: the coal phase-out, heating, hydropower, solar, wind, hydrogen, energy storage, transmission & distribution systems, and smart meters. Especially interesting answers were received for heating, energy storage, and transmission & distribution systems.

In the **heating sector**, the experts underlined the particular importance of space heating. Especially district heating is considered to have a high potential to add value to the Ukrainian market, reflecting the country's extensive district heating infrastructure. Geothermal energy and heat pumps were expected to make the highest contribution to net zero. Major obstacles repeatedly mentioned were the overregulation of prices for heating energy and lack of attractiveness for investments. Modernization, including efficiency and decentralized infrastructure, and expansion of renewable energy were given as priorities.

In the field of **energy storage**, the experts emphasized the importance of solutions to balance a future energy system based largely on intermittent renewable sources. They assigned the highest potential to hydro, lithium-ion batteries, and flow batteries.

Where **transmission and distribution systems** are concerned, the survey respondents reckoned that direct-current technologies and interconnector solutions have the highest potential to contribute to the green transition. This includes compliance with EU legislation and regulations, and full participation in ENTSO-E/EDSO.

Further information and details are available in the survey documentation in Annex 1.

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6. Annex 1: Expert Survey of Innovative and Clean Technologies

The central research question guiding the survey was: „What are the main obstacles in the Ukrainian energy market for green technologies, how should they be overcome, and what is the potential of various renewable technologies for the Ukrainian energy system?" The first part of the survey identified the technology groups which could contribute significantly to the energy transition in Ukraine. The answers are shown in Figure 45.

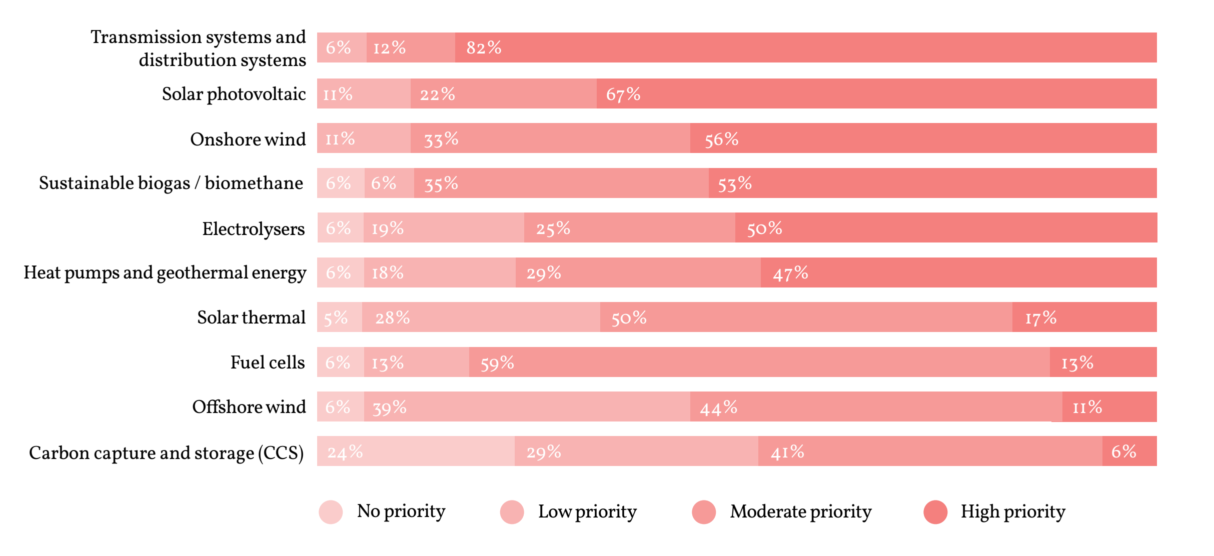

Figure 45: Answers to the question: How would you evaluate the expected contribution of each of the following technologies to a green and climate-neutral rebuilding of the Ukrainian energy sector?
Source: Own illustration.

The vast majority of renewable energy sources and associated technologies were accorded a high to moderate level of priority. The implication is that energy supply should rely on a wide range of diverse systems, and that Ukraine's greatest potential is in wind and solar energy, combined with efficient transmission.

6.1. Obstacles in the Deployment of Renewable Energy Sources

The participants were also asked about the main barriers to the green transition in Ukraine. As shown in Figure 46, the most significant obstacles to implementing renewable energy technologies are expected to be financial. However, public administration, infrastructure, supply chain issues, and legislation will also play crucial roles in Ukraine's energy transition.

