CLEAN ENERGY ROADMAP: FROM RECONSTRUCTION TO DECARBONIZATION IN UKRAINE

Report for COP28

Study commissioned and supported by the Ministry of Energy of Ukraine

Ministry of Energy of Ukraine

NET ZERO WORLD INITIATIVE | Accelerating Global Energy System Decarbonization

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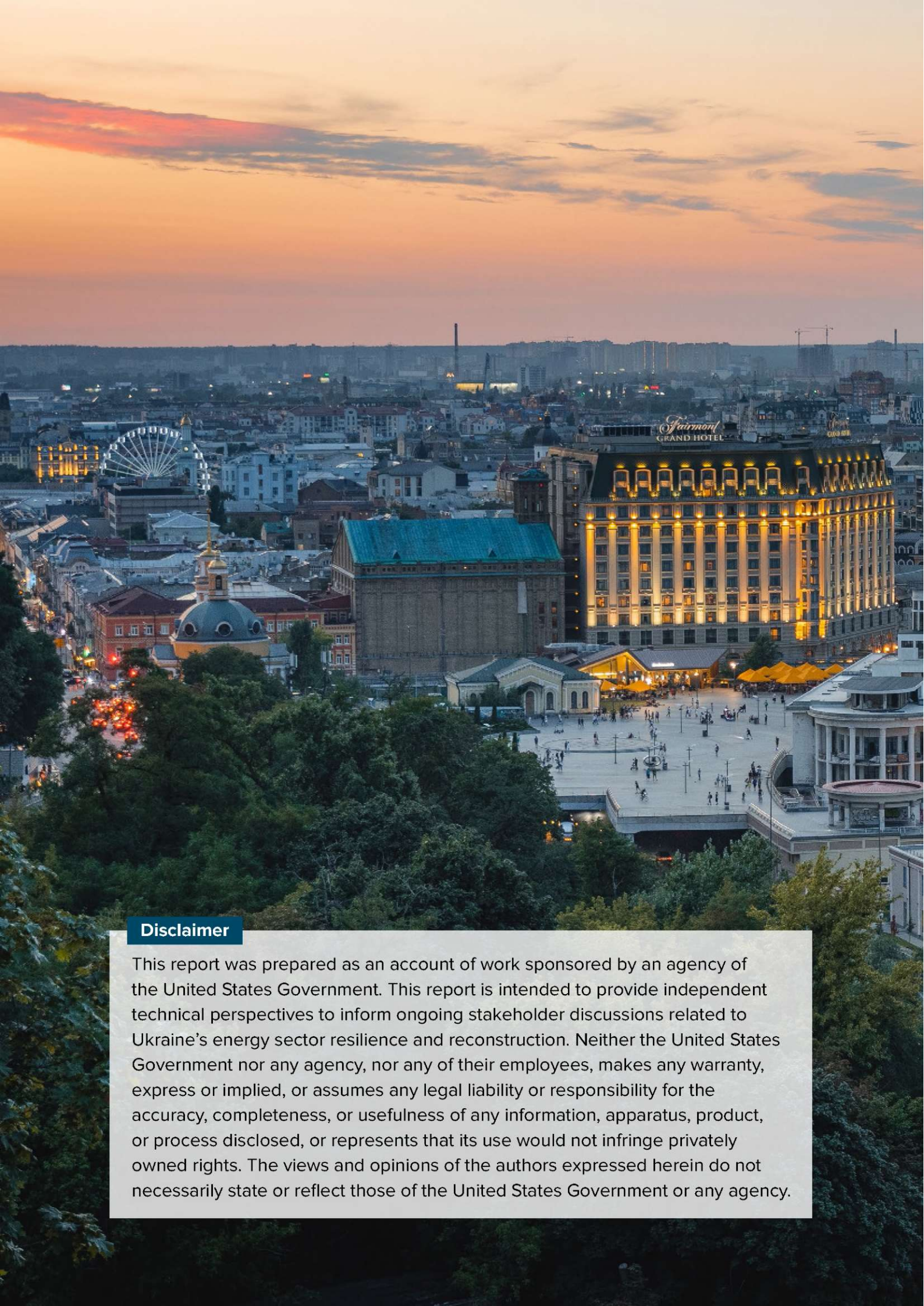

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ACRONYMS AND ABBREVIATIONS

ANL	Argonne National Laboratory
BECCS	bio-energy carbon capture and storage
CCS	carbon capture and storage
CHP	combined heat and power
COP	Conference of the Parties under the United Nations Framework Convention on Climate Change
DAC	direct air capture
DOE	U.S. Department of Energy
EBRD	European Bank for Reconstruction and Development
EU	European Union
G7	Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States
GHG	greenhouse gas
IEF	Institute for Economics and Forecasting of the National Academy of Science of Ukraine
IFI	international financial institution
LBNL	Lawrence Berkeley National Laboratory
NDC	Nationally Determined Contribution
NECP	National Energy and Climate Plan
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
SMR	small modular reactor
TIMES	The Integrated MARKAL-EFOM System model
TPES	total primary energy supply
TPP	thermal power plant
USAID	U.S. Agency for International Development

FOREWORD FROM THE MINISTRY OF ENERGY

I would like to express sincere appreciation to Net Zero World Initiative for its unwavering support to inform the reconstruction and future development of Ukraine. Through collaborative efforts, we have conducted extensive modeling and stakeholder research, the culmination of which is presented in this report. This partnership has laid the foundation for strategic and informed decision-making.

The ongoing russian aggression has not only threatened our resilience but has presented unparalleled challenges to our energy security. In the face of this adversity, our specialists have displayed exceptional dedication, expediting emergency repairs, fortifying energy infrastructure, and persistently demining energy facilities. As we navigate these violent times, comprehensive security remains our first priority, addressing physical, engineering, and cyber aspects.

At the same time, this report reflects our strong commitment to international obligations. Beyond reinforcing energy security, our strategic goals align with European Union standards and our commitment to a global sustainable, low-carbon future. As we aspire to EU membership, our vision encompasses the seamless integration of our energy sector with EU markets, harmonizing with climate objectives.

Looking forward to our strategic goals, we are resolute in developing low-carbon and carbon-neutral capacities. This involves replacing outdated thermal coal power plants with modern biofuel or waste-to-energy facilities, solar and wind power, integration of energy storage, and deployment of other innovative flexible generation technologies. Our commitment extends to the development of nuclear generation, ensuring diversity in our energy mix. Similar intentions guide our approach to the broader energy sector, including industry, buildings, and transport. We aim to foster new technologies such as hydrogen and biomethane production and usage.

