
**CHEMICAL FOUNDATIONS OF UKRAINE'S
SUSTAINABLE DEVELOPMENT IN THE CONTEXT
OF GREEN ENERGY AND INDUSTRIAL
DECARBONIZATION**

Kochubei Olena

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INTRODUCTION

Ukraine's sustainable development is directly linked to the modernization of its energy sector and industry, since these two sectors determine the scale of natural-resource use, the energy intensity of the economy, and the volume of greenhouse gas emissions. Chemical science occupies a central place in this process: it explains the mechanisms of energy conversion and underpins the creation of new materials, catalysts, electrolytes, sorbents, and membranes, as well as the technologies for purification and resource reuse. Chemistry is therefore not an auxiliary discipline but a fundamental basis for the transition to a low-carbon economic model.

For Ukraine, decarbonization carries a dual significance. On the one hand, it is necessary to fulfil climate commitments, improve the competitiveness of domestic products, and move closer to European environmental standards. On the other hand, it is a component of energy security and post-war recovery, since reducing dependence on fossil fuels lowers the economy's vulnerability to external supply and price fluctuations. The strategic benchmarks for this transition are set out in Ukraine's Low-Carbon Development Strategy until 2050 and in the National Energy and Climate Plan until 2030.

The purpose of this section is to substantiate the role of chemical processes and technologies in the development of green energy and the decarbonization of Ukrainian industry. The material is divided into two subsections. The first examines the chemical foundations of solar, wind, hydrogen, bio-based, and electrochemical energy. The second analyses technological pathways for reducing emissions in metallurgy, cement, chemical, and other energy-intensive industries, together with the principles of green chemistry, the circular economy, and carbon capture.

1. Chemical foundations of Ukraine's green energy

The scale and pace of the chemical modernization of the energy sector are defined by official target indicators. Ukraine's National Renewable Energy Action Plan until 2030 envisages increasing the share of renewables in final energy consumption from about 10% (2022) to at least 27%, commissioning roughly 10 GW of new renewable capacity, and cutting greenhouse gas emissions by 65% relative to 1990 levels; the investment required is estimated at USD 41.5–50 billion¹. Indicative targets for individual technologies are summarized in Table 1.

Table 1

Target indicators for the development of Ukraine's renewable and hydrogen energy sectors until 2030

Direction	2022 (baseline)	2030 target	Key chemical challenge
Solar power (photovoltaics)	7,327 MW	12,200 MW, incl. 5,000 MW of distributed prosumer generation	Silicon purification and doping, stability of photoactive layers
Wind power	512 MW (excl. temporarily occupied territories)	6,214 MW, incl. 100 MW offshore	Durability of composite blades, recycling of reinforced polymers
Biomass and biogas	—	876 MW of installed capacity	Purifying biogas of H ₂ S, moisture, and siloxanes to grid quality
Flexible generation and storage	—	656 MW of storage systems	Electrolyte safety, electrode degradation
Hydrogen (electrolyzers)	<0.1 GW	up to 10 GW of capacity; 1.3 Mt H ₂ by 2035, 3.0 Mt by 2050	Efficiency of electrolysis membranes and catalysts, water purity
Share of renewables in final consumption	≈10%	≥27%	—
GHG emission reduction (vs. 1990)	—	–65%	—

Source: compiled by the author based on the National Renewable Energy Action Plan [1], the National Energy and Climate Plan [2], the draft Hydrogen Strategy of Ukraine [13; 14], and the CSIS overview [12].

¹ Про затвердження Національного плану дій з відновлюваної енергетики на період до 2030 року та плану заходів з його виконання : розпорядження Кабінету Міністрів України від 13 серпня 2024 року № 761-р. *Законодавство України* : база даних / Верховна Рада України. URL: <https://zakon.rada.gov.ua/laws/show/761-2024-%D1%80> (дата звернення: 20.07.2026). Про схвалення Національного плану з енергетики та клімату на період до 2030 року : розпорядження Кабінету Міністрів України від 25 червня 2024 року № 587-р. *Законодавство України* : база даних / Верховна Рада України. URL: <https://zakon.rada.gov.ua/laws/show/587-2024-%D1%80> (дата звернення: 20.07.2026). Striving for Access, Security, and Sustainability: Ukraine's Transition to a Modern and Decentralized Energy System. Center for Strategic and International Studies. 2026. URL: <https://www.csis.org/analysis/striving-access-security-and-sustainability> (дата звернення: 20.07.2026).

