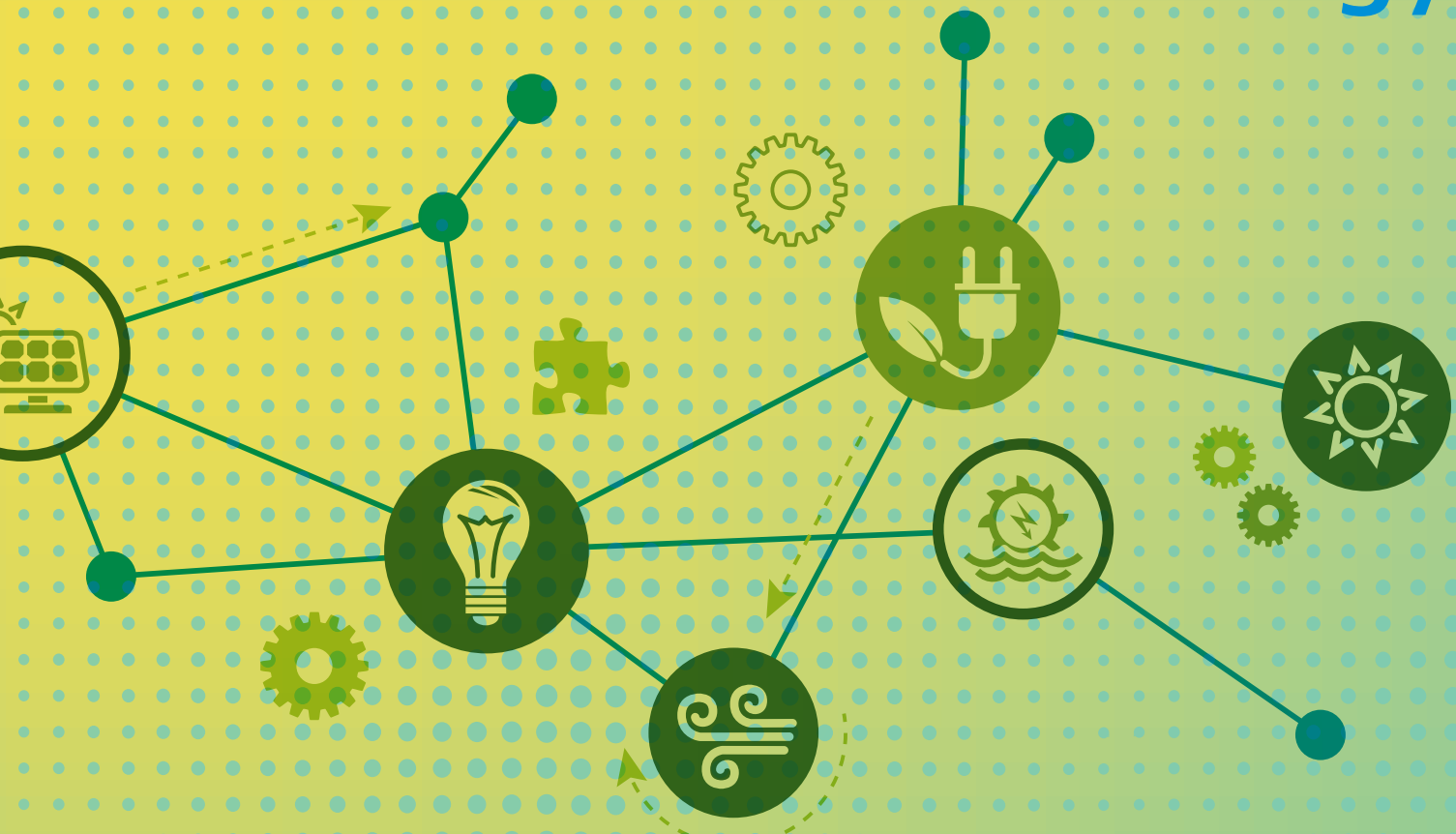
REVITALIZING UKRAINE'S ENERGY SYSTEM:

Exploring V4 Contributions to Reconstruction and EU Accession in the Field of Energy



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REVITALIZING UKRAINE'S ENERGY SYSTEM: Exploring V4 Contributions to Reconstruction and EU Accession in the Field of Energy

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Aim of the study

The aim of this study is to provide an overview on the state of Ukraine's energy sector before the war, assess the impact of the war on its energy infrastructure, and explore its potential for renewable energy sources—solar, wind, biomass, geothermal, and hydropower—as well as nuclear, natural gas, and hydrogen. Based on this, it will identify opportunities for V4 countries to collaborate with and support the reconstruction of Ukraine's energy infrastructure, with particular emphasis on clean technologies that will go the furthest towards ensuring Ukraine's resilient, competitive and independent energy system of the future.

This study operates under the scenario that the war in Ukraine has ended favourably on its terms; free of the immediate constraints of conflict and continuing its pro-Western EU integration pathway opening the door to strategic investments in energy infrastructure.

It should be in the interest of V4 countries to take a leading role in supporting Ukraine's EU accession and shaping its reconstruction process, particularly in the areas of energy and climate, since Ukraine's integration provides opportunities to enhance regional stability and create new economic opportunities.

INTRODUCTION

Russian's military aggression against Ukraine has caused immense suffering and massive damage to the country's critical infrastructure, including its energy system. The damage to key energy facilities, such as the Zaporizhzhia nuclear power plant (NPP)[1], the destruction of the Kakhovka Hydroelectric Dam, and the loss of approximately 44% of the country's thermal power stations and 60% of power generation capacity, has significantly disrupted Ukraine's energy security.[2] This situation has led to a sharp reduction in energy production, with electricity generation and consumption falling by over 30% from before the war.[3]

Ukraine possesses significant untapped renewable energy potential, like solar and wind power, bioenergy, and hydropower. Solar and wind generation could take a leading role in Ukraine's electricity mix with potential total generation of 80% by 2050 (from 12% in 2020), complemented by nuclear, hydro, and bioenergy.[4] Achieving this goal will require a well-defined strategy, substantial investments, and continuous support for nuclear energy, which could serve as a key pillar of the transition.

Environmental activists from Greenpeace are calling for the implementation of a "Marshall Plan for Solar Energy" to help rebuild Ukraine with a focus on renewable energy and clean technologies.[5] The World Bank estimates the total cost of Ukraine's recovery at approximately $486 billion[6] while Kyiv School of Economics is more conservative, at around $155 billion.[7]

The V4 countries (Czech Republic, Hungary, Poland, and Slovakia) are positioned to play a crucial role in this endeavour because of geographical proximity (3 share a boarder) and experience from undergone energy sector transformation and modernisation over the past decades.[8] More recently V4 countries have moved into more sustainable and decentralized energy systems which allows them to provide technical know-how and serve as a valuable source of inspiration for Ukraine.[9] Moreover, a strong and stable energy grid in Ukraine enabling large amounts of cheap, low-carbon energy could benefit V4 countries with the development of interconnectors to import this energy.[10]

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1 Despite the damage, the Zaporizhzhia NPP remains operational, though at the time of writing of this study (October 2024) its at minimal capacity.

2 H. Duggal, "Mapping Russia's Kursk nuclear power plant," *Aljazeera*, August 27, 2024. Available online: https://www.aljazeera.com/news/2024/8/27/mapping-russias-kursk-nuclear-power-plant (accessed on).
S. Jayanti, "Ukraine's Energy Sector Faces Its Biggest Crisis Yet," *Time*, August 10, 2024. Available online: https://time.com/7008613/ukraine-russia-power-sector-frontline/ (accessed on).

3 Enhancing imports of electricity from the European Union to Ukraine," Energy Community Secretariat, Ukraine Energy Market Observatory, 16/2024, October 2024. Available online: https://www.energy-community.org/dam/jcr:55f1ac5c-f53c-492 b-9b56-d4623f5be23a/UA_MO_16_2024_import%20to%20Ukraine.pdf

4 "Rebuilding Ukraine with a Resilient, Carbon-Neutral Energy System," *United Nations Economic Commission for Europe*, 2023. Available online: https://unece.org/sites/default/files/2023-07/EN_Rebuilding%20Ukraine%20with%20a%20Resilient%20Carbon-Neutral%20Energy%20System_V8.pdf (accessed on).

5 L. Limb, "Solar Marshall Plan: Can Ukraine become the world's first post-war country rebuilt on renewables," *Euronews*, June 8, 2024. Available online: https://www.euronews.com/green/2024/06/08/solar-marshall-plan-can-ukraine-become-the-worlds-first-post-war-country-rebuilt-on-renewa (accessed on).

6 "Ukraine's recovery, reconstruction needs seen at $486 billion over next decade," *UNDP*, February 15, 2024. Available online: https://www.undp.org/ukraine/press-releases/ukraines-recovery-reconstruction-needs-seen-486-billion-over-next-decade (accessed on).

7 "$155 billion—the total amount of damages caused to Ukraine's infrastructure due to the war, as of January 2024," *Kyiv School of Economics*, February 12, 2024. Available online: https://kse.ua/about-the-school/news/155-billion-the-total-amount-of-damages-caused-to-ukraine-s-infrastructure-due-to-the-war-as-of-january-2024/ (accessed on).
S. E. Jayanti, "Ukrainian nuclear energy can fuel country's recovery and power Europe," *Atlantic Council*, April 16, 2024. Available online: https://www.atlanticcouncil.org/blogs/ukrainealert/ukrainian-nuclear-energy-can-fuel-countrys-recovery-and-power-europe/ (accessed on).

8 I. Jonek-Kowalska and S. Rupacz, "Transformation of Energy Resources in the Visegrad Group: Strategies, Results, and Climate Effectiveness," *Resources*, Vol. 13, No. 5: 64, 2024. Available online: https://doi.org/10.3390/resources13050064 (accessed on).
P. Žuk, A. Buzogány, M. Mišík, J. Osička and K. Szulecki, "Semi-peripheries in the world-system? The Visegrad group countries in the geopolitical order of energy and raw materials after the war in Ukraine," *Resources Policy*, Vol. 85, Part B, 2023. Available online: https://doi.org/10.1016/j.resourpol.2023.104046 (accessed on).

9 A. Prokip, "Liberalizing Ukraine's Electricity Market: Benefits and Risks," *Wilson Center*, May 6, 2019. Available online: https://www.wilsoncenter.org/blog-post/liberalizing-ukraines-electricity-market-benefits-and-risks (accessed on).
"Integration of Ukrainian power grid with ENTSO-E is strategic direction of cooperation," *Interfax Ukraine*, April 6, 2018. Available online: https://en.interfax.com.ua/news/economic/497339.html (accessed on).