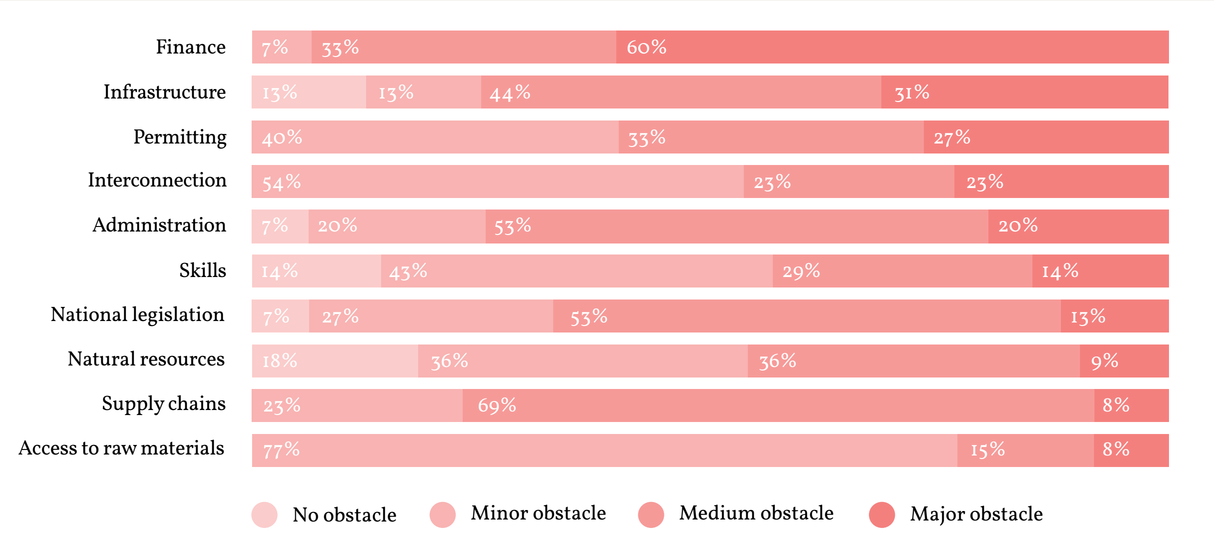

Figure 46: Answers to the question: What are the main national barriers or obstacles standing in the way of a swift deployment of the technologies you have selected?
Source: Own illustration.

6.1.1. Finance

The survey findings unequivocally underscore the formidable challenge posed by financing for the energy transition. Approximately 90% of the surveyed energy experts regard financing as a medium or major obstacle. There are recurring references to a lack of investments among the answers to the survey, making it clear that both private and public sectors need to step up their contributions. This should include the financing of regional projects through public funds which aim to foster renewable initiatives. Moreover, the results of the survey consistently stress the imperative of cultivating an investment-friendly environment. One participant emphasizes that more research is needed to develop strategies to attract investors.

Several participants highlight critical issues with the feed-in-tariff system, which has allegedly led to a significant debt burden. One respondent points out that:

> "financial settlements of the electricity market participants resulted in ever-increasing debts (up to EUR 500 million as of 1 July 2023) to the renewable electricity producers".
>
> **Dr. Andriy Konechenkov,**
> UWEA

Another participant links the establishment of organized exchange trading and standard products to the mitigation of risks which can attract investments in green technologies:

> "[...] it is crucial to support the development of organized exchange trading and standard products to enable hedging risks for investment projects in green technologies. The establishment of such mechanisms will attract both local and foreign investors, ensuring sustainable financing for the sector's development [...].".
>
> **Oleksandr Kovalenko,**
> Ukrainian Energy Exchange

While several respondents offer pragmatic recommendations, the survey primarily reveals a pressing need for substantial investments and financing. However, the specific strategies for creating an investment-friendly and secure environment remain less clearly defined.

6.1.2. Administration

The survey results indicate that approximately 80% of the participants view public administration as a medium or major obstacle in the energy transition process. The primary issue identified within this domain is the lack of effective communication among various stakeholders, including government bodies and local authorities.