Decarbonization, as we envision it, necessitates significant investments. In earnest collaboration with our partners, including international financial institutions and other donors, we are engaged in a dialogue to secure the funding and investments essential for these transformative developments.

The recovery of Ukraine and the modernization of our energy system are also opportunities for business cooperation. Our country, with its natural resources, including critical raw materials, and significant human resources, is exploring opportunities to develop its own production and join global supply chains of climate-neutral technologies.

In conclusion, I extend my deepest appreciation to all contributors, researchers, and partners who have dedicated their expertise and resources to this cause. COP28 serves as a pivotal platform for us to collectively shape ideas about a sustainable, resilient, and decarbonized future.

Thank you for your commitment, dedication, and invaluable contributions.

Sincerely,
German Galushchenko
Minister of Energy of Ukraine

A WORD FROM THE TECHNICAL TEAM

This analysis would not have been possible without the highly responsive and essential support and guidance provided by Deputy Energy Minister **Yaroslav Demchenkov**. We also want to express our appreciation for the work of Deputy Energy Minister **Svitlana Grynchuk** for supporting all COP activities.

Yaroslav Lytvynenko provided invaluable everyday support for the study. On behalf of the technical team, we want to express our sincere appreciation for his hard work.

We express our gratitude to the members of the stakeholder consultation group who participated in our discussions between May and September 2023. These include the Ministry of Energy, Ministry for Communities, Territories and Infrastructure Development, Ministry for Environment and Natural Resources, Reform Support Teams of these ministries, National Energy and Utilities Regulatory Commission, Ukrenergo, DTEK, Ukrainian Bioenergy Association, DiXi group, KPMG, EcoAction, EcoClub, U.S. Department of Energy (DOE), DOE national laboratories, United States Agency for International Development (USAID), USAID's Energy Security Project, Energy Community Secretariat, European Bank for Reconstruction and Development, World Bank, International Energy Agency, International Atomic Energy Agency, Danish Energy Agency, Berlin Economics, and many others. We benefited from your contributions to this study.

Dr. Nazar Kholod, Net Zero World Initiative country coordinator for Ukraine

Dr. Oleksandr Diachuk, team leader of Ukraine's modeling team

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1 Pacific Northwest National Laboratory (PNNL)
2 Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine
3 Argonne National Laboratory (ANL)
4 DiXi Group
5 Lawrence Berkeley National Laboratory (LBNL)
6 National Renewable Energy Laboratory (NREL)

EXECUTIVE SUMMARY

Under the Net Zero World Initiative, the United States is mobilizing the capabilities of nine U.S. government agencies, led by the U.S. Department of Energy (DOE), to partner with philanthropies and multiple countries to cocreate and implement tailored technical and investment pathways to accelerate the decarbonization of global energy systems. The Net Zero World Initiative, committed to accelerating decarbonization and fostering more inclusive, equitable, and resilient energy systems, is pleased to support the Government of Ukraine in developing decarbonization pathways.

In a collaborative effort to promote the resilience and sustainability of the energy system as part of Ukraine's reconstruction, this project has harnessed the expertise of the leading DOE national laboratories and distinguished Ukrainian research institutes and think tanks. The modeling team used the TIMES-Ukraine model, developed by the Institute for Economics and Forecasting (IEF) of the National Academy of Sciences of Ukraine, and improved in 2023 with the support of the DOE national laboratories to model decarbonization pathways. Together, we have developed scenarios for achieving net-zero emissions in the energy sector, which are aligned with the goals of the Energy Strategy of Ukraine through 2050. The team explored three main scenarios: Reference, Net Zero Base, and Net Zero Intense. Both Net Zero scenarios are designed to achieve net-zero greenhouse gas (GHG) emissions in the energy sector; the Net Zero Intense scenario assumes higher economic growth and clean energy exports.

The modeling results underscore the significant sectoral and technological opportunities for Ukraine to expedite its clean energy transition. Ukraine has a significant potential to reduce GHG emissions through energy efficiency improvements, renewables, phasing out coal, electrification, and low-carbon fuels. Renewable sources make up about half of Ukraine's total primary energy supply in 2050, with nuclear providing the other half in the Net Zero Base scenario. In the more ambitious Net Zero Intense scenario, there is a much greater increase in total primary energy supply driven by faster economic growth and the development of green industry. Nuclear and wind supply are at more than twice the 2050 levels of the Net Zero Base scenario, with solar at more than three times the base recovery levels. Ukraine exports green hydrogen, electricity, and steel to support the decarbonization of the European continent and the rest of the world. Negative CO2 emissions from the power sector balance small remaining emissions from the industry, transport, and supply sectors, achieving net zero in 2050.

The Government of Ukraine used the outcomes of this study to prepare the National Energy and Climate Plan through 2030. The results are also being used to inform policy measures and implementation actions that support Ukraine's long-term decarbonization goals while also prioritizing the country's recovery and energy strategy. At the Ukraine Recovery Conference in London, G7 members pledged support for Ukraine's energy ambitions, emphasizing climate neutrality and a green transition as key recovery principles. The Net Zero World team, together with Ukrainian partners, is dedicated to developing detailed scenarios and policy measures to advance Ukraine's reconstruction and decarbonization objectives.

THE SITUATION IN UKRAINE

Russia's unprovoked full-scale invasion of Ukraine, which started in February 2022, has led to enormous human suffering and damage to Ukraine's economy. The invasion caused a GDP contraction of around 30% in 2022 and significantly reduced the labor supply. Due to its crucial role in the Ukrainian economy and the functioning of the country, energy infrastructure became a main target of brutal attacks. As of May 2023, Russia had destroyed or damaged 61% of Ukraine's electricity generating capacity, reducing installed capacity from 37.6 to 18.3 GW [1].

Ukraine has lost 43% of its nuclear, 75% of its thermal, and 33% of its combined heat and power (CHP) generating capacities [2] as a result of the war. In the south of Ukraine, many renewable energy facilities were destroyed or are located in temporarily occupied territories. As of February 2023, the Government of Ukraine, the World Bank, the European Union (EU), and the United Nations estimated damage to the energy sector to be above 10 billion U.S. dollars (without accounting for Russia's destruction of the Kakhovka Hydroelectric Power Plant) [3]. The dramatic reduction in generation capacities, coupled with the destruction of transmission and distribution lines, transformers, gas and heat networks, and other crucial energy infrastructure, poses an obstacle to the recovery of the Ukrainian economy.