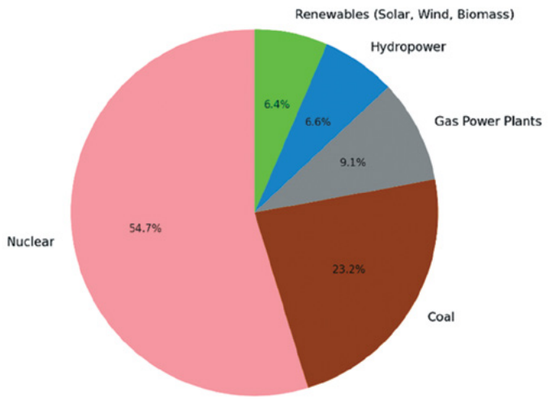
10 G. Masežnikov, "Stance of the V4 countries towards Russian military aggression against Ukraine," *Heinrich Böll Stiftung*, December 20, 2022. Available online: https://cz.boell.org/en/2022/12/13/postoje-krajin-v4-voci-ruskej-agresii-proti-ukrajine (accessed on).

UKRAINE'S ENERGY SECTOR BEFORE THE WAR

Electricity Mix of Ukraine in 2021

Ukraine, before the war, has long relied on two primary pillars in its energy sector: nuclear and coal. Nuclear energy accounted for approximately 54% (86,206 GWh) and coal about 23% of electricity generated (36,536 GWh).[11] This was supplemented by gas power plants (9% or 14,341 GWh) and hydropower plants (6% or 10,332 GWh. Renewable energy sources (solar, wind, biomass) produced about 6% of the energy in 2021 (10,151 GWh). It is important to note that Ukraine's overall electricity mix was also influenced by natural gas, which made up as much as 27%.[12]

Figure 1. Ukraine's Electricity Generation by Source in 2021 (GWh)



Source: IEA

11 "Ukraine," *International Energy Agency*, 2022. Available online: https://www.iea.org/countries/ukraine (accessed on).

12 "Energy Statistics Data Browser," *International Energy Agency*, December 21, 2023. Available online: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=UKR&fuel=Energy%20supply&indicator=ElecGenByFuel (accessed on).

Coal for Ukrainian Industry

Ukraine has significant coal reserves, particularly in the eastern part (Donbas), which represents up to 90% of all Ukrainian deposits.[13] Since 2014, mining in Donbas has been disrupted due to conflict and a boycott of coal purchases from mines controlled by separatists, creating a need for energy reforms and diversification.[14] Thus in 2021, Ukraine imported 14.0 million tons (72%) of coal from Russia, 3.0 million tons (15%) from Kazakhstan, and 2.6 million tons (13%) from other countries to ensure its energy security.[15]

Natural Gas and Oil Reserves

Ukraine holds the second-largest natural gas reserves in Europe (1.09 trillion cubic meters as of 2019), second only to Norway. Despite this, only a small portion of these reserves is currently utilized, with an annual extraction rate of just 2%. This was enough to cover about 60% of domestic consumption (20 billion cubic meters) in 2021—mostly used by industry and for heat production, especially heating of households—with the rest imported from European countries via reverse flow.[16] There is potential for further exploration, which could uncover new gas fields and increase overall production capacity. In recent decades, the government has been striving to increase domestic production and more efficiently utilize existing reserves to improve the country's energy security.[17]

Ukraine's gas infrastructure includes an extensive network of transit pipelines—most importantly the Brotherhood and Soyuz pipelines which transport gas from Russia to Europe—along with large underground gas storage facilities that serve for seasonal balancing and supply stabilization.

Although Ukraine has substantial hydrocarbon reserves estimated at 9 billion tonnes of oil equivalent, it is highly dependent on imports, with 50% coming through Black Sea ports in 2021.[18] The same goes for petroleum products, where imports accounted for about 80% of total demand (12 million tons) in 2021. Of the total fuel demand, diesel accounted for the largest share at 66% (8 million tons), followed by gasoline at 18% (2.2 million tons), and LPG at 16% (2 million tons).

13 "Ukraine Coal Industry Restructuring Sector Report," *World Bank Group*, Report No.15056-UA, March 4, 1996, p. 24. Available online: https://documents1.worldbank.org/curated/en/179841468778209054/pdf/multi0page.pdf (asccessed on).

14 V. Melkozerova, "Ukraine's war-torn Donbas region is on the verge of environmental disaster," *NBC News*, May 16, 2021. Available online: https://www.nbcnews.com/news/world/ukraine-s-war-torn-donbas-region-verge-environmental-disaster-n1266372 (accessed on).

15 Ukraine's coal imports up 15% in Jan-Dec 2021," The Coal Hub, 2021. Available online: https://thecoalhub.com/ukraines-coal-imports-up-15-in-jan-dec-2021.html

16 Ibid
S. Elliott, "Ukraine's UGV brings new high-throughput domestic gas well into production," *S & P Global*, March 6, 2024. Available online: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/030624-ukraines-ugv-brings-new-high-throughput-domestic-gas-well-into-production (accessed on).
P. Polityuk and N. Chestney, "Ukraine's energy options limited in event of Russian gas disruption," *Reuters*, February 24, 2022. Available online: https://www.reuters.com/business/energy/ukraines-energy-options-limited-event-russian-gas-disruption-2022-02-24/ (accessed on).

17 "Ukraine energy profile Energy security," *International Energy Agency*, n.d. Available online: https://www.iea.org/reports/ukraine-energy-profile/energy-security (accessed on).

18 Ukraine Energy Profile," International Energy Agency (IEA), 2020. Available online: https://www.iea.org/reports/ukraine-energy-profile (accessed online).

When Russia invaded in February 2022, Ukraine was almost immediately cut off from its primary fuel suppliers Russia and Belarus, which had provided the majority of its diesel (65%), gasoline (40%), and LPG (65%). Altogether, Ukraine experienced a drastic 70% reduction in fuel availability, forcing it to quickly reorganize supply chains. Although the EU stepped in to fill some of the gap, it could only cover10% of Ukraine's pre-war demand, leaving the country in a precarious situation.[19]

Role of Ukraine's Transit Infrastructure

The transit of fossil fuel commodities through Ukraine, a traditional linchpin of both Ukrainian and European energy security, has been in decline.[20] The Yamal-Europe natural gas pipeline, completed in the late 1990s, was one of the first major projects to bypass Ukraine, transporting natural gas through Belarus and Poland to Germany.[21] In the 2000s and 2010s, Russia further reduced its reliance on Ukraine by developing the Nord Stream pipeline, and later, Nord Stream 2, which directly connect Russia to Germany via the Baltic Sea.[22] These projects, along with geopolitical tensions since 2014, have drastically reduced the volume of gas transiting through Ukraine, lessening its strategic role within the European energy system and decreasing revenues from transit fees.[23]

Similarly, once a crucial oil transit route from Russia to Central and Western Europe, the significance of Ukraine's oil transit system has been eroded. The is a result of both shifting geopolitical alignments and the development of new infrastructure intended to reduce Europe's dependence on Russian supplies.[24]

The decline in Ukraine's strategic role as a transit nation for gas and oil has had significant economic consequences, most directly felt by the reduction in transit revenues that once played a vital role in its economy. For Ukraine to regain its strategic importance, significant infrastructure modernization and improved cooperation with European partners will be essential.[25]

19 P. Przybyło, "Past, present and the future of the Ukrainian fuel sector. The origins of the fuel crisis and analysis of the viable support options during and post the Russian aggression," *Casimir Pulaski Foundation*, op. cit.
Ukraine Energy Profile," International Energy Agency (IEA), 2020. Available online: https://www.iea.org/reports/ukraine-energy-profile (accessed online).

20 Ukraine's Gas Sector," Pirani, Oxford Institute for Energy Studies, 2007. Available online: https://web.archive.org/web/20080527194203/http:/www.oxfordenergy.org/pdfs/NG21.pdf (accessed online).

21 "Yamal—Europe Gas Pipeline," Hydrocarbons Technology, n.d. Available online: https://www.hydrocarbons-technology.com/projects/yamal-europegaspipel/ (accessed on).
"Gazprom launches Yamal megaproject," *Gazprom*, December 3, 2008. Available online: https://web.archive.org/web/20090116180039/https:/www.gazprom.com/eng/news/2008/12/32740.shtml (accessed on).

22 „WhoWeAre,"*NordStreamAG*,n.d.Availableonline:https://web.archive.org/web/20090116180039/https:/www.gazprom.com/eng/news/2008/12/32740.shtml (accessed on).

23 A. Losz, "Q & A | Russian Gas Transit through Ukraine," *The Center on Global Energy Policy*, October 3, 2023. Available online: https://www.energypolicy.columbia.edu/qa-russian-gas-transit-through-ukraine/ (accessed on).

24 S. Morrow, "Ukraine halts oil transit through Druzhba pipeline," *Energy Terminal*, August 9, 2022. Available online: https://www.aa.com.tr/en/energy/oil/ukraine-halts-oil-transit-through-druzhba-pipeline/36010 (accessed on).

25 B. McWilliams, S.Tagliapietra and G. Zachmann, "Europe's Russian oil embargo: significant but not yet," *Bruegel*, June 1, 2022. Available online: https://www.bruegel.org/blog-post/europes-russian-oil-embargo-significant-not-yet (accessed on).

In 2022, the situation took a decisive turn as major European gas importers, including Germany, France, Italy, Austria, and the Czech Republic, ceased to be clients of Gazprom.[26] For many, this marked the end of the era of gas transit through Ukraine (and Slovakia). Future developments, however, may change this (considered in the idealistic scenario of this study) if, hypothetically, Russia were to lose the ongoing war and be compelled to pay reparations, potentially renewing partial transit as part of a broader economic reparations deal. In addition, Ukraine's initiative to establish a regional gas hub for Central and Eastern Europe leveraging its extensive western gas storage facilities could be the focus of future gas market cooperation rather than Russian gas transit alone.[27]

Figure 2. Major routs of gas pipelines via Ukraine

Source: NBC News—2014

Energy Reforms After 2014

In response to geopolitical challenges, Ukraine initiated significant energy reforms to reduce its dependence on Russian gas and oil, modernize its energy market, and integrate with the European energy network. In 2011, Ukraine joined the European Energy Community, signalling its commitment to aligning

26 S. Gross and C. Stelzenmüller, "Europe's messy Russian gas divorce," *Brookings*, June 18, 2024. Available online: https://www.brookings.edu/articles/europes-messy-russian-gas-divorce/ (accessed on).