According to the survey participants, addressing these communication challenges among public administrations and other actors requires improved communication channels. This includes enhancing dialogue between the government and business entities, promoting effective communication between local communities/authorities and the central government, and facilitating contacts between Ukraine's partners and domestic civil society. One participant recommends the creation of more efficient communication platforms to overcome these barriers. Two other respondents criticize what they see as the persistence of a high level of bureaucracy in Ukraine left over from the Soviet era.

6.1.3. Infrastructure

The findings from the survey underline that, while Ukraine does have a well-developed gas and power infrastructure, it needs investment and modernization. According to one participant, the decentralization brought on by the green transition will require new strategies, including:

> "The development of a micro grid as a technology that creates conditions for sustainable provision of critical utility infrastructure at the local level, as well as the development of aggregators and virtual power plants. This is very closely linked to the recovery and development of small and medium-sized businesses, as well as commercial real estate and logistics. It is expected that every large enterprise and every large building will be partially equipped with PV generation and storage systems and thus become an active consumer."
>
> **Kucher Serhii Vladyslavovych,**
> PJSC UkrHydroEnergo

6.1.4. Supply Chains and Access to Raw Materials

One obstacle pointed out in the survey is the disruption of supply chains due to the war. Investments are required both to remedy this and expand the supply chains further. One participant points out that supply chains are important to the green transition and can represent a bottleneck, but are unlikely to be the main obstacle. Another respondent links the renovation of buildings and smart supply chains with energy controls and efficiency in new net zero energy buildings, and points out that the latter will massively decrease the loads required on the energy system.

6.1.5. Legislation

Around 70% of respondents view national legislation in Ukraine as a medium or major obstacle to the deployment of green technologies. Many elements, such as finance, are closely tied to legislation. The participants emphasize the need for more political will, clear legal frameworks, and adaptation of the legislation to support the energy transition. Moreover, they suggest that strategies with clear objectives and time schedules be developed.

Participants point out that challenges arise from unstable and frequently changing renewable energy legislation, coupled with high interest rates on bank loans, which hinder the development of renewable energy technologies. One respondent writes that experience has shown that resolving legal and administrative issues can swiftly address challenges linked to financing, access to resources, skill development, and infrastructure rebuilding.

Moreover, participants repeatedly underline that electricity and gas markets are not fully liberalized. To overcome these obstacles, national legislation should encourage market-based mechanisms and facilitate the integration of green technologies into the market.

6.1.6. Priorities of EU Climate Policies

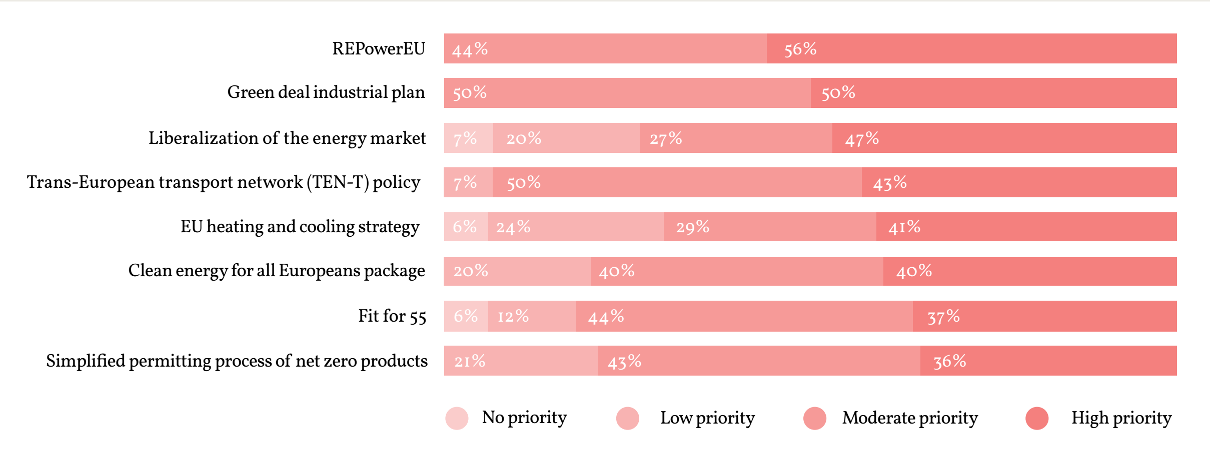

Figure 47: Answers to the question: In your opinion, which EU climate policy should Ukraine prioritize?
Source: Own illustration.