In June 2023, Ukraine presented its Energy Strategy through 2050 at the Ukraine Recovery Conference in London. This strategy envisions decarbonizing Ukraine's energy sector by 2050. Given the country's ambitions to join the EU, we modeled Ukraine's net-zero greenhouse gas (GHG) emission pathways through 2050. Ukraine is committed to achieving rapid, deep, and sustained reductions in GHG emissions while providing affordable, reliable, and secure energy to all Ukrainians and designing long-term, low-emission development strategies aligned with the EU's goal of net-zero emissions by 2050.

With 68% of Ukraine's coal-generating capacity damaged or destroyed [1], the Government of Ukraine is considering phasing out coal from its power sector by 2035. Ukraine also plans to significantly increase power generation using wind, solar, nuclear, and biofuel technologies [4] and to improve system balancing with robust energy storage capabilities. The country aims to evolve into a prominent European green energy hub focused on the production of carbon-neutral electricity. Currently, Ukraine is actively engaged in the development of commercial energy flow potential and endeavors to seamlessly integrate with the EU energy markets. Additionally, it aspires to play a key role in the emerging hydrogen economy in the EU. Similarly, the country is considering developing certified gas storage to enhance energy security and flexibility in Ukraine and Europe. Further, involvement in the global energy equipment production chains is expected to foster economic growth and technological advancement within the country.

METHODOLOGY OF THE STUDY

GOAL OF THE STUDY

The goal of this study is to model several pathways for Ukraine's energy sector to show key sectoral and/or technological changes and opportunities for accelerating the clean and green energy transition through 2050. The scope of the study includes the power sector as well as other sectors of the economy (heat sector, industry, buildings, transport, and agriculture). The team was tasked to estimate investment needs for the pathway implementation to achieve net zero GHG emissions in Ukraine's energy sector. Finally, the Ministry of Energy asked the team to identify the main sources of international financial support for decarbonization in Ukraine.

MODEL

The modeling team used the TIMES-Ukraine model, developed by the Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine, and improved in 2023 with the support of the U.S. Department of Energy national laboratories (Pacific Northwest National Laboratory, Argonne National Laboratory, and National Renewable Energy Laboratory) under the Net Zero World Initiative. The TIMES-Ukraine model is the primary tool for the system-wide analysis.[1]

TIMES-Ukraine is a linear optimization energy system model of the TIMES (The Integrated MARKAL-EFOM System) model family [5] that provides a technology-rich representation of the energy system (bottom-up framework) of Ukraine for the long-term estimation of the energy dynamics [6]. The structure of the model is harmonized with Eurostat and International Energy Agency methodology with approximately 2050 technologies. The model was used to prepare numerous energy and strategic climate documents for the Government of Ukraine, such as the Building Retrofit Strategy, the National Energy Efficiency Action Plans, the Nationally Determined Contributions [7], the 2050 Low Emission Development Strategy [8], and other documents, and to prepare reports on renewables and climate neutrality for and World Bank [9] and the United Nations Economic Commission for Europe [10]. TIMES models satisfy the methodological recommendations of the Secretariat of the United Nations Framework Convention on Climate Change for the development of energy and environmental forecasts [11].

1 Full description of the TIMES-Ukraine model, socio-economic assumptions, assumptions about the cost of technologies, the scenarios and modeling results is available at http://ief.org.ua/wp-content/uploads/2023/11/NZW-IEF-TIMES-Ukraine-Description_and_Assumption.pdf

SCENARIOS

The team modeled three scenarios:

1. **The Reference scenario** assumes no fundamental changes will occur throughout Ukraine. Specifically, this includes no additional emission reduction measures or policies. Implementation of energy efficiency improvements, deployment of renewable energy resources, adoption of new technologies, and implementation of environmental and climate commitments are consistent with rates from past years. The purpose of this scenario is to show the energy sector development pathways in the post-war recovery of a severely damaged Ukraine, when the opportunities to attract the necessary investments in the decarbonization of the economy will be limited and the demand for energy services and goods will be covered in any available way. We consider this scenario to be hypothetical and only for comparison with Net Zero scenarios.

2. **The Net Zero Base scenario** includes all technological change capabilities; additional sectoral targets (e.g., in buildings, transport, and industry); developing bioenergy, nuclear, green, and clean energy options; and integrating European energy and climate obligations. This scenario is designed to achieve net-zero GHG emissions in the energy sector in the context of Ukraine's course toward membership in the European Union.

3. **The Net Zero Intense scenario** includes all the technological options and energy and climate obligations of the Net Zero Base scenario, along with greater economic growth driven by green industry and modeled exports of green electricity, green hydrogen, green fertilizers, and green steel. The relevant scenario includes the restoration and development of Ukraine as an energy hub in Europe, considering climate commitments and decarbonization of Ukraine's energy sector. This scenario provides not only the possibility of achieving climate neutrality for Ukraine but also a significant contribution to the decarbonization of the European continent and the rest of the world.

The team also used the TIMES-Ukraine model to estimate the required investment for each scenario.

SOURCES OF FINANCING

The team explored the financial mechanisms available to facilitate Ukraine's energy transition and contribute to the global discourse on decarbonization and sustainable energy solutions. During September and October 2023, we interviewed representatives from prominent organizations, including the following:

- World Bank
- European Bank for Reconstruction and Development (EBRD)
- European Investment Bank (EIB)
- European Commission and the EU Delegation in Ukraine
- Deutsche Gesellschaft für Internationale Zusammenarbeit
- UK Foreign, Commonwealth & Development Office
- U.S. International Development Finance Corporation
- U.S. Trade and Development Agency
- Export-Import Bank of the United States.

These discussions provided invaluable insights into the multifaceted financial support extended to Ukraine for its energy transition. Sincere appreciation is extended to the participants for generously sharing their time, expertise, and cooperation during these interviews. Their contributions have been instrumental in shaping the content and insights presented in this report.

MODELING RESULTS

TOTAL PRIMARY ENERGY SUPPLY

In the Reference scenario, with no new policies, no emissions or energy transition targets, and historical rates of efficiency and fuel switching, the mix of total primary energy supply (TPES) shifts only gradually from 2020 through 2050 (Figure 1). The impact of the war is visible in the sharp decrease in TPES between 2020 and 2025, followed by recovery at a rate of increase that is mitigated by increasing efficiency. There is a gradual shift away from coal toward wind, solar, and biofuels, but fossil sources remain more than half of TPES by 2050.