27 M.Kolisnyk, "Ukrainian storage and pipelines can be key to east Europe's gas supply security," *Euractiv*, March 29, 2024. Available online: https://www.euractiv.com/section/europe-s-east/opinion/ukrainian-storage-and-pipelines-can-be-key-to-east-europes-gas-supply-security/ (accessed on).
S. Makogon, "Ukraine's gas storage facilities can play a key role in European energy security," *Atlantic council*, July 25, 2023. Available online: https://www.atlanticcouncil.org/blogs/ukrainealert/ukraines-gas-storage-facilities-can-play-a-key-role-in-european-energy-security/ (accessed on).

with European energy legislation.[28] Following the annexation of Crimea and conflicts in Donbas in 2014, Ukraine ceased direct gas purchases from Russia and began importing gas from the EU.[29] Subsequent reforms in 2015 and 2017 included the adoption of laws to liberalize the gas and electricity markets, creating a competitive market closer to EU standards.[30] Ukraine later joined ENTSO-E in the first days of the war.[31] In 2018, the Verkhovna Rada passed a new Law on the Electricity Market, designed to establish a retail electricity market in Ukraine similar to those in the European Union. Early reforms also supported renewable energy and prepared for diversifying gas supplies.[32]

Challenges in Reforming the Energy Sector

Despite a victory in the key legal dispute before the Swedish Arbitration Court, Ukraine experienced delays in energy reforms due to fears of a crisis and social resistance to European integration.[33] Between 2014 and 2017, legislative measures were taken to align the Ukrainian energy sector with European standards, yet threats persisted as Ukraine faced cyberattacks linked to Russia, which repeatedly targeted energy facilities and caused power outages. Energy reforms from the early 2010s to 2022 were inconsistent, as attention to energy security often fluctuated due to public expectations and subsidies. The main problem was the politically sensitive issue of energy prices for households, where attempts to introduce market prices were repeatedly postponed to avoid political backlash, which ended in failure to create real market liberalization.[34] Before the 2022 invasion, Ukraine undertook some legislative measures to enhance energy efficiency and promote renewable energy. The Law on Energy Efficiency of Buildings (2017) established energy performance standards for new constructions and major renovations, introducing mandatory energy certification to ensure compliance.[35] Additionally, the National Renewable Energy Action Plan until 2020 aimed to increase the share of renewables in Ukraine's total energy consumption to 11% by 2020.[36] Despite these initiatives, challenges such as regulatory instability, limited funding, and inconsistent policy enforcement hindered substantial progress in energy efficiency and renewable energy adoption before 2022.

28 "Commission welcomes Ukraine in Energy Community," *European Commission*, September 24, 2010. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_10_1173 (accessed on).

29 A. Gardner, "Russia cuts gas to Ukraine," *Politico*, June 16, 2014. Available online: https://www.politico.eu/article/russia-cuts-gas-to-ukraine/ (accessed on).
S. Walker, "Russia cuts off gas supply to Ukraine after talks collapse," *The Guardian*, June 16, 2014. Available online: https://www.theguardian.com/world/2014/jun/16/russia-cuts-off-gas-supply-ukraine (accessed on).

30 "Implementation of the EU-Ukraine Memorandum of Understanding on Energy Cooperation during 2014," *European Commission*, *EU-Ukraine Energy Cooperation*, Ninth joint EU–Ukraine report, April 28, 2015. Available online: https://energy.ec.europa.eu/system/files/2015-05/EU-UKRAINE%2520ENERGY%2520COOPERATION_0.pdf (accessed online).

31 Ukrainian Transmission System Operator, NPC Ukrenergo, joins ENTSO-E as new member," ENTSO-E, 14 December 2023. Available online: https://www.entsoe.eu/news/2023/12/14/ukrainian-transmission-system-operator-npc-ukrenergo-joins-entso-e-as-new-member/

32 A. Prokip, "Liberalizing Ukraine's Electricity Market: Benefits and Risks," *Wilson Center*, May 6, 2019. Available online: https://www.wilsoncenter.org/blog-post/liberalizing-ukraines-electricity-market-benefits-and-risks (accessed on).

33 *The Stockholm arbitration court ruled in favor of Ukraine's Naftogaz in its dispute with Russia's Gazprom over take-or-pay gas contracts, with Naftogaz seeking $30.3 billion in compensation, a lower gas price, and removal of the take-or-pay clause, while Gazprom is demanding $47.1 billion for both contract obligations and transit fees for gas supplied to Europe.*
"Arbitration court rules in favour of Ukraine in Russian dispute," *Enerdata*, June 2, 2017. Available online: https://www.enerdata.net/publications/daily-energy-news/arbitration-court-rules-favour-ukraine-russian-dispute.html (accessed on).

34 A. Prokip, "The State of Ukraine's Energy Sector after Ten Years of War," *Wilson Center*, February 8, 2024. Available online: https://www.wilsoncenter.org/blog-post/state-ukraines-energy-sector-after-ten-years-war (accessed on).
"Ukraine Country Report 2024," *Bertelsmann Stiftung's Transformation Index*, 2024. Available online: https://bti-project.org/en/reports/country-report/UKR (accessed on).

35 Law No. 2118-VIII on Energy Efficiency of Buildings," Climate Change Laws, 2017. Available online: https://climate-laws.org/documents/law-no-2118-viii-on-energy-efficiency-of-buildings_984e?id=law-no-2118-viii-on-energy-efficiency-of-buildings_0259 (accessed online).

36 "National Renewable Energy Action Plan (NREAP) through 2020," *State Agency on Energy Efficiency and Energy Saving of Ukraine*, n.d. Available online: https://saee.gov.ua/documents/NpdVE_eng.pdf (accessed on).

IMPACT OF THE WAR ON ENERGY INFRASTRUCTURE

From the Annexation of Crimea to the 2022 Invasion

Ukraine has been in a state of *de facto* war since 2014, which has significantly affected the functioning of the entire energy sector. As mentioned above, the coal reserves Ukraine depended on—and the only energy resource where the country was self-sufficient[37]—were primarily located in the Donetsk region, which was under the control of pro-Russian separatists. This led to a shift away from coal towards alternative sources and marked the beginning of instability and uncertainty for the entire energy infrastructure.[38]

Consequences of the 2022 Invasion

By the end of 2021 and the beginning of 2022, it was evident that a major conflict was approaching, raising concerns about the possible impact on Ukraine's energy infrastructure.[39] After the start of Russia's full-scale invasion, which coincided a critical test of Ukraine's electricity system operating in an island–Ukrainian energy infrastructure was heavily hit by missile attacks, drones, and artillery, leading to the destruction of more than two dozen fuel depots and refinery facilities. The electricity sector suffered significant losses, especially after the occupation of the Zaporizhzhia NPP—the largest in Europe—which before the war represented 44% of Ukraine's nuclear capacity. Additionally, 30% of Ukraine's solar capacity and 90% of its wind capacity remained in occupied areas.[40]

37 "International Coal Dialogue: Quo vadis Ukraine," *European Economic and Social Committee, European Association for Coal and Lignite*, November 18, 2014. Available online: https://public.euracoal.eu/download/Public-Archive/Events/Conferences/20141118-EESC-EURACOAL-Ukraine/20141118-EESC-EURACOAL-Int-Coal-Dialogue-Ukraine-rev04.pdf (accessed on).

38 T. Laffitte and I. Moshenets, "Synchronized: The Impact of the War on Ukraine's Energy Landscape," *Foreign Policy Research Institute*, December 5, 2023. Available online: https://www.fpri.org/article/2023/12/the-impact-of-the-war-on-ukraines-energy-landscape/ (accessed on).

39 A. Prokip, "Ukrainian Energy at Gunpoint," *Wilson Center*, February 3, 2022. Available online: https://www.wilsoncenter.org/blog-post/ukrainian-energy-gunpoint (accessed on).

40 A. Prokip, "The State of Ukraine's Energy Sector after Ten Years of War," Wilson Center, op.cit. "Towards a Green Transition of the Energy Sector in Ukraine," *United Nations Development Programme*, June, 2023. Available online: https://www.undp.org/sites/g/files/zskgke326/files/2023-06/undp-ua-energy-damage-assessment.pdf (accessed on).

Russian Attacks on Energy Infrastructure

In September 2022, Russia launched a massive campaign of aerial attacks against Ukrainian energy infrastructure, aimed at destroying production and transmission capacities. More than half of the transmission infrastructure was destroyed or critically damaged, and missile strikes completely decimated the 750 kV high-voltage grid.[41] By the end of April 2023, the available capacity of thermal power plants had dropped by 65% from 2022, while the capacity of hydroelectric power plants fell 29.8%.[42] in June 2023, Russians detonated the Kakhovka dam, which threatened people, the environment, and the economy.[43] Between 2022 and 2023, roughly half of Ukraine's electricity production capacity was either occupied by Russian forces, destroyed, or damaged, with approximately half of the major grid substations similarly affected.[44]

Increased Attacks and Further Energy Shortages

Between March and May 2024, Ukraine lost another 9 GW of production capacity[45], bringing it down to about one-third of pre-war levels, even before the summer attacks of 2024.[46] In addition, district heating and natural gas infrastructure were targeted, with 18 major combined heat and power (CHP) plants and over 800 boiler houses damaged or destroyed. Above-ground natural gas storage infrastructure suffered damage while underground reserves remained intact.[47]

41 A. Grabchuk, "The energy system has lost 40 220-750 kV transmission lines due to war—Ukrenergo," *Mind*, July 10, 2023. Available online: https://mind.ua/en/news/20259743-the-energy-system-has-lost-40-220-750-kv-transmission-lines-due-to-war-ukrenergo (accessed on).

42 Y. Valova, "How Ukrainian power engineers are preparing for the winter," *Emerging Europe*, October 5, 2023. Available online: https://emerging-europe.com/analysis/how-ukrainian-power-engineers-are-preparing-for-the-winter/ (accessed on).

43 A. Prokip, "The Kakhovka Dam Disaster: Responsibility and Consequences," *Wilson Center*, June 14, 2023. Available online: https://www.wilsoncenter.org/blog-post/kakhovka-dam-disaster-responsibility-and-consequences (accessed on).

44 T. Vatman and C. Hart, "Russia's attacks on Ukraine's energy sector have escalated again as winter sets in," *International Energy Agency*, January 17, 2024. Available online: https://origin.iea.org/commentaries/russias-attacks-on-ukraines-energy-sector-have-escalated-again-as-winter-sets-in (accessed on).

45 "Russia has destroyed 9.2 GW of Ukrainian power generation, EU ambassador says," *Ukrainska Pravda*, June 3, 2024. Available online: https://www.pravda.com.ua/eng/news/2024/06/3/7458900/ (accessed on).

46 J. E. Herbst, O. Khakova and Ch. Lichfield, "Reconstructing Ukraine at war: The journey to prosperity starts now," *Atlantic Council*, June 7, 2024. Available online: https://www.atlanticcouncil.org/in-depth-research-reports/report/reconstructing-ukraine-at-war-the-journey-to-prosperity-starts-now/ (accessed on).

47 S. Elliott, "Ukraine's Naftogaz reports damage to gas storage facility after Russian attack," *S & P Global*, March 25, 2024. Available online: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/032524-ukraines-naftogaz-reports-damage-to-gas-storage-facility-after-russian-attack (accessed on).