The chemical basis of solar power lies in the fact that semiconductor materials, primarily crystalline silicon, convert photon energy into electric current. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include silicon purification and doping, the stability of photoactive layers, and module recycling. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling².

The chemical basis of wind power lies in the fact that electricity is generated without fuel combustion, although turbine structures require polymer composites, lubricants, and rare-earth components. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include blade durability, corrosion resistance, and the recycling of reinforced polymers. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling³.

The chemical basis of energy storage lies in the fact that lithium-ion, sodium-ion, and flow batteries operate through reversible redox reactions. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include electrolyte safety, the resource availability of metals, electrode degradation, and battery reuse. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling⁴.

The chemical basis of green hydrogen production lies in the fact that water electrolysis converts electrical energy into the chemical energy of molecular hydrogen. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include the efficiency of electrodes,

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³ REmap 2030: Renewable Energy Prospects for Ukraine. Abu Dhabi : International Renewable Energy Agency, 2015. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/Apr/IRENA_REmap_Ukraine_paper_2015.pdf (date of access: 20.07.2026). World Energy Transitions Outlook 2024: 1.5 °C Pathway. Abu Dhabi : International Renewable Energy Agency, 2024. URL: <https://www.irena.org/publications/2024/Nov/World-Energy-Transitions-Outlook-2024> (date of access: 20.07.2026).

⁴ Kudria S., Ivanchenko I., Tuchynskyi B., Petrenko K., Karmazin O., Riepin O. Resource potential for wind-hydrogen power in Ukraine. *International Journal of Hydrogen Energy*. 2021. Vol. 46. Issue 1. P. 157–168. DOI: 10.1016/j.ijhydene.2020.09.211

membranes and catalysts, water purity, and the source of the electricity used. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling⁵.

The chemical basis of hydrogen storage lies in the fact that hydrogen can be stored in compressed, liquefied, or chemically bound form. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include leakage, hydrogen embrittlement of metals, the energy cost of compression, and infrastructure safety. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling⁶.

The chemical basis of green ammonia lies in the fact that the ammonia synthesis reaction combines atmospheric nitrogen with hydrogen to yield a feedstock for fertilizers and energy applications. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include replacing grey hydrogen with green hydrogen, improving catalytic efficiency, and controlling toxicity. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling.

The chemical basis of biogas and biomethane lies in the fact that the anaerobic digestion of organic waste produces a mixture of methane and carbon dioxide. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include the removal of hydrogen sulphide, water vapour, and siloxanes, and upgrading the gas to grid quality. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling.

The chemical basis of liquid biofuels lies in the fact that the transesterification of oils and the fermentation of sugars yield biodiesel and bioethanol. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include using waste feedstocks instead of food crops, product purification, and the processing of by-product streams. The environmental assessment should

⁵ Strielkowski W. Efficient low-carbon development in green hydrogen and ammonia economy: a case of Ukraine. arXiv. 2025. arXiv:2503.22326. URL: <https://arxiv.org/abs/2503.22326> (date of access: 20.07.2026).

⁶ World Energy Transitions Outlook 2024: 1.5 °C Pathway. Abu Dhabi : International Renewable Energy Agency, 2024. URL: <https://www.irena.org/publications/2024/Nov/World-Energy-Transitions-Outlook-2024> (date of access: 20.07.2026).

cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling⁷.

The chemical basis of heat pumps lies in the fact that phase transitions of refrigerants transfer heat from a low-temperature source to the consumer. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include the transition to refrigerants with low global warming potential and improved system tightness. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling⁸.

The chemical basis of fuel cells lies in the fact that the electrochemical oxidation of hydrogen directly yields electricity and water. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include catalyst cost, fuel purity, membrane lifetime, and thermal management. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling.

The chemical basis of synthetic fuels lies in the fact that green hydrogen can react with captured CO₂ to form methanol or hydrocarbons. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include low overall energy efficiency and the need to limit use to hard-to-electrify sectors. The environmental assessment should cover the full life cycle: raw-material extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling.