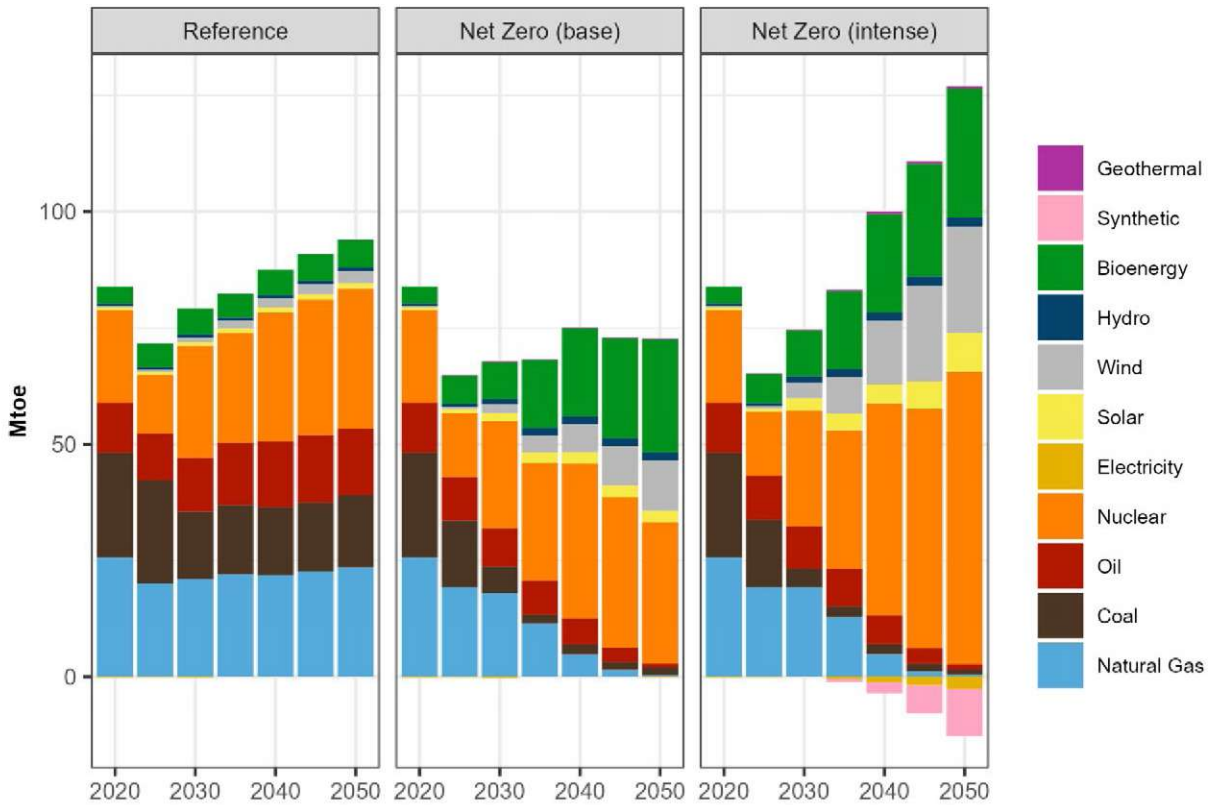

Figure 1. Total primary energy supply

In the Net Zero scenarios, on the other hand, there is a rapid phase-out of fossil fuels – first coal, followed by natural gas and oil – and increases in wind, biofuels, solar, hydro, and nuclear. In the Net Zero Base scenario, efficiency gains from investments in end-use efficiency and electrification roughly balance increases in energy service demands, and total primary energy supply remains nearly the same after 2025. Renewable sources make up just over 50% of TPES in 2050, with nuclear providing another 49%. The growth in bioenergy production in Ukraine in 2020-2050 is similar to the historical data for Germany between 1990 and 2020 [12], while Ukraine's bioenergy potential is larger than Germany's.

In the Net Zero Intense scenario, there is a much greater increase in TPES after 2025, driven by faster economic and population growth and the development of green industry.

Exports of green hydrogen and green electricity begin in 2035 and increase rapidly until 2050. The 2050 supply mix is roughly half nuclear and half renewables. Nuclear and wind supply are at more than twice the 2050 levels of the Net Zero Base scenario, with solar at more than three times the base levels.

ELECTRICITY GENERATION AND CAPACITIES

Electrification is a major decarbonization strategy for the Ukraine economy, so the Net Zero scenarios show substantially increased generation over the Reference case (Figure 2). In the Reference scenario, there is a gradual shift in the electricity generation mix as coal and gas generation decrease and nuclear, bioenergy, hydro, solar, and especially wind power increase over the projection period. Renewables provide just over 25% of total generation by 2050 and nuclear has increased to nearly 60% of total generation in the Reference scenario.