Electricity Shortages and Managed Rationing

During the summer of 2024, Ukraine faced an acute electricity shortage, with production capacity lagging behind peak demand by 2.3 GW, even with electricity imports from western European neighbors.[48] Ukraine's state transmission system operator, Ukrenergo, navigated this with planned shutdowns, limiting electricity supply in the most affected areas to just a few hours per day. Approximately half of Ukrenergo's high-voltage substations, as well as many distribution substations, were damaged. [49]

Current Energy Situation and Temporary Solutions

In summer 2024, Ukraine's demand peaked at 12 GW with a 2 GW deficit. In the winter, demand could rise to 18.5 GW, with a potential deficit of 6 GW, even with 1.7 GW from Europe.[50] Households rely heavily on smaller generators, which have become widely available. Diesel generators are being donated as part of humanitarian aid through EU initiatives like 'Generators of Hope,' from strategic reserves such as rescEU, and by the FAO UN (Food and Agriculture Organization of the United Nations).[51] In 2022 alone, Ukraine imported

48 N. Chestney, "Ukraine faces winter power shortfall of one-third of peak demand, IEA says," *Reuters*, September 19, 2024. Available online: https://www.reuters.com/world/europe/ukraine-faces-6-gw-power-supply-shortfall-this-winter-iea-says-2024-09-19/ (accessed on).

49 G. P. Noone et al., "Are Russian Attacks on Ukraine's Electrical Grid a War Crime," *Public International Law & Policy Group*, August 11, 2023. Available online: https://www.publicinternationallawandpolicygroup.org/lawyering-justice-blog/2023/8/11/are-russian-attacks-on-ukraines-electrical-grid-a-war-crime (accessed on).
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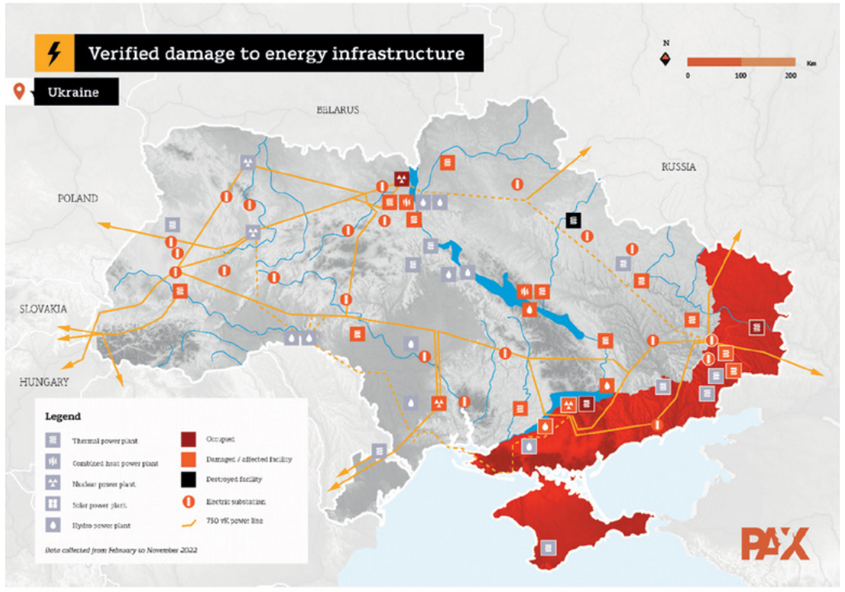
A. Matuszak and M. Jędrysiak, "Ukraine: the energy infrastructure crisis and the potential for a new wave of refugees," *The Centre for Eastern Studies*, June 24, 2024. Available online: https://www.osw.waw.pl/en/publikacje/analyses/2024-06-24/ukraine-energy-infrastructure-crisis-and-potential-a-new-wave (accessed on).

50 N. Chestney, "Ukraine faces winter power shortfall of one-third of peak demand, IEA says," Reuters, September 19, 2024. Available online: https://www.reuters.com/world/europe/ukraine-faces-6-gw-power-supply-shortfall-this-winter-iea-says-2024-09-19/ (accessed on).
Ukraine's Energy Security and the Coming Winter," International Energy Agency, September 2024. Available online: https://www.iea.org/reports/ukraines-energy-security-and-the-coming-winter/executive-summary

51 "Generators of hope: city-to-city relief for Ukraine," *Euro Cities*, November 23, 2022. Available online: https://eurocities.eu/latest/generators-of-hope-city-to-city-relief-for-ukraine/?gad_source=1&gclid=CjwKCAjwjsi4BhB5EiwAFAL0YCGlmVhTThfUFwh29P80_30YylV2ojX-v0hJGw5LehuRDHCn-Pn9PPxoCY-gQAvD_BwE (accessed on).
EU Sends Additional 500 Power Generators to Ukraine," European Commission, 2023. Available online: https://civil-protection-humanitarian-aid.ec.europa.eu/news-stories/news/eu-sends-additional-500-power-generators-ukraine-2023-12-22_en (accessed online).
"Energy support: Ukrainian food producers received generators from FAO and Germany," *Food and Agriculture Organization of the United Nations*, July 30, 2024. Available online: https://www.fao.org/countryprofiles/news-archive/detail-news/en/c/1708166 (accessed on).
Energy Infrastructure Attacks: Outlook and Impact During 2024–2025 Cold Season," ACAPS, 2024. Ukraine_Analysis_hub_Attacks_on_the_energy_infrastructure_in_Ukraine.pdf (accessed online).

over 650,000 power generators.[52] The situation is expected to improve further, with even more generators available now for the upcoming winter, and the question becomes whether sufficient diesel supplies are available to run them. Ukraine is dependent on diesel imports from Western countries, mainly sourced from or passing through Lithuania, Poland, Romania, Slovakia, and Hungary. As an example, in 2023 Romania increased diesel imports by 30% compared to 2022, while imports from the Russian Federation dropped by 87% due to sanctions. Additional supplies have been sourced from Kuwait, Italy, and Turkey.[53]

Figure 3. Verified damage to energy infrastructure in Ukraine



Source: PAX—Damage to energy infrastructure—November 2022

Furthermore, in each city, so-called 'Points of Invincibility' have been established—locations equipped with state-supplied generators where residents can warm up, charge their devices, and access basic services during power cuts, especially critical in winter.[54] These efforts have been part of a larger campaign called 'Winterization of Ukraine' launched before the winter of 2022/23

52 On the Verge of a Blackout: Ukraine Facing Attacks on Its Electricity," OSW Commentary, 2023. Available online: https://www.osw.waw.pl/en/publikacje/osw-commentary/2023-01-18/verge-blackout-ukraine-facing-attacks-its-electricity.

53 War in Ukraine: Kiev's Efforts to Ensure the Availability of Petroleum Products," IEŚ Commentaries, 2023. Available online: https://ies.lublin.pl/en/comments/war-in-ukraine-kievs-efforts-to-ensure-the-availability-of-petroleum-products/.

54 "Nova Ukraine's Points of Invincibility Project with Ukrzaliznytsia and the Howard G. Buffett Foundation Extended Through 2025," *Nova Ukraine*, May 23, 2024. Available online: https://novaukraine.org/points-of-invincibility-project-extended-through-2025/?gad_source=1&gclid=CjwKCAjwjsi4BhB5EiwAFAL0YFFesNehUJ2seAg4i6et6MTgBLY_f4TjnuA5IIThd0BDv8xOaO74IRoCo3QQAvD_BwE (accessed on).

to enhance the country's resilience.[55] In July 2024, the European Commission and Ukraine's Ministry of Energy established the Ukraine Energy Support Fund to enhance the coordination of financial and in-kind assistance to the country.[56]

55 "Ukraine Winterization Plan 2023–2024," *UNHCR*, n.d. Available online: https://www.unhcr.org/ua/wp-content/uploads/sites/38/2023/10/2023-2024-Ukraine-winterization-plan_rev2.pdf (accessed on).

56 Supporting Ukraine's Resilience Through the Ukraine Energy Support Fund," European Commission, 2024. Available online: https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_24_3763 (accessed online).

UKRAINE'S ENERGY POTENTIAL

Ukraine is the second-largest country on the European continent after Russia. This vast territory is geographically diverse rich natural resources and biodiversity. The western region is known for mountainous forests and pastures, while central areas are dominated by extensive agricultural fields and steppe ecosystems.[57]

Ukraine has ambitious plans to expand its renewable energy production capacity as part of its post-war recovery.[58] The National Recovery Plan includes investments of approximately $130 billion to support energy independence and the development of green energy in two phase (from 2023–2025 and 2026–2032), aiming to add 5–10 GW of solar and wind capacity, localize renewable energy equipment production, construct over 30 GW for hydrogen production, and develop smart grids.[59] However, much of the potential for renewable energy development is concentrated in regions that are or were under Russian control, complicating the execution. Currently, 66% of solar and wind installations are located in regions such as Odesa, Zaporizhzhia, Mykolaiv, Kherson, and Dnipro, areas that may require repairs and maintenance once Ukraine regains full control.[60]

Wind Energy

The total area suitable for wind farm construction and operation in Ukraine is estimated at up to 9,000 km², mostly in the south[61], supporting total wind energy potential of 16–30 GW, 10 to 20 times the country's pre-war capacity.[62] The most attractive areas for wind energy development are along the Black Sea and Azov Sea coasts, the southern coast of Crimea, parts of the Ukrainian

57 "Maps of Ukrine," *World Atlas*, December 7, 2022. Available online: https://www.worldatlas.com/maps/ukraine (accessed on).

58 "Rebuilding Ukraine's energy future: a Ukrainian perspective of the Ukraine Reconstruction Conference," *Energy Transition*, June 26, 2024. Available online: https://energytransition.org/2024/06/rebuilding-ukraines-energy-future-a-ukrainian-perspective-of-the-ukraine-reconstruction-conference/ (accessed on).

59 Developing Renewable Energy in Ukraine," Cahill and Dawes, Center for Strategic and International Studies (CSIS), 2022. Available online: https://www.csis.org/analysis/developing-renewable-energy-ukraine (accessed online).