The chemical basis of thermal energy storage lies in the fact that molten salts and phase-change materials can store substantial amounts of heat. For Ukraine, this area is important not only as a way to reduce the use of fossil fuels, but also as an opportunity to build new technological chains. Key issues include corrosion, cycling stability, thermal conductivity, and material safety. The environmental assessment should cover the full life cycle: raw-material

⁷ REmap 2030: Renewable Energy Prospects for Ukraine. Abu Dhabi : International Renewable Energy Agency, 2015. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/Apr/IRENA_REmap_Ukraine_paper_2015.pdf (date of access: 20.07.2026). Ukraine Energy Profile. International Energy Agency. Paris, 2020. URL: <https://www.iea.org/reports/ukraine-energy-profile> (date of access: 20.07.2026).

⁸ Decarbonisation Roadmap for the Contracting Parties of the Energy Community : General Policy Guidelines 01/2021/MC-EnC. *Energy Community*. 2021. URL: https://www.energy-community.org/dam/jcr:45eab70a-051a-41be-a530-864adb2a669b/19thMC_Decarbonisation_Roadmap_301121.pdf (date of access: 20.07.2026).

extraction, equipment manufacturing, operation, maintenance, and end-of-life recycling⁹.

The development of solar power requires the alignment of chemical, energy, and economic parameters. Even a technology with minimal emissions during operation may have a significant hidden impact if its materials are obtained through energy-intensive methods or become hazardous waste after use. This is why particular attention should be paid to aspects such as silicon purification and doping, the stability of photoactive layers, and module recycling. For Ukrainian projects, it is advisable to combine equipment imports with the localization of servicing, laboratory control, and the gradual domestic production of components.

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The prospects of solar power are determined by the ability to integrate the technology into the energy system and industrial clusters. Since semiconductor materials, primarily crystalline silicon, convert photon energy into electric current, process efficiency depends on feedstock quality, temperature, pressure, catalysts, and operating conditions. Ukrainian research institutions could focus on reducing material intensity, replacing scarce elements, extending service life, and developing recycling technologies. This approach is consistent with the principles of green chemistry and Ukraine's National Renewable Energy Action Plan.

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The prospects of fuel cells are determined by the ability to integrate the technology into the energy system and industrial clusters. Since the electrochemical oxidation of hydrogen directly yields electricity and water, process efficiency depends on feedstock quality, temperature, pressure, catalysts, and operating conditions. Ukrainian research institutions could focus on reducing material intensity, replacing scarce elements, extending service life, and developing recycling technologies. This approach is consistent with the principles of green chemistry and Ukraine's National Renewable Energy Action Plan.

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The prospects of thermal energy storage are determined by the ability to integrate the technology into the energy system and industrial clusters. Since molten salts and phase-change materials can store substantial amounts of heat, process efficiency depends on feedstock quality, temperature, pressure, catalysts, and operating conditions. Ukrainian research institutions could focus on reducing material intensity, replacing scarce elements, extending service life, and developing recycling technologies. This approach is consistent with the principles of green chemistry and Ukraine's National Renewable Energy Action Plan.

Ukraine's green energy sector should develop as an interconnected system. Solar and wind generation produce low-carbon electricity; batteries provide short-term balancing; hydrogen and synthetic energy carriers can serve as seasonal storage and industrial feedstock; biomethane makes use of local organic resources. Studies of Ukraine's wind-hydrogen resource potential confirm the feasibility of further developing this direction¹².

At the same time, scaling up new technologies must not outpace the development of safety and waste-management systems. Batteries, solar panels,

¹² Kudria S., Ivanchenko I., Tuchynskiy B., Petrenko K., Karmazin O., Riepin O. Resource potential for wind-hydrogen power in Ukraine. *International Journal of Hydrogen Energy*. 2021. Vol. 46. Issue 1. P. 157–168. DOI: 10.1016/j.ijhydene.2020.09.211. REmap 2030: Renewable Energy Prospects for Ukraine. Abu Dhabi : International Renewable Energy Agency, 2015. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/Apr/IRENA_REmap_Ukraine_paper_2015.pdf (date of access: 20.07.2026).

membranes, catalysts, and composites contain substances that require controlled collection, transport, and processing. Extended producer responsibility, eco-design standards, and laboratory monitoring should become an integral part of energy policy.