The participants were also asked which EU climate policy should be prioritized in Ukraine, and gave REPowerEU and the Green Deal Industrial Plan as their preferred choices. However, over 60% of the participants also assigned a moderate to high priority to the other strategies (see Figure 47).

6.2. Evaluation of the Centralization Level of the Ukrainian Energy System

The second part of the survey evaluates the centralization of the energy market, with the experts' preferred strategies indicated in Figure 48. The results clearly show the importance of decentralization in the eyes of the experts.

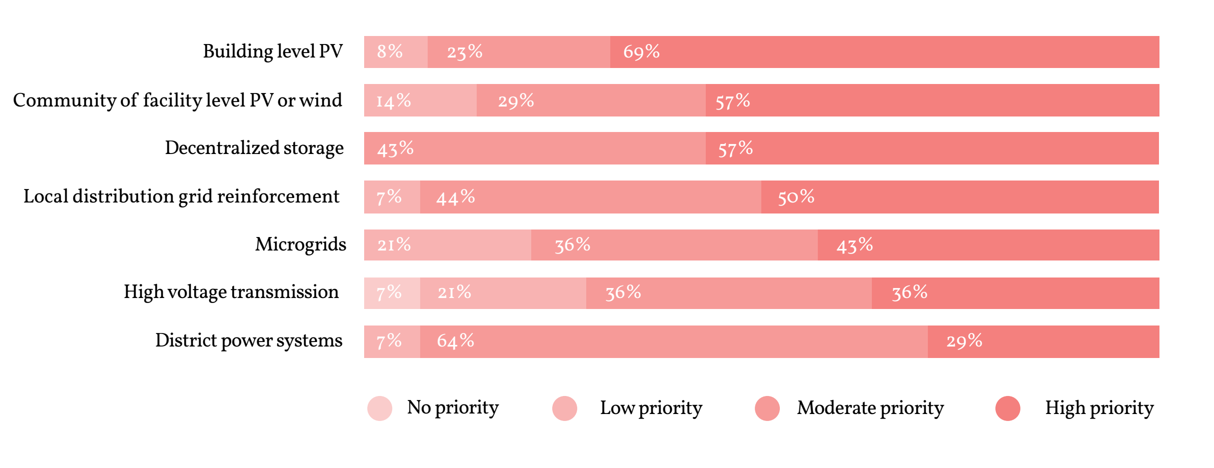

Figure 48: Answers to the question: What priority should the decentralization of given power plants and grids have within the future Ukrainian energy system?
Source: Own illustration

Moreover, the participants were asked how these priorities could be implemented in a new Ukrainian energy strategy. The most common response was that a roadmap or energy strategy should be developed (possibly for each region) or that the national energy and climate plan (NECP) should be refined. Moreover, the respondents formulate the need for strategies with clear objectives and time schedules, which should include pathways to decentralizing the energy system. Other suggestions include seeking support and collaboration from national and international stakeholders. Most participants underline that more investments are needed to implement the suggestions.

On the technology side, the respondents suggest a range of solutions to implement more renewable energy in a decentralized energy system. One participant points out that, while a decentralized energy generation system would probably provide more security than a centralized one, "a mix of both seems crucial to allow sufficient generation." The participant adds that "decentralized storage (e.g. in form of grid connected batteries) will play an increasing role in stabilizing the grid."

In addition, the participants list obstacles and opportunities resulting from the decentralization. Opportunities include:

- improved energy security through the diversification of energy sources, and
- the possibility to enter the decentralized generation market.

Obstacles include:

- insufficient regulatory and policy frameworks to support decentralized systems and corruption,
- limited availability of financing and investment for decentralized systems,
- technical challenges related to integrating decentralized systems with the existing grid as grid management and planning on DSO and local level, and
- potential resistance from incumbent utilities and centralized power generation interests.

6.3. Potential of Different Technologies to Foster the Energy Transition

6.3.1. Coal Phase-Out

The survey asked participants to describe targets and further steps for a coal phase-out in the Ukrainian energy market. The responses are diverse, emphasizing transparency in the coal sector and for a comprehensive analysis of whether a short-term coal phase-out is realistic given the current challenges in the energy sector. Considerations include ensuring the stability of renewable generation facilities, enhancing energy supply reliability, and addressing seasonal changes in electricity demand.