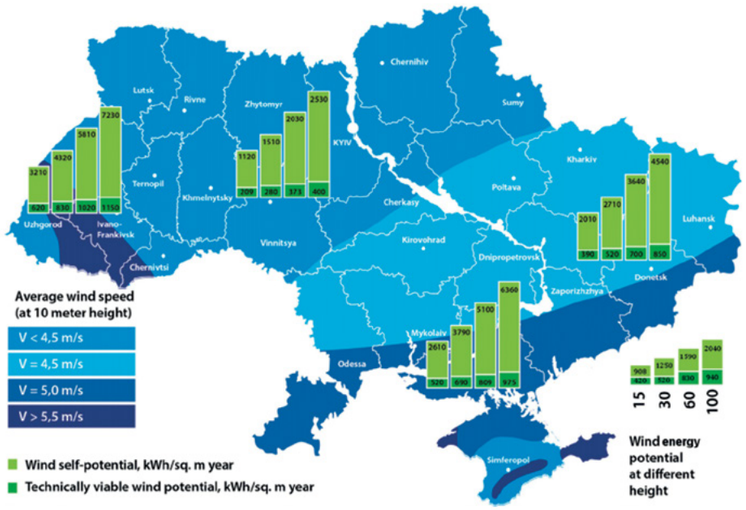
60 B. Cahill and A. Dawes, "Developing Renewable Energy in Ukraine," The Center for Strategic and International Studies, December 19, 2022. Available online: https://www.csis.org/analysis/developing-renewable-energy-ukraine (accessed on).

61 "Wind Power," Renewables for Ukraine, n.d. Available online: https://www.renewables4ukraine.org/wind/ (accessed on).

62 N. Antoniuk, M. Baldzhy and O. Perkhach, "The performance potential of wind energy in Ukraine and prospects for its recovery after the war," *Energy Policy Journal*, Vol. 25, No. 3, 2022, pp. 91-104. Available online: https://doi.org/10.33223/epj/153978 (accessed on).
Y. Makarovskiy and V. Zinych, "Wind Energy Potential Assessment of Ukraine," *Romanian Journal of Geography*, March 30, 2013. Available online: http://www.rjgeo.ro/issues/revue%20roumaine%2058_2/makarovskiy%20et%20al.pdf (accessed on).

Carpathians, the Crimean Mountains, and the Donbas region.[63] Ukraine also has ideal conditions for offshore wind generation, with average annual wind speeds of 7.0–8.5 m/s (on land at about 100 meters, and at about 50 meters in coastal areas). These conditions allow for the use of highly efficient megawatt-class wind turbines with annual capacity utilization rates of 0.3–0. 4.

Figure 4. Wind power potential in Ukraine



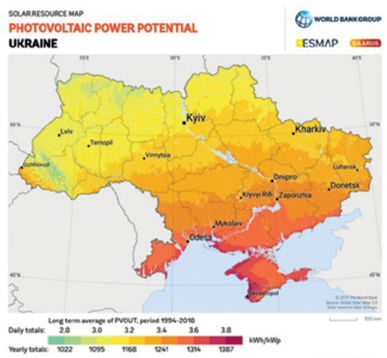
Source: Zoria—2017[64]

Solar Energy

Ukraine has relatively high solar potential, especially in southern regions like Odesa, Zaporizhzhia, and Mykolaiv, with annual solar radiation between 1,070 and 1,400 kWh/m².[65] Solar energy experienced significant growth before the war, reaching an installed capacity of over 6 GW.[66] Several studies estimate that up to 14 GW of installed solar capacity is technically and economically feasible by 2030, but the southern regions most suitable for solar power are largely under occupation or face the threat of destruction.[67] [68]

Ukraine also has immense potential in the agricultural industry for integrating agrivoltaics. Given the vast agricultural areas in Ukraine, agrivoltaics could play a crucial role in enhancing the country's energy independence and contribute to the decarbonization of its energy system. Investment in agrivoltaics provides clean electricity generation and enhances agricultural productivity by retaining water due to the shading effect. This dual benefit makes agrivoltaics a highly attractive option for Ukraine, as it seeks to modernize both its energy and agricultural sectors.[69]

Figure 5. Photovoltaic Power Potential in Ukraine



Source: World Bank—2024

Hydropower

Hydropower plants play a key role in Ukraine's energy system, stabilizing the grid and responding to fluctuations in energy demand. Installed hydropower capacity stands at 6,229 MW, with 1,528 MW of pumped-storage power plants,

63 "Ukraine lost 90% of wind power and 50% of solar power due to Russian attacks," *Wind Energy and Electric Vehicle Magazine*, October 23, 2022. Available online: https://www.evwind.es/2022/10/23/ukraine-lost-90-of-wind-power-and-50-of-solar-power-due-to-russian-attacks/88477 (accessed on).

64 Available at: https://euromaidanpress.com/2017/07/30/most-powerful-wind-turbines-in-ukraine-produced-in-kramatorsk-45-km-away-from-the-frontline/

65 "Solar Energy: Path to Ukraine's Energy Independence," *RePower Ukraine*, September 19, 2024. Available online: https://repowerua.org/uncategorized/solar-energy-path-to-ukraine-s-energy-independence/ (accessed on).

66 "Ukraine's energy system under attack" *International Energy Agency*, 2024. Available online: https://www.iea.org/reports/ukraines-energy-security-and-the-coming-winter/ukraines-energy-system-under-attack (accessed online).

67 "Ukraine should invest in solar and wind to rebuild war-torn energy system, ETH researchers say," *Science Business*, September 19, 2024. Available online: https://sciencebusiness.net/network-updates/ukraine-should-invest-solar-and-wind-rebuild-war-torn-energy-system-eth-researchers (accessed on).

68 C. Owen, "Ukraine set to install 5x more solar capacity than expected," *Solar & StorageXtra*, June 10, 2024. Available online: https://solarstoragextra.com/ukraine-set-to-install-5x-more-solar-capacity-than-expected/ (accessed on).
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69 "Solar farming and agrivoltaics instead of gas and coal—examples of their use in Ukraine and globally (photo)," *East Fruit*, February 23, 2023. Available online: https://east-fruit.com/en/horticultural-business/stories/solar-farming-and-agrivoltaics-instead-of-gas-and-coal-examples-of-their-use-in-ukraine-and-globally-photo/ (accessed on).
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which is about half of what is technically feasible (21,500 GWh).[70] Ukraine plans to realize this potential over the next decade, reaching a 15% share of total energy supply.

The majority of this is concentrated between Dnipro, Dniester, and Southern Bug rivers,[71] with the former anchoring the sector 3.8 GW capacity. In addition to large hydropower plants, Ukraine has significant untapped potential small and medium hydropower, which could help decentralize the energy system and improve energy access in remote areas.[72]

Biomass

Given the country's vast agricultural base and forest resources, biomass is one of the most promising renewable energy sources, suitable for producing heat, electricity, and biofuels. Agricultural residues, such as straw, corn stalks, and sunflower husks, can be effectively used for energy production.[73] Additionally, Ukraine has the option to shift some of its production to grow specialized energy crops.[74] Furthermore, Ukraine has extensive forested areas covering about 16% of its total land area, which can provide forestry biomass, including wood waste and trimmings, as well as fast-growing trees like poplar and willow.[75]

Natural Gas and Hydrogen

With an estimated volume of approximately 1,000 billion cubic meters (bcm), Ukraine possesses the second-largest reserves in Europe after Norway.[76] Under normal circumstances, production is close to 20 bcm.[77] Ukraine aims to increase domestic production to reduce reliance on imports by adopting new technologies and enhancing extraction efficiency.[78] The main challenge for gas extraction is that most reserves are located in conflict zones such as Kharkiv and Poltava regions.[79]

In addition, Ukraine has significant untapped shale gas potential which could be developed to improve its energy security. The greatest potential lies with the Yuzivska gas field in Eastern Ukraine, estimated to have 10–20 bcm.[80] Shell signed a major development deal in 2013 but withdrew in 2015 because of geopolitical instability in the region. Despite these challenges, Naftogaz has been working to revive the project and further explore Ukraine's shale gas potential.

As far as infrastructure, Ukraine's gas transit system exceeds 140 bcm, although utilization has declined due to the diversification of European supplies and supply routes, such as Nord Stream.[81] Ukraine needs to modernize this infrastructure to improve efficiency and reliability, including upgrades to compressor stations and pipelines.[82] Ukraine also possesses one of the largest gas storage capacities in Europe at over 31 bcm combined.[83]

Ukraine also has significant potential for green hydrogen production[84] to pair with an adaptable gas infrastructure network. This could make it an integral partner for the European Union's hydrogen market[85], as well as importing from third countries.[86] This development would not only bolster Ukraine's energy security but also contribute to decarbonization efforts and reduce dependence on fossil fuels, supporting the EU's climate neutrality goals.[87]

70 "Hydro News Special a New Old Continent Europe," *Adritz Hydro GmbH*, May 2019. Available online: https://www.andritz.com/resource/blob/302626/656c0f72cd86ff28b5d4361d8cf3014d/hydronews-europe-en-data.pdf (accessed on).

71 O. Vasyliuk and E. Simonov, "Hydroelectric dams as weapons: virtual and actual," *Ukraine War Environmental Consequences Work Group*, October 24, 2022. Available online: https://uwecworkgroup.info/hydroelectric-dams-as-weapons-virtual-and-actual/ (accessed on).

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73 M. Chepeliev, O. Diachuk, R. Podolets and G. Trypolska, "The role of bioenergy in Ukraine's climate mitigation policy by 2050," *Renewable and Sustainable Energy Reviews*, Vol. 152, 2021. Available online: https://doi.org/10.1016/j.rser.2021.111714 (accessed on).

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76 A. Amelin, A. Prokip and A. Umland, "The Forgotten Potential of Ukraine's Energy Reserves," *Harvard International Review*, October 10, 2020. Available online: https://hir.harvard.edu/ukraine-energy-reserves/ (accessed on).

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78 V. Afanasiev, "Ukraine boosts gas production as end of Russian transit deal looms," *Upstream*, September 20, 2024. Available online: https://www.upstreamonline.com/energy-security/ukraine-boosts-gas-production-as-end-of-russian-transit-deal-looms/2-1-1712941?zephr_sso_ott=AGvWuz (accessed on).

79 K. Marcinek, "Russia Does Not Seem to Be After Ukraine's Gas Reserves," *RAND*, April 11, 2022. Available online: https://www.rand.org/pubs/commentary/2022/04/russia-does-not-seem-to-be-after-ukraines-gas-reserves.html (accessed on).

80 J. Donovan, "Ukraine Signs Drilling Deal with Shell for Shale Gas," *Royal Dutch Shell*, January 24, 2013. Available online: https://royaldutchshellplc.com/2013/01/24/ukraine-signs-drilling-deal-with-shell-for-shale-gas/ (accessed on).
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81 "Ukraine's Low-Carbon Gas Potential and the European Union," *Harvard International Review*, August 5, 2021. Available online: https://hir.harvard.edu/ukraines-low-carbon-gas-potential-and-the-eu/ (accessed on).
G. Gotev, "Ukraine Gas Transit: What's at Stake," *Euractive*, December 2019. Available online: https://eurac.tv/9RaF (accessed on).

82 A. Corbeau and T. Mitrova, "Will the Ukrainian Gas Transit Contract Continue Beyond 2024," *The Center on Global Energy Policy*, June 8, 2023. Available online: https://www.energypolicy.columbia.edu/will-the-ukrainian-gas-transit-contract-continue-beyond-2024/ (accessed on).