The chemical foundations of green energy therefore encompass not a single technology but a complex of processes for converting, storing, and transporting energy. Their deployment must rest on life-cycle assessment, resource security, regional characteristics, and Ukraine's scientific potential.

2. Chemical technologies for the decarbonization of Ukraine's industry

Industry-level data confirm the scale of the decarbonization challenge. In 2020, Ukraine's ferrous metallurgy sector generated about 48 Mt of CO₂ (≈15% of national emissions), and before the war the country ranked 14th in the world with a crude steel output of 21.4 Mt (2021)¹³. Specific emissions at individual enterprises range from 1.29 to 1.71 t CO₂ per tonne of product, and under the IEA criterion, "green steel" is defined as output with emissions below 0.4 t CO₂-eq./t for ore-based production and 0.05 t CO₂-eq./t for scrap-based production¹⁴. Indicative figures for other energy-intensive industries are given in Table 2.

The decarbonization of ferrous metallurgy involves replacing coke with hydrogen, direct iron reduction, and electric-arc melting. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are the cost of green hydrogen, ore quality, scrap availability, and grid modernization. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

The decarbonization of the cement industry involves reducing the clinker factor and using calcined clays, slag, and CO₂ capture. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are process emissions from limestone decalcination and the stability of cement

¹³ Devlin A., Mykhnenko V., Zagoruichyk A., Salmon N., Soldak M. Techno-economic optimisation of steel supply chains in the clean energy transition: A case study of post-war Ukraine. *Journal of Cleaner Production*. 2024. Vol. 466. Art. 142675. DOI: 10.1016/j.jclepro.2024.142675. Decarbonization of Ukraine's steel industry: the European way. GMK Center. 2025. URL: <https://gmk.center/en/posts/decarbonization-of-ukraine-s-steel-industry-the-european-way/> (date of access: 20.07.2026).

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properties. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport¹⁵.

Table 2

**Specific CO₂ emissions and decarbonization benchmarks
for Ukraine’s energy-intensive industries**

Industry	Current CO ₂ emission intensity	Key process factor	Target / reduction potential
Ferrous metallurgy	48 Mt CO ₂ (2020); 1.29–1.71 t CO ₂ /t of product at individual enterprises	Share of the blast-furnace/converter route, scrap volume	–25...–26% by 2030 (vs. 2023); “green steel” threshold < 0.4 t CO ₂ -eq./t; investment need ≈ USD 12 billion
Cement industry	832–1,075 kg CO ₂ -eq./t of clinker; clinker factor ≈75%	Limestone decalcination (≈2/3 of total emissions)	Reducing the clinker factor to 65%; near-zero-emission class ≤125 kg CO ₂ -eq./t
Ammonia production	–	Haber – Bosch reaction, hydrogen source	Replacing grey hydrogen with green (electrolytic) hydrogen
Nitric acid production	–	By-product N ₂ O in tail gases	Catalytic destruction of N ₂ O in tail gases

Source: compiled by the author based on [5; 11; 15].

The decarbonization of ammonia production involves using green hydrogen in the Haber – Bosch reaction. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are the energy intensity of compression, catalyst efficiency, and the safe handling of ammonia. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

The decarbonization of nitric acid production involves the catalytic destruction of by-product N₂O in tail gases. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are catalyst reliability, temperature control, and continuous monitoring. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport¹⁶.

¹⁵ Decarbonisation Roadmap for the Contracting Parties of the Energy Community : General Policy Guidelines 01/2021/MC-EnC. *Energy Community*. 2021. URL: https://www.energy-community.org/dam/jcr:45eab70a-051a-41be-a530-864adb2a669b/19thMC_Decarbonisation_Roadmap_301121.pdf (date of access: 20.07.2026).

¹⁶ World Energy Transitions Outlook 2024: 1.5 °C Pathway. Abu Dhabi : International Renewable Energy Agency, 2024. URL: <https://www.irena.org/publications/2024/Nov/World-Energy-Transitions-Outlook-2024> (date of access: 20.07.2026).