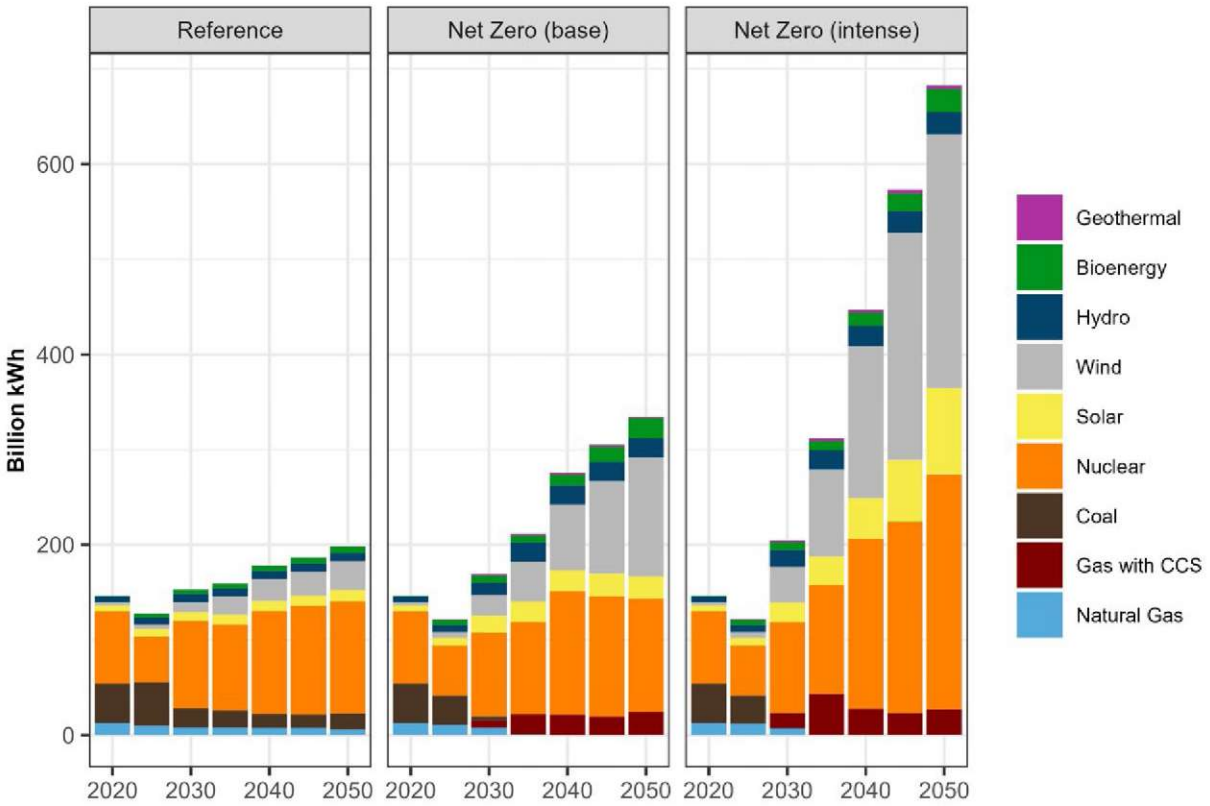

Figure 2. Electricity generation by technology

In the Net Zero scenarios, there is a much faster phase-down of coal and gas generation, with no coal electricity generation after 2035. Fossil sources with carbon capture and storage (CCS) provide a small fraction of generation, with most of the increase coming from renewables and nuclear. Some fossil fuels like natural gas are replaced by biomethane after 2035 with a full switch to bioenergy by 2045 at new gas power plants and CHPs equipped with bio-energy carbon capture and storage (BECCS). These new generating facilities provide dispatchable renewable electricity, heat, and negative CO_2

emissions. Renewable sources make up roughly 65% of electricity generation in both Net Zero scenarios by 2050, with nuclear comprising just over one-third. However, the total generation is much larger in the Net Zero Intense scenario due to both greater electrification and substantial generation for hydrogen production (see Figure 9). Figures 3 and 4 provide details on renewable and nuclear generation.

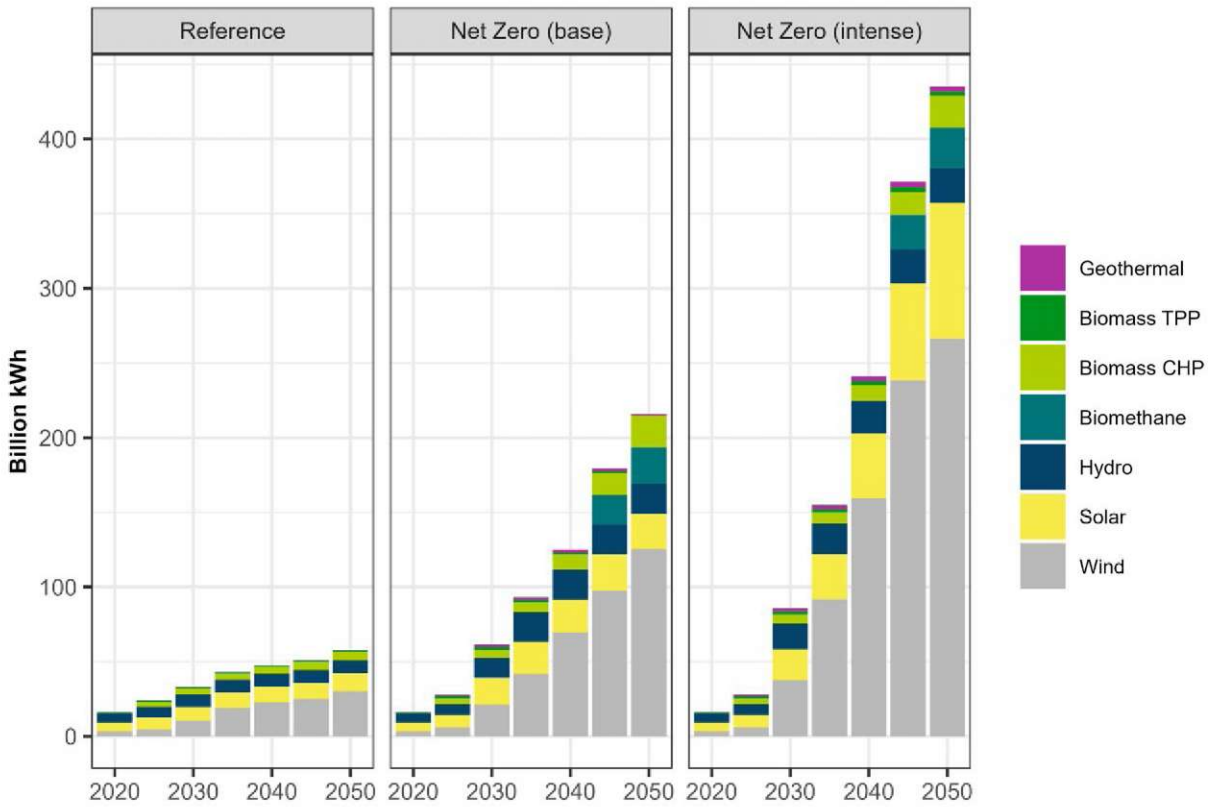

Figure 3. Electricity generation from renewable sources

Figure 3 breaks down the production of electricity from renewable sources. In all three scenarios, wind – both onshore and offshore – is the primary source of renewable electricity. The greater demands for renewable electricity in the Net Zero scenarios are met by steady increases in hydro, biomass (primarily CHP), and solar (both centralized and distributed systems), along with small amounts of geothermal generation. The much greater increase in renewable electricity production in the Net Zero Intense scenario is met by scaling up all of these sources, especially through a large investment in offshore wind production.