83 S. Elliott, "Ukraine's UkrTransGaz eyes increased foreign use of gas storage capacity," *S & P Global*, February 27, 2024. Available online: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/022724-ukraines-ukrtransgaz-eyes-increased-foreign-use-of-gas-storage-capacity (accessed on).

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86 L. Oleniak, "Water energy: What green hydrogen is and how Ukraine plans to produce it," *RBC-Ukraine*, July 29, 2024. Available online: https://newsukraine.rbc.ua/news/water-energy-what-green-hydrogen-is-and-how-1722242520.html (accessed on).

87 S. Dubko et al., "Draft Roadmap for production and use of hydrogen in Ukraine," *United Nations Economic Commission for Europe*, March 9, 2021. Available online: https://unece.org/sites/default/files/2021-03/Hydrogen%20Roadmap%20Draft%20Report_ENG%20March%202021.pdf (accessed on).

Nuclear Energy

Traditional Nuclear Power Plants

Nuclear energy has long been a cornerstone of Ukraine's energy mix.[88] Successive governments have expressed interest in expanding nuclear capacities, with the most ambitious plan from 2006 aiming for the construction of 11 new reactors.[89] These were intended to complement the existing fleet of 15 reactors, boosting installed capacity to 16.5 GW. However, little of this plan has been realized, largely due to economic challenges, corruption, and inefficiencies in government institutions.[90] The latest key projects include the expansion of the Khmelnytskyi NPP with the construction of Units 3 and 4, which are already underway, and Units 5 and 6 in the next phase.[91] The South Ukraine NPP will also be expanded with Units 4 and 5.[92] These seven new reactors are expected to add over 7 GW of installed capacity, all using AP1000 technology from the U.S. company Westinghouse. Additionally, there are discussions about completing the abandoned Chyhyryn site with four reactors with totalling a capacity of 4 GW.[93]

Small Modular Reactors (SMR)

Small modular reactors (SMRs) could be an ideal complement to Ukraine's existing nuclear infrastructure.[94] The modular design of SMRs offer greater flexibility, quicker installation and lower investment costs compared to traditional large nuclear reactors. Moreover, their advanced safety systems can help alleviate public concerns regarding nuclear energy safety.

Ukrainian Energoatom has signed partnerships with Holtec, Westinghouse, and Rolls-Royce to deploy advanced SMR technologies in Ukraine. Holtec offers its SMR-160 model, a 160 MW reactor designed for flexibility, passive cooling without external power, and the ability to run for up to four years without refuelling. This model is also intended for various applications, including industrial use and electricity generation.[95] Westinghouse will deploy its AP300™ SMR, a 300 MW reactor based on the proven AP1000 design, featuring highly efficient design and simplified systems for easier maintenance and scalability. Construction could begin by 2030.[96] The Rolls-Royce 470 MW reactor is factory-built to ensure rapid deployment, and is capable of powering one million homes with carbon-free electricity for over 60 years. This reactor is also designed for energy independence and post-war recovery, featuring scalable deployment for faster energy restoration.[97]

Geothermal energy

Ukraine possesses significant geothermal energy resources, with an estimated annual potential of 438 GWh, or 8.4 million tons of oil equivalent (Mtoe), which could replace 10 bcm of natural gas.[98]

Geothermal is included in the State Program for renewable energy development. The State Commission of Ukraine on Mineral Resources has approved the cogeneration potential of geothermal water resources at 27.3 million m^3/day, with a thermal power capacity of 351 million GJ/year.[99]

Ukraine has a medium geothermal gradient, with its most promising regions for future development located in Transcarpathian, Crimea (south), and the Dnipro-Donetsk basin[100] where it could be utilized for heating and electricity production.[101]

88 S. E. Jayanti, "Ukrainian nuclear energy can fuel country's recovery and power Europe," *Atlantic Council*, April 16, 2024. Available online: https://www.atlanticcouncil.org/blogs/ukrainealert/ukrainian-nuclear-energy-can-fuel-countrys-recovery-and-power-europe/ (accessed on).

89 "Nuclear Power in Ukraine," *World Nuclear Association*, March 25, 2024. Available online: https://www.iea.org/countries/ukraine (accessed on).

90 Ibid

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93 J. Salavec, "Ukrajina vybrala lokalitu pro novou jadernou elektrárnu s americkými reaktory," *oEnergetice*, September 3, 2024. Available online: https://oenergetice.cz/jaderne-elektrarny/ukrajina-vybrala-lokalitu-pro-novou-jadernou-elektrarnu-s-americkymi-reaktory (accessed on).

94 S. E. Jayanti, "Ukrainian nuclear energy can fuel country's recovery and power Europe," *Atlantic Council*, April 16, 2024. Available online: https://www.atlanticcouncil.org/blogs/ukrainealert/ukrainian-nuclear-energy-can-fuel-countrys-recovery-and-power-europe/ (accessed on).

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96 "Westinghouse and Ukraine's Energoatom Pursuing Deployment of AP300™ Small Modular Reactor to Meet Climate, Energy Security Goals," *Westinghouse Electric Company*, September 12, 2023. Available online: https://info.westinghousenuclear.com/news/westinghouse-and-ukraines-energoatom-pursuing-deployment-of-ap300-small-modular-reactor-to-meet-climate-energy-security-goals (accessed on).

97 "Rolls-Royce SMR signs agreement to support Ukraine re-build," *Rolls-Royce SMR*, March 23, 2023. Available online: https://www.rolls-royce-smr.com/press/rolls-royce-smr-signs-agreement-to-support-ukraine-re-build (accessed on).

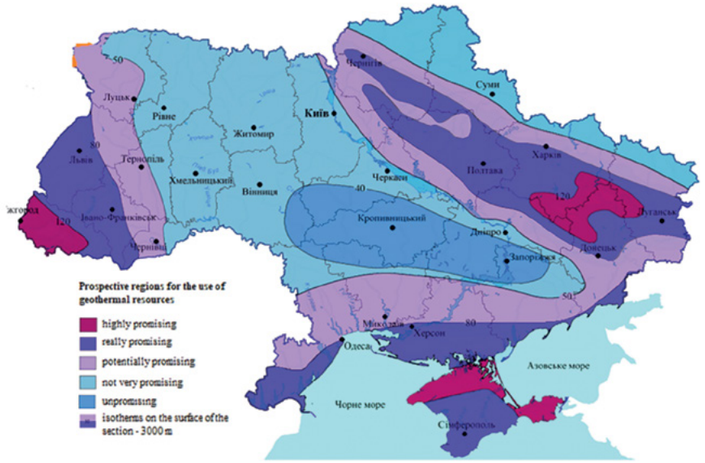
98 Yu. V. Demchuk and H. Livensteva, "Geothermal Overview of Ukraine," *Mining Geology & Geoecology*, No. 1: 6, 2023. Available online: 10.59911/mgg.2786-7994.2023.1(6).287850. (accessed on).

99 Ibid

100 Yu. V. Demchuk and H. Livensteva, "Geothermal Overview of Ukraine," Mining Geology & Geoecology, op.cit.
"Geothermal Potential of Ukraine poster presentation," *Geothermal Ukraine*, November 2023. Available online: https://www.geothermalukraine.org/en/news/geothermal-potential-of-ukraine-poster-presentation (accessed on).
Direct Utilization of Geothermal Energy 2020 Worldwide Review," Lund and Toth, 2021, p. 30. Available online: https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01018.pdf (accessed online).

101 Geothermal Energy Country Update Report from Ukraine, 2020," Morozov et al., 2021, p. 2. Available online: https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01060.pdf (accessed online).
Studies Show Large, Untapped Geothermal Potential in Ukraine," Cariaga, ThinkGeoEnergy, 2023. Available online: https://www.thinkgeoenergy.com/studies-show-large-untapped-geothermal-potential-in-ukraine/ (accessed online).

Figure 6. Prospective regions for the use of geothermal resources



Source: Institute of Renewable Energy of the National Academy of Sciences of Ukraine—2020

Role of Interconnectors

Ukraine's high-voltage power grid encompasses a total length of 19,000 km and includes 103 substations. Before the synchronization with continental Europe, the system featured more than 50 cross-border links, with a significant high-voltage backbone of 750 kV. Interconnectors play a pivotal role in linking Ukraine's energy grid with those of neighbouring European countries, offering a dual benefit of energy security and market flexibility. This is especially vital given the damage inflicted by Russia on Ukraine's energy infrastructure. Despite these challenges, Ukraine has successfully exported electricity to countries such as Hungary, Moldova, Romania, Poland, and Slovakia. In March 2024, for instance, Ukraine exported a record 13 gigawatt hours of electricity.[102]

A significant milestone occurred on March 16, 2022, when Ukraine and Moldova synchronized their electricity grids with the continental European grid, integrating into the 50 Hertz alternating current system.

The potential role of interconnectors becomes even more apparent when considering Ukraine's fluctuating energy supply. For example, to optimize solar power in summer months, measures such as dynamic line rating (DLR) could be applied to enhance the efficiency of power transfers between Ukraine and its neighbours. By winter 2025/26, grid-enhancing technologies along with the completion of interconnection projects with Slovakia and Romania,

102 A. Sabadus, "Ukraine expands EU energy exports in fresh display of wartime resilience," *Atlantic Council*, March 12, 2024. Available online: https://www.atlanticcouncil.org/blogs/ukrainealert/ukraine-expands-eu-energy-exports-in-fresh-display-of-wartime-resilience/ (accessed on).
"Ukraine breaks record for daily electricity exports," *Ukrainska Pravda*, March 5, 2024. Available online: https://www.pravda.com.ua/eng/news/2024/03/5/7445052/ (accessed on).