The decarbonization of oil refining and organic synthesis involves electrifying heating, replacing fossil feedstocks with bio-based ones, and using low-carbon hydrogen. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are the complexity of process schemes, the quality of alternative feedstocks, and capital intensity. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

The decarbonization of glass and ceramics production involves electric or hydrogen heating of high-temperature furnaces. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are temperature-field stability, batch composition, and refractory-material lifetime. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

The decarbonization of the mining and processing sector involves electrifying transport, optimizing crushing, and reusing water. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are the high energy intensity of crushing, tailings generation, and the need to recover valuable components. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

The decarbonization of industrial wastewater treatment involves membrane separation, sorption, electrodialysis, and oxidative processes. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are concentrate management, sorbent regeneration, energy costs, and water recirculation. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

The decarbonization of industrial waste management involves sorting, chemical stabilization, metal recovery, and mineralization. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are toxic contaminants, feedstock heterogeneity, and confirming environmental safety. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

The decarbonization of carbon capture involves amine absorption, adsorption, and membrane or cryogenic separation. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are the

heat required for solvent regeneration, sorbent degradation, and long-term CO₂ storage. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

The decarbonization of industrial electrification involves induction, resistive, and plasma heating, and high-temperature heat pumps. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are power-supply reliability, modernization costs, and the need for low-carbon generation. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

The decarbonization of circular chemistry involves the regeneration of solvents, acids, alkalis, and catalysts, together with industrial symbiosis. This direction is chemical in nature, since it changes the reagents, reaction mechanisms, gas-stream composition, and material balances involved. The main constraints are secondary-feedstock quality standards, traceability, and inter-enterprise economic coordination. Investment decisions must weigh not only direct emissions but also the carbon footprint of electricity, feedstock, and transport.

In the field of ferrous metallurgy, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, the cost of green hydrogen, ore quality, scrap availability, and grid modernization remain important risk factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved.

In the field of the cement industry, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, process emissions from limestone decalcination and the stability of cement properties remain important risk factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved.

In the field of ammonia production, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, the energy intensity of compression, catalyst efficiency, and the safe handling of ammonia remain important risk factors. Modernization

must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved.

In the field of nitric acid production, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, catalyst reliability, temperature control, and continuous monitoring remain important risk factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved¹⁷.

In the field of oil refining and organic synthesis, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, the complexity of process schemes, the quality of alternative feedstocks, and capital intensity remain important risk factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved¹⁸.

In the field of glass and ceramics production, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, temperature-field stability, batch composition, and refractory-material lifetime remain important risk factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved¹⁹.

In the field of the mining and processing sector, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, the high energy intensity of crushing, tailings generation, and the need to recover valuable components remain important risk

¹⁷ World Energy Transitions Outlook 2024: 1.5 °C Pathway. Abu Dhabi : International Renewable Energy Agency, 2024. URL: <https://www.irena.org/publications/2024/Nov/World-Energy-Transitions-Outlook-2024> (date of access: 20.07.2026).

¹⁸ Kudria S., Ivanchenko I., Tuchynskiy B., Petrenko K., Karmazin O., Riepin O. Resource potential for wind-hydrogen power in Ukraine. *International Journal of Hydrogen Energy*. 2021. Vol. 46. Issue 1. P. 157–168. DOI: 10.1016/j.ijhydene.2020.09.211

¹⁹ Strielkowski W. Efficient low-carbon development in green hydrogen and ammonia economy: a case of Ukraine. arXiv. 2025. arXiv:2503.22326. URL: <https://arxiv.org/abs/2503.22326> (date of access: 20.07.2026).

factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved.

In the field of industrial wastewater treatment, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, concentrate management, sorbent regeneration, energy costs, and water recirculation remain important risk factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved.

In the field of industrial waste management, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, toxic contaminants, feedstock heterogeneity, and confirming environmental safety remain important risk factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved.

In the field of carbon capture, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, the heat required for solvent regeneration, sorbent degradation, and long-term CO₂ storage remain important risk factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved.

In the field of industrial electrification, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, power-supply reliability, modernization costs, and the need for low-carbon generation remain important risk factors. Modernization must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved.

In the field of circular chemistry, it is advisable to combine radical technological change with phased energy-efficiency measures. Even before a full overhaul of production, heat losses can be reduced, gas cleaning improved, catalysis optimized, and part of the secondary streams returned to the process. At the same time, secondary-feedstock quality standards, traceability, and inter-enterprise economic coordination remain important risk factors. Modernization

must therefore be accompanied by laboratory control, digital accounting, and verification of the actual emission reductions achieved.