Participants propose a national energy and climate plan with a long-term strategy for phasing out coal and replacing it with clean energy technologies, while emphasizing a just transition roadmap. At the national level, a comprehensive plan should be formulated to phase out coal-fired power generation, offering incentives for decommissioning and replacing traditional coal plants with renewable sources. One respondent points out that war damage and difficulties attracting investments into the coal sector mean that a coal phase-out is expected to occur naturally, and another recommends retraining programs for coal industry workers and support for the economies of coal regions and cities previously reliant on thermal power plants.

6.3.2. Heating

Related to the heating sector, participants felt that housing and district heating were crucial, while industrial processes were not considered particularly important (see Figure 49). This shows that space heating, especially in the residential sector, is the area of greatest interest for the experts.

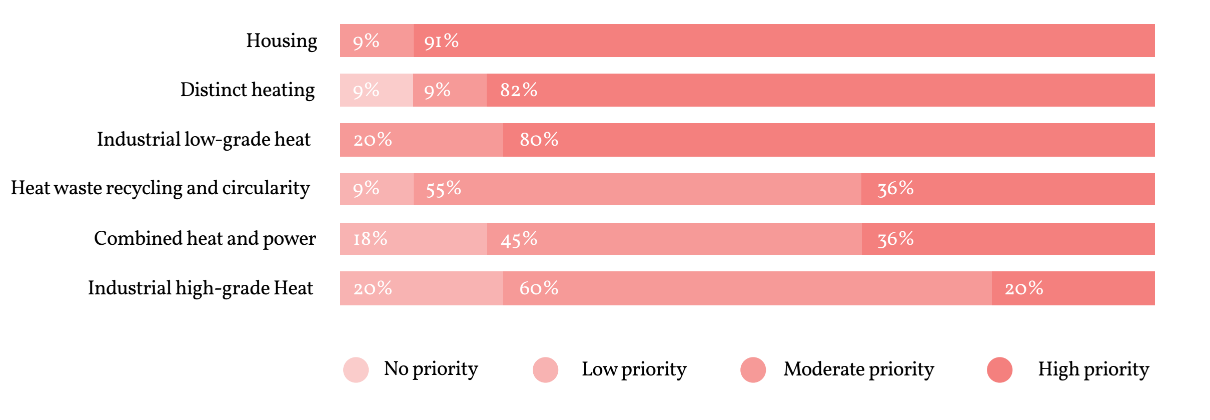

Figure 49: Answers to the question: What priority do the following applications have in terms of contributing to a green and climate-neutral rebuilding of the Ukrainian heating sector?
Source: Own illustration

In addition, the participants were asked to evaluate the different heating technologies in five different categories related to their potential in the green transition. The results show that especially district heating is considered to have a high potential to add value to the Ukrainian market, reflecting the country's extensive district heating infrastructure. Solar power for heating, geothermal energy, and heat pumps were given the highest score in terms of compatibility with European strategic energy priorities, while geothermal energy and heat pumps are expected to make the highest contribution to net zero.

Another question in the survey aimed to identify obstacles and opportunities within the heating system, and the findings shed light on a range of key points. One obstacle that is repeatedly mentioned is the fact that prices for heating energy are heavily regulated. Another recurring issue is the lack of attractiveness for investments and financial resources. Respondents suggest that effective financial mechanisms should be developed to facilitate measures to modernize urban heat supply.

Modernization and expansion of renewable energy sources emerge as a significant concern. Positive change requires that outdated thermal power plants and inefficient gas boiler houses be replaced with efficient renewable energy systems featuring decentralized infrastructure. One participant points out that education and awareness-raising campaigns can help increase public knowledge and acceptance of new heating technologies. This could help reduce resistance to change and promote the adoption of new technologies. Another participant writes that there is a need to promote biomass and waste utilization, energy efficiency measures and construction of passive houses, PV and wind for heating and electricity production.

Energy efficiency is frequently mentioned in the answers to the survey, as is the fact that it comes with substantial upfront costs. The pursuit of enhanced energy efficiency also faces technical challenges when new technologies are integrated into existing heating systems. To resolve this, Ukraine needs more instruments that can support private households and small enterprises in the implementation of low-carbon heating.

The current legislation is found by many respondents to be an obstacle; this emphasizes the importance of updating and aligning regulations to current needs and developments in the heating sector. The commitment and consistent action of the government are identified as essential factors in overcoming hurdles and driving positive change in the sector. According to the survey, this includes the adoption of legislation for energy communities and cooperatives backed up with primary and secondary legislation.