Ukraine's import capacity could rise to 3.6 GW, significantly reducing potential power shortages. Romania is particularly important in this regard, with the 400 kV Pivdennoukrainska NPP–Isaccea line to provide over 1 GW transfer capacity, possibly by 2026. Trilateral talks with Moldova also outlined plans to supply Ukraine with 150 MW and propose an additional 350 MW via regional interconnections.[103]

As Ukraine moves toward rebuilding its energy sector, modernizing and expanding interconnectors will be critical for leveraging its renewable energy capacity. The expansion of the Zamość-Dobrotvir 220 kV line and the potential for future upgrades to 400 kV could play a pivotal role in stabilizing regional energy flows. Additionally, Ukraine's vast gas transmission infrastructure, which is already an important asset, could be used to transport natural gas from non-Russian sources. In the future, this infrastructure could be repurposed to support hydrogen transport, positioning Ukraine as a key player in Europe's transition to cleaner energy.[104]

Renewable Energy and Export Potential

Ukraine has an ambitious long-term vision to become a renewable energy powerhouse producing up to 850 GW from renewable sources.[105] Ukraine's National Energy and Climate Plan (NECP) sets a goal of reducing greenhouse gas emissions by 65% by 2030.[106] However, the 27% renewable energy target for 2030 lags behind the EU's 42% target, a gap that Ukraine will need to bridge.[107]

With the right investments and policies, Ukraine can become a major energy exporter to Europe.[108] The success of this energy transition depends on

103 Geothermal Energy Country Update Report from Ukraine, 2020," Morozov et al., 2021, p. 2. Available online: https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01060.pdf (accessed online).
Nies and Savytskyi, "Six options to boost power grid transfers from Continental Europe to Ukraine for the next two winters," *Green Deal Ukraina*, August 2024. Available online: https://greendealukraina.org/products/analytical-reports/six-options-to-boost-power-grid-transfers-from-continental-europe-to-ukraine-for-the-next-two-winters (accessed on).
Three Seas Initiative. (2024). *Construction of the interstate line Pivdennoukrainska NPP–Isaccea (Romania) submitted by Ukraine*. Retrieved from https://projects.3seas.eu/projects/construction-of-the-interstate-line-pivdennoukrainska-npp-isaccea-(romania)-submited-by-ukraine

104 Ibid

105 "Rebuilding Ukraine's energy future: a Ukrainian perspective of the Ukraine Reconstruction Conference," *Energy Transition*, June 26, 2024. Available online: https://energytransition.org/2024/06/rebuilding-ukraines-energy-future-a-ukrainian-perspective-of-the-ukraine-reconstruction-conference/ (accessed on).

106 "Ukraine approves National Energy and Climate Plan developed with EU support," *EU Neighbours East*, June 26, 2024. Available online: https://euneighbourseast.eu/news/latest-news/ukraine-approves-national-energy-and-climate-plan-developed-with-eu-support/ (accessed on).

107 "Rebuilding Ukraine's energy future: a Ukrainian perspective of the Ukraine Reconstruction Conference," *Energy Transition*, op. cit.
O. Diachenko, "Investments in Solar Energy in a Decentralized Energy System as a Factor in Strengthening the Energy Security of Ukraine During Wartime," *Institute of Renewable Energy of the National Academy of Sciences of Ukraine*, No. 2: 77, July 1, 2024. Available online: https://doi.org/10.36296/1819-8058.2024.2(77).73-78 (accessed online).
"Aleksandr Katsuba: What Ukraine's Energy Sector Should Look Like," *British Wire*, July 23, 2024. Available online: https://britishwire.com/business/aleksandr-katsuba-what-ukraines-energy-sector-should-look-like/ (accessed on).

108 G. Crestti et al., "Integrating Ukraine's Energy Sector into the EU," *Clingendael Institute*, September 2024. Available online: https://www.clingendael.org/sites/default/files/2024-09/EU-Ukraine_Energy_Cooperation.pdf (accessed on).

strong market-based incentives and investor confidence. By adopting the EU Clean Energy Package and creating a stable regulatory framework, Ukraine can attract the necessary investment to expand its renewable energy capacity and fully integrate with the European energy market.[109]

Importance of RES and V4

Renewable energy sources are a critical part of Ukraine's future energy system because they are decentralized and, therefore, more resilient to enemy attacks. Unlike centralized power plants, such as nuclear facilities, renewable energy systems like solar and wind farms are spread over large areas, making them harder to target and disrupt. However, Ukraine faces another major challenge: a shortage of energy experts due to the war. This is where the expertise of other countries, particularly the V4 nations, could play a vital role. V4 countries, having undergone their own energy transitions, can offer both technical know-how and practical experience to help rebuild Ukraine's energy sector based on clean technologies.

109 S. Kardaś, "Energising eastern Europe: How the EU can enhance energy sovereignty through cooperation with Ukraine and Moldova," *European Council on Foreign Relations*, March 11, 2024. Available online: https://ecfr.eu/publication/energising-eastern-europe-how-the-eu-can-enhance-energy-sovereignty-through-cooperation-with-ukraine-and-moldova/ (accessed on).

POTENTIAL CONTRIBUTION OF THE SLOVAK REPUBLIC

Slovakia is focusing on development its eastern region, emphasizing the strengthening of connectivity between Ukraine and the EU. Key medium-term objectives include the modernization of highways, railways, waterways, and ports, as well as the construction of energy interconnections.[110] The current government supports these initiatives through its strategy titled "Framework for the Involvement of the Slovak Republic in the Reconstruction of Ukraine," which aims to actively engage Slovak entities, particularly companies, in Ukrainian reconstruction projects. This approach not only creates new business opportunities but also enhances the competitiveness of Slovak enterprises internationally. Additionally, it will attract new foreign direct investments to eastern Slovakia with increased interest in exports to Ukraine[111] In this section, we explore the potential for the V4 countries, including Slovakia, to contribute to the reconstruction of Ukraine, the utilization of Ukraine's vast energy potential, and the integration of Ukraine into the EU energy systems.

Gas and electricity interconnectors

After Gazprom increased prices in 2014, the Ukrainian government signed a deal with Slovakia to secure alternative gas supplies. Since then, the majority of Ukraine's gas imports have transited through Slovakia. However, Slovakia did not allow Ukraine to utilize its main transit pipelines with free capacity exceeding 50 bcm per year, thereby denying Ukraine access to larger volumes of gas. Instead, a technical solution was found for the reverse flow of gas from Europe to Ukraine by modernizing a previously unused pipeline from Vojany to Uzhgorod, unlocking capacity of up to 14.5 bcm per year. This pipeline was put into operation on September 2, 2014, ensuring alternative gas supplies for Ukraine and reducing its dependence on Russian gas.[112]

Beyond reverse gas flows, Slovakia's gas transmission system operator, Eustream, has been collaborating with Ukraine's Naftogaz to explore the feasibility of repurposing existing pipelines for hydrogen transport as part of the

110 This includes the Košice airport, with plans for a railway connection to facilitate passenger travel between Kyiv and Košice, thereby allowing Ukrainian citizens to utilize the Košice airport.

111 Rámec zapojenia Slovenskej republiky do obnovy Ukrajiny," Úrad podpredsedu vlády pre plán obnovy a odolnosti a využívanie eurofondov, 2024. Available online: https://lrv.rokovania.sk/data/att/185887_subor.pdf (accessed online)

112 "Ukraine, Slovakia extend increased firm capacity for gas imports," *Ukrinform*, April 3, 2023. Available online: https://www.ukrinform.net/rubric-economy/3690572-ukraine-slovakia-extend-increased-firm-capacity-for-gas-imports.html (accessed on).
"Eustream offers Ukrainian partner assistance with reverse flow of gas supplies," *Eustream*, April 16, 2014. Available online: https://www.eustream.sk/en/about-us/press/news/eustream-offers-ukrainian-partner-assistance-reverse-flow-gas-supplies.html (accessed on).
"Vojany-Uzhgorod gas pipeline to reach maximum capacity in October 2014," *Kyiv Post*, April 28, 2014. Available online: https://archive.kyivpost.com/article/content/business/vojany-uzhgorod-gas-pipeline-to-reach-maximum-capacity-in-october-2014-345468.html (accessed on).

Central European Hydrogen Corridor, a joint project between several gas infrastructure companies.[113]

In addition to the Vojany–Uzhgorod pipeline, Slovakia and Ukraine share the "Brotherhood" pipeline (Urengoy–Pomary–Uzhgorod), the largest carrier of Russian gas into Europe, with a capacity of over 100 bcm per year. The total reverse flow capacity between the two is up to 14.5 bcm per year, representing a significant contribution to Ukraine's energy security.[114] This also helps position Ukraine as a future energy hub, leveraging its underground gas storage.[115]

Slovakia also plays a crucial role in enhancing Ukraine's energy security through the development and modernization of key cross-border projects, such as the 200 million euro[116] rehabilitation of the Mukachevo—Velké Kapušany interconnector, a 51 km 400 kV overhead line. This project is essential not only for facilitating the cross-border flow of electricity but also for expanding gas storage capabilities, thereby contributing to the broader Eastern European energy hub envisioned by Ukrainian Prime Minister Denys Shmyhal.[117] It will also be vital for stabilizing Ukraine's grid and enabling its energy sources to be exported to Slovakia and further into Europe.[118] Slovakia has become a net exporter of electricity, with clean exports rising to nearly 1,900 GWh in the first half of 2024, marking a year-on-year increase of 70.5%.[119]

The two-stage project begins as a single-circuit line with a second circuit added at a later stage. The single circuit will add about 600–800 MW of transfer capacity from 264 MW in 2024. With 70% of the work completed in Ukraine, efforts are being made to expedite its commissioning scheduled for 2026, though newer sources suggest it may be 2028.[120]

113 "Energy Transformation Projects," *Eustream*, n.d. Available online: https://www.eustream.sk/en/transparency/network-development/energy-transformation-projects/ (accessed on).
"Ukraine will build 10 GW of capacity to produce renewable hydrogen, which the EU urgently needs," *Hydrogen Central*, April 30, 2024. Available online: https://hydrogen-central.com/ukraine-will-build-10-gw-of-capacity-to-produce-renewable-hydrogen-which-the-eu-urgently-needs/ (accessed on).
"Ukrtransgaz has joined an international hydrogen production project in western Ukraine," *Ukraine Business News*, November 29, 2021. Available online: https://ubn.news/ukrtransgaz-has-joined-an-international-hydrogen-production-project-in-western-ukraine/ (accessed on).

114 "Ukraine launches virtual gas reverse flow from Slovakia," *Enerdata*, March 3, 2020. Available online: https://www.enerdata.net/publications/daily-energy-news/ukraine-launches-virtual-gas-reverse-flow-slovakia.html Accessed on).

115 J. Roberts, "Responding to Russia: Time to back backhaul," *Atlantic Council*, March 8, 2018. Available online: https://www.atlanticcouncil.org/blogs/energysource/responding-to-russia-time-to-back-backhaul/ (accessed on).

116 "Ficova vláda plánuje veľkú investíciu do elektrického prepojenia s Ukrajinou," *Štandard*, September 3, 2024. Available online: https://standard.sk/746873/ficova-vlada-planuje-velku-investiciu-do-elektrickeho-prepojenia-s-ukrajinou (accessed on).

117 A. Tumanova, "Ukraine and Slovakia agree to speed up the reconstruction of the Mukachevo–Veľké Kapušany interconnector," *Ukrainian National News*, January 24, 2024. Available online: https://unn.ua/en/news/ukraine-and-slovakia-agree-to-speed-up-the-reconstruction-of-the-mukachevo-velke-kapusany-interconnector (accessed on).

118 V. Volokita, "Ukraine and Slovakia to create Eastern European energy hub—Ukrainian PM," *Ukrainska Pravda*, October 7, 2024. Available online: https://www.pravda.com.ua/eng/news/2024/10/7/7478561/ (accessed on).