The prospects of ferrous metallurgy in a low-carbon economy will be determined by enterprises' ability to deploy replacing coke with hydrogen, direct iron reduction, and electric-arc melting. Ukraine has the opportunity to embed such solutions in its post-war recovery programmes rather than reproducing outdated production schemes. Priority should go to technologies that simultaneously reduce emissions, decrease local pollution, improve resource efficiency, and generate higher-value-added products.

The prospects of the cement industry in a low-carbon economy will be determined by enterprises' ability to deploy reducing the clinker factor and using calcined clays, slag, and CO₂ capture. Ukraine has the opportunity to embed such solutions in its post-war recovery programmes rather than reproducing outdated production schemes. Priority should go to technologies that simultaneously reduce emissions, decrease local pollution, improve resource efficiency, and generate higher-value-added products²⁰.

The prospects of ammonia production in a low-carbon economy will be determined by enterprises' ability to deploy using green hydrogen in the Haber–Bosch reaction. Ukraine has the opportunity to embed such solutions in its post-war recovery programmes rather than reproducing outdated production schemes. Priority should go to technologies that simultaneously reduce emissions, decrease local pollution, improve resource efficiency, and generate higher-value-added products.

The prospects of nitric acid production in a low-carbon economy will be determined by enterprises' ability to deploy the catalytic destruction of by-product N₂O in tail gases. Ukraine has the opportunity to embed such solutions in its post-war recovery programmes rather than reproducing outdated production schemes. Priority should go to technologies that simultaneously reduce emissions, decrease local pollution, improve resource efficiency, and generate higher-value-added products.

The prospects of oil refining and organic synthesis in a low-carbon economy will be determined by enterprises' ability to deploy electrifying heating, replacing fossil feedstocks with bio-based ones, and using low-carbon hydrogen. Ukraine has the opportunity to embed such solutions in its post-war recovery programmes rather than reproducing outdated production schemes. Priority should go to technologies that simultaneously reduce emissions, decrease local pollution, improve resource efficiency, and generate higher-value-added products.

²⁰ Decarbonisation Roadmap for the Contracting Parties of the Energy Community : General Policy Guidelines 01/2021/MC-EnC. *Energy Community*. 2021. URL: https://www.energy-community.org/dam/jcr:45eab70a-051a-41be-a530-864adb2a669b/19thMC_Decarbonisation_Roadmap_301121.pdf (date of access: 20.07.2026).

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The prospects of the mining and processing sector in a low-carbon economy will be determined by enterprises' ability to deploy electrifying transport, optimizing crushing, and reusing water. Ukraine has the opportunity to embed such solutions in its post-war recovery programmes rather than reproducing outdated production schemes. Priority should go to technologies that simultaneously reduce emissions, decrease local pollution, improve resource efficiency, and generate higher-value-added products.

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The prospects of industrial waste management in a low-carbon economy will be determined by enterprises' ability to deploy sorting, chemical stabilization, metal recovery, and mineralization. Ukraine has the opportunity to embed such solutions in its post-war recovery programmes rather than reproducing outdated production schemes. Priority should go to technologies that simultaneously reduce emissions, decrease local pollution, improve resource efficiency, and generate higher-value-added products²¹.

The prospects of carbon capture in a low-carbon economy will be determined by enterprises' ability to deploy amine absorption, adsorption, and membrane or cryogenic separation. Ukraine has the opportunity to embed such solutions in its post-war recovery programmes rather than reproducing outdated production schemes. Priority should go to technologies that simultaneously reduce emissions, decrease local pollution, improve resource efficiency, and generate higher-value-added products²².

²¹ World Energy Transitions Outlook 2024: 1.5 °C Pathway. Abu Dhabi : International Renewable Energy Agency, 2024. URL: <https://www.irena.org/publications/2024/Nov/World-Energy-Transitions-Outlook-2024> (date of access: 20.07.2026).

²² Decarbonisation Roadmap for the Contracting Parties of the Energy Community : General Policy Guidelines 01/2021/MC-EnC. *Energy Community*. 2021. URL: https://www.energy-community.org/dam/jcr:45eab70a-051a-41be-a530-864adb2a669b/19thMC_Decarbonisation_Roadmap_301121.pdf (date of access: 20.07.2026).