6.3.3. Hydropower

As mentioned above, the section on hydropower only had a single respondent, who found that storage power plants have great potential in terms of supply security impact, contribution to net zero, and compatibility with European strategic energy priorities. However, they also indicate that storage power plants are not as technically easy to implement as pump storage power plants.

6.3.4. Solar Technologies

In the survey the participants had to evaluate the potential of various solar technologies, including silicon photo voltaic, tandem cells, heterojunction solar cells, ultralight fabric cells and agri-PV. Only one participant answered the questions in this block, reducing the significance of the results. This person indicates that silicon photovoltaic and agri-PV have high potential in Ukraine, and that tandem cells, heterojunction solar cells, and – especially – ultralight fabric solar cells, are less promising, particularly given the technical ease of implementation.

6.3.5. Wind

The section concerning wind energy also received only one response. The respondent suggests that onshore wind should constitute 40% of the Ukrainian energy mix by the year 2050, while offshore wind should contribute 19%. Measures required to achieve these proportions include substantial investments in local wind turbine manufacturing and the establishment of a stable policy framework and legislation. This would encompass the formulation of a comprehensive offshore wind strategy, the implementation of offshore wind-specific regulations, and strategic investments. Furthermore, the respondent highlights the potential for prosumers to harness not only solar power but also wind power, particularly through the utilization of smaller-scale wind turbines.

6.3.6. Hydrogen

The questions on hydrogen received a single response as well. The main takeaway is that:

> "In [...] Ukraine, hydrogen [...] can only be an export commodity produced from electricity residues. However, the existing technologies for its production and modes of green electricity supply do not provide a competitive price as a mass energy resource, especially in Ukraine, which will have low purchasing power for many years to come. The obstacle is the low economic efficiency of the hydrogen production and consumption cycle, as well as transport costs."
>
> **Kucher Serhii Vladyslavovych,**
> PJSC UkrHydroEnergo

Consistent with this statement, the participant also assessed the potential of hydrogen technologies as comparatively low.

6.3.7. Storage

In this section, respondents were invited to evaluate the potential of various storage technologies. As shown in Figure 50, pumped hydro, lithium-ion batteries and flow batteries are found to have the highest potential.

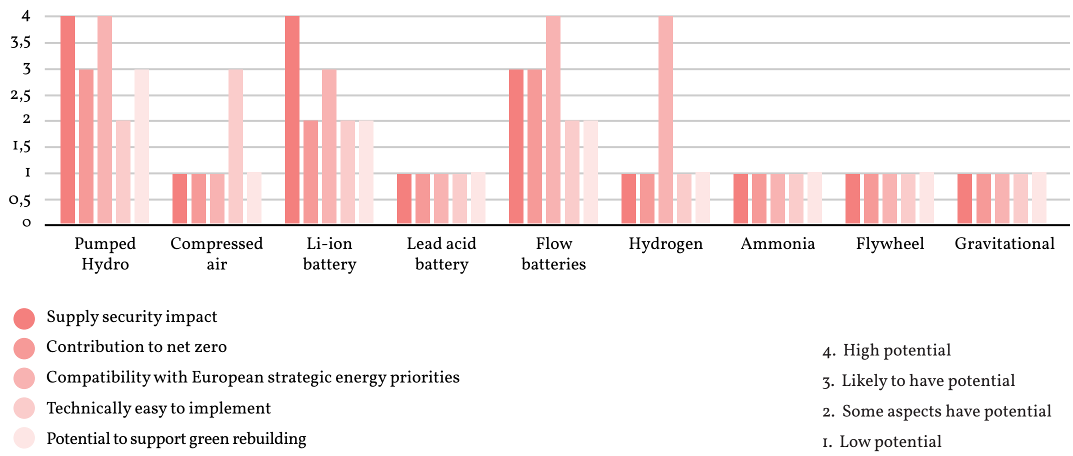

Figure 50: Answers to the question: What do you consider to be the most promising storage technologies, and can you estimate their potential within the green transition?
Source: Own illustration.

One respondent points out that further relevant technologies include sector coupling and efficiency enhancement. Moreover, the inherent volatility of renewable energy resources means that the role of energy storage in ensuring energy supply security is paramount, and a diverse array of storage systems in a range of capacities and configurations is indispensable for the seamless functioning of a renewable energy system.