119 R. Potočár, "Slovensko posilňuje ako exportér elektriny. V prvom polroku 2024 vývoz stúpol o 70%," *Energie Portal*, August 1, 2024. Available online: https://www.energie-portal.sk/Dokument/export-vyvoz-elektriny-slovensko-2024-statistika-111000.aspx (accessed on).

120 Nies and Savytskyi, "Six options to boost power grid transfers from Continental Europe to Ukraine, for the next two winters," *Green Deal Ukraina*, August 2024. Available online: https://greendealukraina.org/products/analytical-reports/six-options-to-boost-power-grid-transfers-from-continental-europe-to-ukraine-for-the-next-two-winters (accessed on).
M. Tril, "Ukraine and Slovakia agree on East European energy hub," *Euromaidan Press*, October 7, 2024. Available online: https://euromaidanpress.com/2024/10/07/ukraine-and-slovakia-agree-on-east-european-energy-hub/ (accessed on).

Biomass

As an agricultural country, Ukraine has a unique opportunity to leverage biomass production, which is a field Slovakia is very experienced in.

Several biomass projects have been implemented in Slovakia, perhaps most significant among them being the advanced biofuels plant in Leopoldov, where Enviral and Clariant are building a facility for the production of cellulosic ethanol from agricultural residues with an annual capacity of 50,000 tons. Another important initiative is the Biomass Association's project, which focuses on creating a sustainable market for wood pellets, including the retrofitting of 44 public buildings from coal to pellet boilers, with a planned production capacity of 12,000 tons of pellets annually. The facility in Kysucké Lieskovce processes 20,000 tons of wood residues into 12,000 tons of pellets per year, demonstrating another successful project in this field. The Poľana Region Bioenergy Project transitioning to biomass heating systems and the co-firing project at Elektrárne Nováky, where biomass is replacing 30% of the coal, are other examples.[121]

Legislative measures supporting biomass include the Renewable Energy Support Act, which facilitates biomass energy production and establishes sustainability criteria for its utilization. Slovakia has outlined sustainability criteria to ensure that biomass is sourced from sustainable origins and does not compromise biodiversity. Slovak legislative provisions also offer financial support for biomass cogeneration systems, ensuring priority access to the distribution grid and guaranteed electricity buy-back agreements. The FTP initiative and the LignoSilva Center of Excellence aim to enhance strategic processes in the forestry bioeconomy and promote innovations. The LIFE 3.0 Project focuses on integrating renewable resources, including biomass, across various sectors.[122]

Promoting biomass development could significantly impact regions in eastern Slovakia adjacent to Ukraine, enhancing cross-border cooperation with western Ukrainian areas rich in woody biomass. These forested regions represent

121 S. Kovár and M. Lučivjanský, "Slovakia Supports Biomass," *Schönherr*, February 1, 2014. Available online: https://www.schoenherr.eu/content/slovakia-supports-biomass/ (accessed on).
"Slovak Villages Tap into Biomass Potential Creating Energy Security and Jobs," European Commission, 2013. Available online: https://ec.europa.eu/regional_policy/en/projects/Slovensko/slovak-villages-tap-into-biomass-potential-creating-energy-security-and-jobs (accessed online).
"Advanced biofuels plant to be built in Slovakia," *Biofuels International*, September 18, 2017. Available online: https://biofuels-news.com/news/advanced-biofuels-plant-to-be-built-in-slovakia/ (accessed on).
L. Zidek and D. Bohunicka, "Development of the new pellet market in Slovakia," *Global Biofuel Portal*, July 11, 2008. Available online: https://pellets-wood.com/development-of-the-new-pellet-market-in-slovakia-o42.html (accessed on).
"Renewable Energy Sector Profile—Slovak Republic," *Klean Industries*, February 5, 2008. Available online:https://kleanindustries.com/resources/market-analysis-research/renewable-energy-sector-profile-slovak-republic/ (accessed on).

122 S. Kovár and M. Lučivjanský, "Slovakia Supports Biomass," *Schönherr*, op. cit.
"FTP brings the forest-based bioeconomy in Slovakia closer," *Forest-based Sector Technology Platform*, n.d. Available online: https://www.forestplatform.org/2018/08/21/ftp-brings-the-forest-based-bioeconomy-in-slovakia-closer/ (accessed on).
"Projekt Zelená domácnostiam III (2022–2023)," *Slovenská Inovačná a Energetická Agentura*, n.d. Available online: https://www.siea.sk/zelena-domacnostiam/projekt-zelena-domacnostiam-iii-2022-2023/ (accessed on).
"Podmienky podpory," *Zelená domácnostiam*, n.d. Available online: https://zelenadomacnostiam.sk/podmienky-podpory/podporovane-zariadenia/#kotly-biomasa (accessed on).
"Zelená domácnostiam a Zelená solidarita," *Slovenská Inovačná a Energetická Agentura*, n.d. Available online: https://www.siea.sk/zelena-domacnostiam/ (accessed on).

substantial potential for biomass production.[123] This approach would not only improve the living standards of the population but also support rural development and diversify income sources for farmers.[124]

Legislative measures

Ukraine's energy system is not ready for full market-based pricing, since it must still prioritize its social policy. In this regard, Slovakia's model of partially controlled energy prices may be more relevant and adaptable to Ukraine's current situation than, for example, the Czech Republic's fully liberalized energy market.

123 "Implementation of the EU-Ukraine Memorandum of Understanding on Energy Cooperation during 2014," *European Commission*, *EU-Ukraine Energy Cooperation*, Ninth joint EU-Ukraine report, April 28, 2015. Available online: https://energy.ec.europa.eu/system/files/2015-05/EU-UKRAINE%2520ENERGY%2520COOPERATION_0.pdf (accessed online).
"The Slovak engineering company of technologies for the development of biomass reuse is looking for foreign distributors and partners," *Enterprise Europe Network*, n.d. Available online: https://een.ec.europa.eu/partnering-opportunities/slovak-engineering-company-technologies-development-biomass-reuse-looking (accessed on).

124 C. Panoutsou and T. Zheliezna, "Strategic guide for biomass heat policy in Ukraine," *S2Biom*, October 2016. Available online: https://s2biom.wenr.wur.nl/doc/D8.3d_S2Biom_strategic_guide_for_biomass_heat_policy_in_Ukraine.pdf (accessed on).

POTENTIAL CONTRIBUTION OF V4 PARTNERS

Czech Republic

The Czech Republic has much to offer when it comes to supporting Ukraine's energy reconstruction. Their experience with building nuclear power plants, particularly navigating the legislative and financial hurdles, could provide Ukraine with a roadmap for developing its own nuclear capabilities. The Czech Republic has also been exploring the use of SMRs, which could offer more flexible and efficient energy solutions for Ukraine's energy system. Furthermore, Czech Republic has also been developing agrovoltaics

Hungary

Ukraine would also stand to benefit from Hungary's expertise in geothermal energy, with projects like Szeged geothermal district heating showcasing how geothermal resources can be effectively harnessed, Hungary has also made significant progress in solar energy, with large-scale projects and supportive policies that could serve as a useful model for Ukraine. Additionally, Hungary's position as a bordering country makes it a key player in developing energy interconnections, whether electricity, gas, or even hydrogen networks.

Poland

Poland's experience with wind energy, particularly in the development of offshore and on-shore wind farms, could be invaluable for Ukraine. Particularly its experience with project development, regulatory processes, and logistic. Moreover, Poland's geographical proximity and strong trade ties with Ukraine make it an ideal partner for developing cross-border energy infrastructure, including gas and electricity networks, as well as exploring opportunities for hydrogen transport.

CONCLUSION

Risks, challenges and opportunities

The V4 countries face considerable risks in supporting Ukraine's energy reconstruction, stemming largely from ongoing geopolitical instability. The destruction and occupation of significant energy-producing areas by Russian forces pose a persistent threat to long-term investments and infrastructure projects. Currently, about 66% of Ukraine's wind and solar installations are located in regions like Zaporizhzhia, Kherson, and Mykolaiv—areas under Russian control or at risk of conflict. Additionally, critical infrastructure has been devastated, with over 50% of high-voltage substations damaged, 30% of solar capacity disrupted, and a 65% reduction in thermal generation capacity since the invasion began.

Ukraine's dependence on fossil fuels, which constituted 70% of its energy mix pre-war, also complicates alignment with EU climate targets. Shifting to renewable energy will require extensive modernization and decarbonization efforts. Rebuilding the energy grid will require massive investments, with the World Bank estimating Ukraine's total reconstruction cost at $486 billion. The EU and international partners will need to secure large-scale financial commitments, while investor confidence must be strengthened through stable regulatory frameworks and risk mitigation strategies.

The 2024 mobilization law exempts energy workers from military service, yet retaining enough qualified professionals in the clean energy sector will remain a challenge for Ukraine. Additionally, regulatory alignment with the EU is essential but complex, as Ukraine must bring its market and environmental standards up to EU compliance—a task requiring substantial financial and technical support.

At the same time, these challenges present opportunities for partnership presents between Ukraine and the V4 countries, particularly in RES development and strategic energy storage and distribution. Ukraine's renewable energy resources, especially in wind and solar, are among the largest in Europe, with an estimated 30 GW of wind capacity and 14 GW of solar potential, particularly concentrated in southern regions with optimal solar irradiance reaching up to 1,400 kWh/m² annually. These vast RES resources can provide the foundation for a decentralized and resilient energy network that can bolster Ukraine's energy security and provide clean energy exports to neighbouring countries.

Ukraine's strategic location and existing infrastructure also position it as a critical energy hub for Central and Eastern Europe. With natural gas reserves totalling 1.09 trillion cubic meters—second largest in Europe—and a storage capacity of 31 bcm, Ukraine can play a central role in stabilizing gas supplies for the V4 region. Especially as Europe seeks alternatives to Russian gas, Ukraine can play a key role bolstering the region's energy independence.

In addition, Ukraine is well-positioned to become a major player in green hydrogen, leveraging its RES potential and nuclear power. The development of green hydrogen production and storage would not only enhance Ukraine's own energy resilience but also support the EU's hydrogen market and long-term decarbonization goals. With investments in hydrogen infrastructure, Ukraine could become a leading supplier for Central and Eastern Europe, facilitating the region's transition to low-carbon economies and contributing to broader EU climate objectives.

V4-Ukraine cooperation in energy is essential for Ukraine's recovery and regional energy security. The V4 countries bring vital experience transitioning away from coal towards towards cleaner and more modern energy systems that meet EU standards, and their support can help Ukraine do the same. Key priorities include rebuilding Ukraine's renewable capacity, modernizing cross-border interconnections, and ensuring regulatory alignment with EU standards. With coordinated efforts, V4-Ukraine energy cooperation can create a resilient energy system that meets both regional security needs and EU climate goals.