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The prospects of circular chemistry in a low-carbon economy will be determined by enterprises' ability to deploy the regeneration of solvents, acids, alkalis, and catalysts, together with industrial symbiosis. Ukraine has the opportunity to embed such solutions in its post-war recovery programmes rather than reproducing outdated production schemes. Priority should go to technologies that simultaneously reduce emissions, decrease local pollution, improve resource efficiency, and generate higher-value-added products.

Green metallurgy is of particular importance for Ukraine. Shifting from the blast-furnace/converter route to direct hydrogen-based iron reduction and electric-arc melting can substantially reduce the carbon intensity of steel. Studies for post-war Ukraine show that combining renewable electricity, green hydrogen, and modern logistics could establish a new competitive model for the metallurgical sector²³.

Carbon capture should primarily be considered for process emissions that are difficult to avoid through technological substitution. Amine absorption is a mature method, but it requires substantial heat for solvent regeneration. Solid sorbents, membranes, and mineralization can complement this approach. What matters most is demonstrating genuine, long-term emission reductions rather than merely shifting CO₂ between streams.

The principles of green chemistry require preventing waste formation at the process-design stage, using safer substances, improving atom efficiency, and favouring renewable feedstocks. For Ukrainian industry, this means shifting from end-of-pipe pollution control to redesigning production itself.

Industrial decarbonization is therefore a systemic change in how materials are produced. It requires low-carbon energy, new reagents and catalysts, closed water and feedstock cycles, accurate emissions accounting, and the training of specialists. Chemistry provides the scientific basis for each of these directions.

²³ Devlin A., Mykhnenko V., Zagoruichyk A., Salmon N., Soldak M. Techno-economic optimisation of steel supply chains in the clean energy transition: A case study of post-war Ukraine. *Journal of Cleaner Production*. 2024. Vol. 466. Art. 142675. DOI: 10.1016/j.jclepro.2024.142675

CONCLUSIONS

Chemical technologies underpin Ukraine's transition to green energy and low-carbon industry. They enable the creation of photovoltaic materials, batteries, electrolyzers, fuel cells, biofuels, and purification systems. Their sustainability depends on the full life cycle, the safety of materials, and the possibility of reuse.

The most promising directions for Ukraine are combining renewable electricity with hydrogen technologies, developing biomethane, expanding energy storage, and electrifying thermal processes. At the same time, water resources, critical materials, infrastructure security, and future waste streams must be taken into account.

In industry, the greatest effect can be achieved through green metallurgy, a reduced clinker factor in cement, green ammonia, the catalytic destruction of N_2O , heat integration, the circular use of feedstocks, and the capture of unavoidable process emissions.

Post-war recovery offers an opportunity to embed modern low-carbon solutions from the outset. This requires a coordinated national policy, investment, scientific research, laboratory infrastructure, and the training of specialists in chemistry, materials science, energy, and industrial ecology.

SUMMARY

This section examines the chemical foundations of Ukraine's sustainable development in the context of green energy and industrial decarbonization. It shows that chemical processes and materials – semiconductors, electrolytes, catalysts, membranes, and sorbents – form the scientific basis for the transition to a low-carbon economic model. The chemical foundations of solar, wind, hydrogen, battery, biogas, and other forms of green energy are analysed against the targets of the National Energy and Climate Plan (an increase in the renewable share from $\approx 10\%$ to $\geq 27\%$ and a 65% cut in greenhouse gas emissions by 2030). The section reviews technological pathways for decarbonizing energy-intensive industries – ferrous metallurgy, cement and ammonia production, nitric acid, glass and ceramics – presenting specific CO_2 emission figures and reduction benchmarks. The principles of green chemistry and the circular economy are substantiated as a basis for industrial modernization. It is shown that combining renewable electricity with hydrogen technologies, green metallurgy, and the capture of unavoidable process emissions could deliver the greatest benefit for Ukraine. The role of post-war recovery as an opportunity to embed modern low-carbon solutions from the outset is emphasized.

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Information about the author:

Kochubei Olena,

Doctor of Philosophy,

Lecturer at the Department of Biology and Chemistry

Uman National University

1, Instytutaska Street, Uman, Ukraine