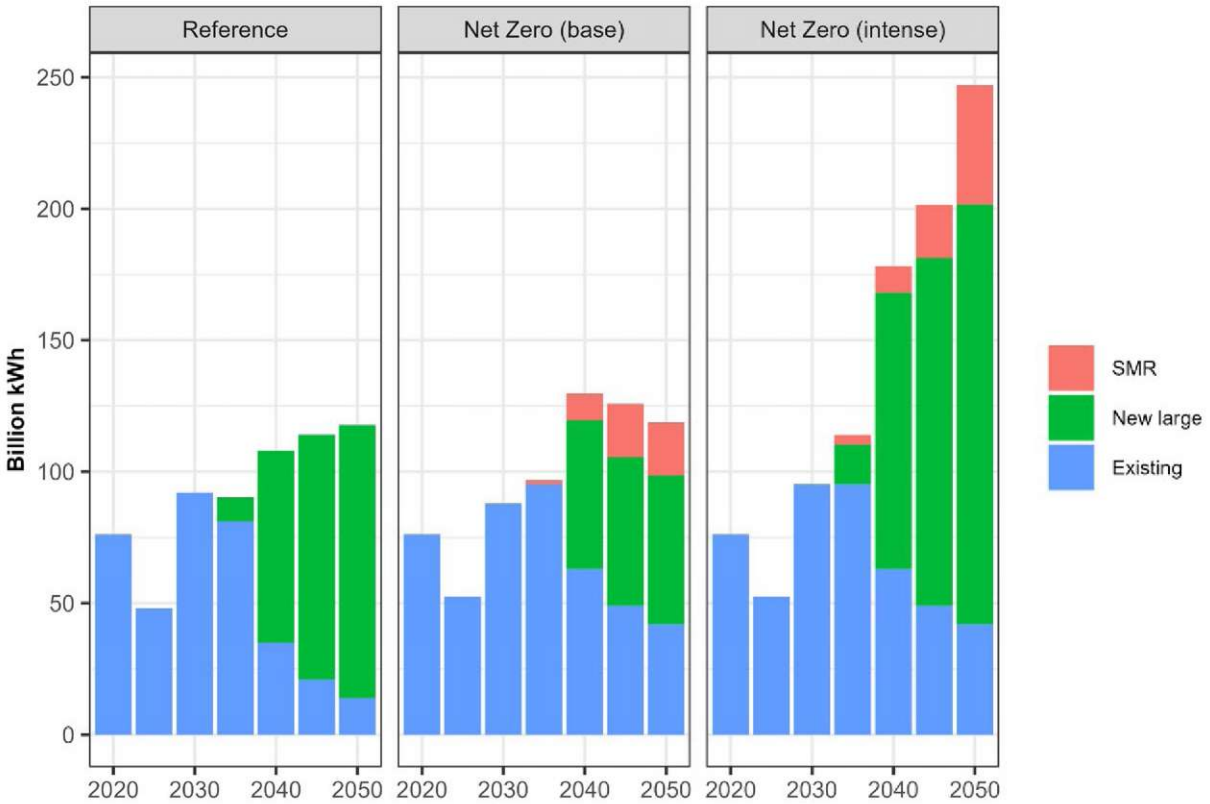

Figure 4. Electricity generation by nuclear reactors

Figure 4 breaks down the production of electricity from nuclear reactors. In all three scenarios, there is a gradual phase-down of generation from existing units after 2035 as these reactors begin to retire. Most of the increasing generation is produced by new large reactors, with smaller investments in new small modular reactors (SMRs) in the Net Zero scenarios. SMRs are defined as nuclear reactors with a capacity of up to 300 MWe.

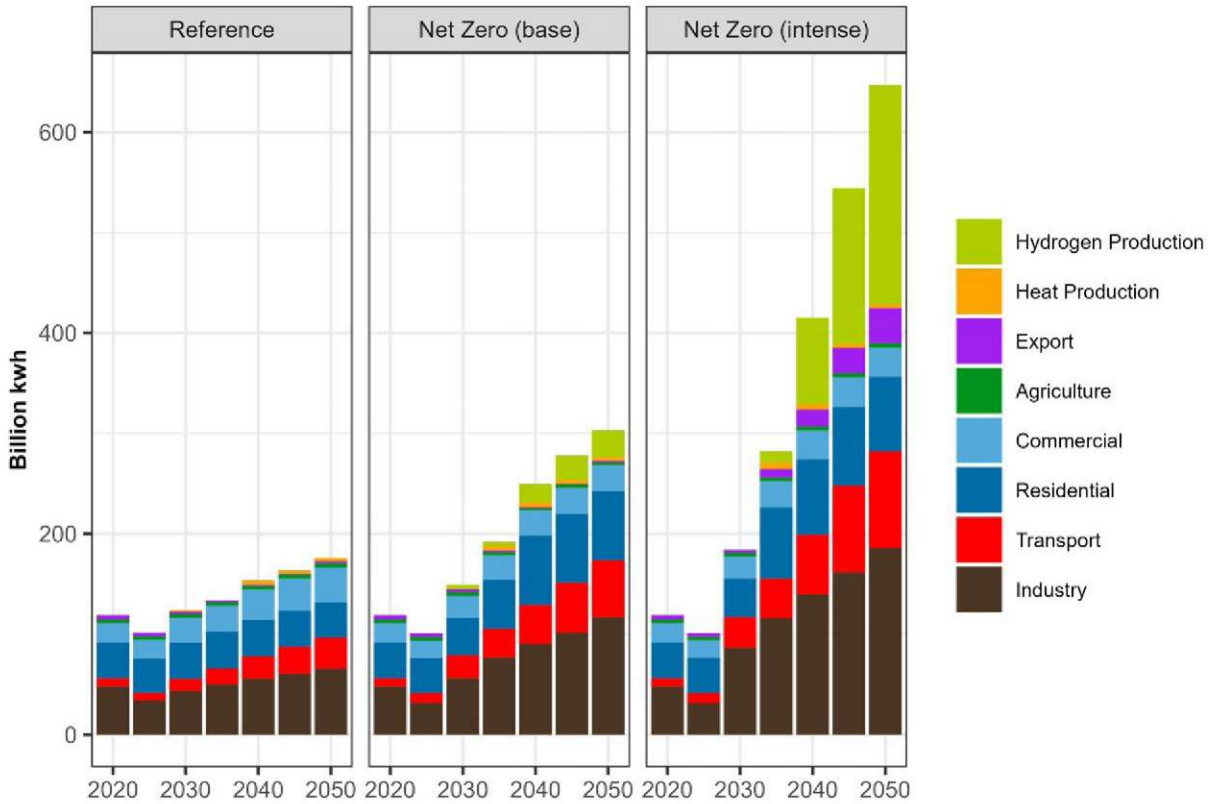

Figure 5. Electricity consumption by sector

Figure 5 shows that in the Reference scenario, electricity consumption grows slowly due to electricity use by industry and some electrification of transport – primarily light-duty vehicles and buses. Electrification is much more rapid in the Net Zero Base scenario, with complete electrification of light-duty vehicles by 2050, along with moderate electrification of freight transport, heating, cooking, and water heating in buildings, and both light and heavy industry. There is also increasing consumption of electricity for hydrogen production beginning after 2030. By 2050, total electricity consumption is nearly 2.5 times 2020 levels.