Another participant pointed out, that in the future, only pumped storage power plants and lithium-ion batteries will be commercially available in the transmission grid of Ukraine. Therefore, for the ambitious task of developing wind and solar generation, it is necessary to focus on these areas, except in exceptional cases. This participant points out that:

> "The life-cycle cost for lithium-ion batteries is still too high. To overcome this obstacle, it is necessary to develop renewable energy [...] programs integrated with storage development. There is no other way."
>
> **Kucher Serhii Vladyslavovych**
> PJSC UkrHydroEnergo

He goes on to provide an estimation of the impact of small-scale storage systems operated by private households and micro-enterprises on the Ukrainian energy system.

6.3.8. Transmission and Distribution Systems

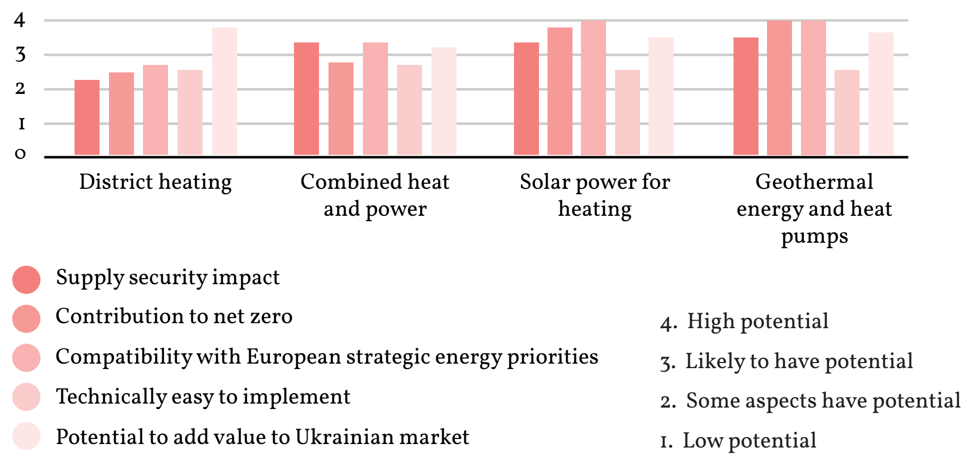

Figure 51: Answers to the question: What do you consider to be the most promising transmission and distribution technologies, and can you estimate their potential within the green transition?
Source: Own illustration.

The survey shows that the participants assume that direct-current technologies have the highest potential in the fields of supply security impact and contribution to net zero. In addition, interconnector technologies are estimated to have a high potential for supply security impact. Alternating-current technologies are also considered to have good potential, but not as much as direct-current ones.

The participants name other technologies which are also relevant for the green transition with regards to the transmission and distribution system. One participant mentions the latest technologies for dispatch centers, such as SCADA, and the development of new tools for grid integration of renewables, such as wind forecasting. Another participant names decentralized cellular structure as a technology for the overall energy system.

As in the previous parts of the study, participants see the lack of investment as a serious obstacle, and emphasize further interconnection of the EU and Ukrainian energy markets, specifically compliance with EU legislation, regulations and full participation in ENTSO-E/EDSO. Respondents also find that Ukraine needs a strong commitment by government and state-owned enterprises to provide necessary investments and cost recovery, and that a reliable energy supply based on renewable energy highly decentralized system structure is needed.

Asked what opportunities and obstacles the Ukrainian transmission system and distribution networks will face in a decentralized energy system, one participant points out that possible increased urbanization could be an obstacle, which can be overcome with careful planning and modelling. Another respondent names investment and planning constraints as an obstacle, which can be remedied through commitments from the government and state-owned enterprises to streamline planning processes and provide cost recovery for needed investments. One participant mentions higher resilience, easier implementation, and better management of renewable resources as an opportunity, suggesting quick launching of relevant pilot projects and diversification of the energy system to boost energy security and contribute to a stable EU market.

6.3.9. Smart Meters

Questions concerning the smart meters again only received answers from one participant, who finds that smart and advanced metering structures can provide the highest potential regarding supply security impact, contribution to net zero, and potential to add value to the Ukrainian market. According to this participant, smart meters can increase the stability of the transmission system and distribution networks by enabling a better data system and prediction of energy demand and planning for the grid. Moreover, they can strengthen demand response markets. The participant suggests having a full roll-out of smart meters by 2030 in all buildings, providing the capacity to implement demand-side response as facilitated by the market from 2030.