The increase in electricity consumption is much more rapid in the Net Zero Intense scenario, reaching roughly more than five times 2020 levels by 2050. The increase is driven by greater economic growth, greater industrial production, and deeper electrification in transport, building, and industrial uses. There is also rapid growth in electricity consumption for hydrogen production – for domestic consumption and exports – after 2035.

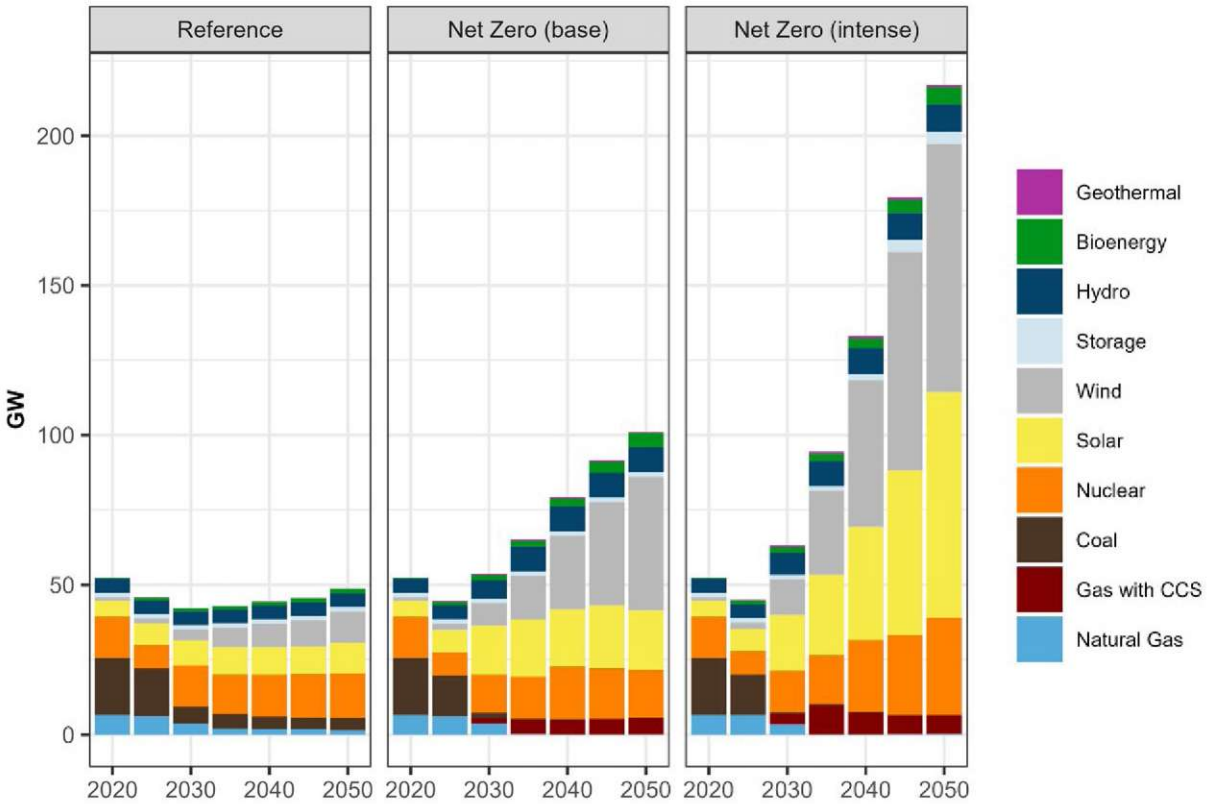

Figure 6. Electricity generation capacity

Figure 6 shows the modeled installed capacity to supply electricity. In the Reference scenario, the capacity mix shifts over time from fossil and nuclear dominated to a mix of primarily nuclear and renewables, but the total capacity remains around 2020 levels at nearly 50 GW by 2050. To meet the much greater electricity demand, total capacity grows to over 100 GW by 2050 in the Net Zero Base scenario and over 250 GW in the Net Zero Intense scenario. Because of their lower capacity factors, the capacities of wind and solar grow faster than their contributions to the generation mix (Figure 4). In 2050, there are 44 GW of wind and 20 GW of solar in the Net Zero Base scenario, and over 80 GW of wind and 75 GW of solar in the Net Zero Intense scenario. The nuclear capacity in 2050 is roughly 15 GW in both the Reference and Net Zero Base scenarios and around 32 GW in the Net Zero Intense scenario.

Overall, electrification is the most important factor in achieving net-zero emissions by 2050. With fossil fuels phased out, generation capacity from renewable sources should grow manyfold, especially in the Net Zero Intense scenario to meet the domestic demand and support clean electricity exports to Europe. The share of nuclear in the electricity mix remains one of the highest in the world [13].

HEAT GENERATION

In the Reference scenario, heat is generated by fossil fuel and bioenergy and supplied by district heat (Figure 7). In the Net Zero scenarios, the share of bioenergy grows fast between 2030 and 2050, and fossil fuels are replaced by electricity and technologies with CCS systems. Note that Ukraine uses heat produced by nuclear power plants and this share increases in the future.

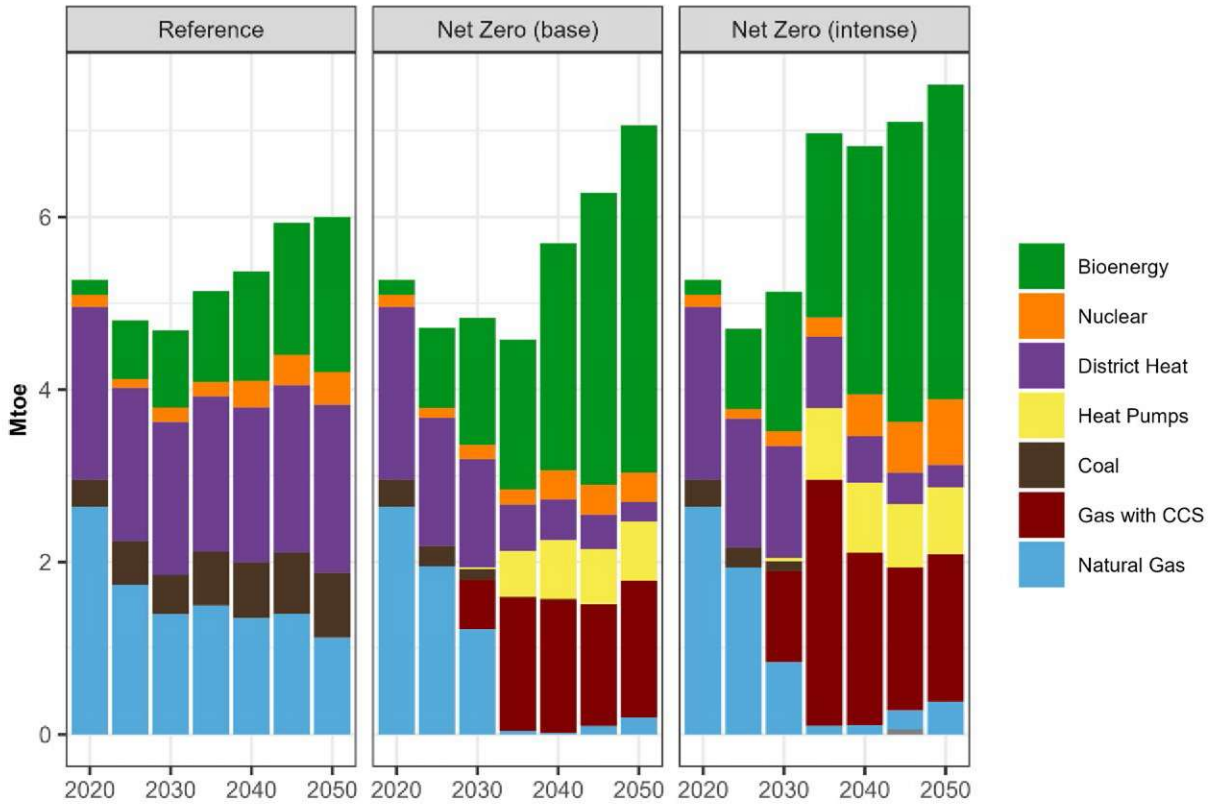

Figure 7. Heat generation by technology

Heat pumps as part of the district heat systems play an important role in decarbonizing the heat sector. District heat uses all sources of energy, including biofuels and industrial waste heat. Biogases and synthetic fuels gradually replace natural gas for heat generation in district heat.

TOTAL FINAL CONSUMPTION

Figures 8 and 9 show final consumption by sector and fuel, respectively. As with primary energy, there is a sharp decrease in final energy between 2020 and 2025 due to the war, particularly for natural gas use in industry. In the Reference scenario, total final consumption expands with recovery. Growth in final consumption slows after 2030 as increasing efficiency of use mitigates the impact of increasing energy service demand. The final consumption mix in 2050 is very similar to the mix in 2020.

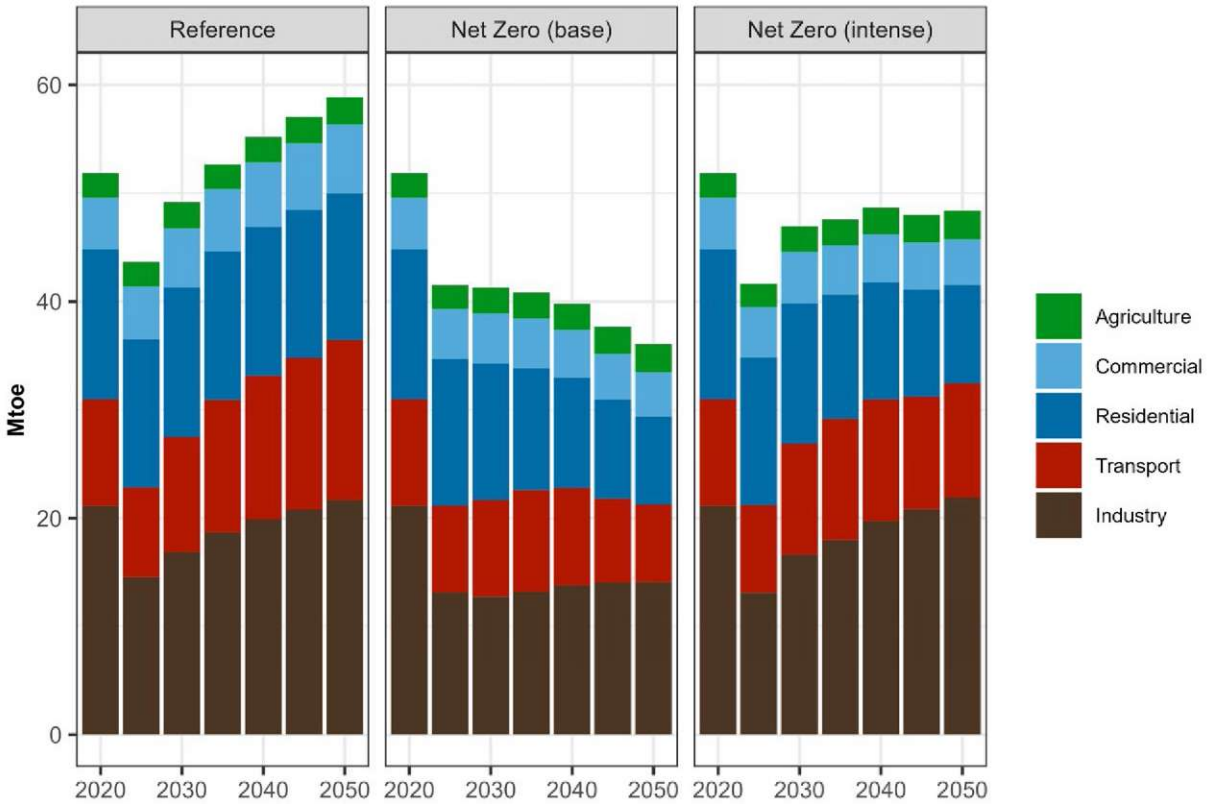

Figure 8. Total final consumption by sector

In the Net Zero Base scenario, total final consumption continues to decrease after 2025 due to more intensive investment in efficiency and the greater end-use efficiency of electrification, reaching two-thirds of 2020 levels in 2050. Electricity makes up 60% of the 2050 energy mix (Figure 9), and fossil sources have been almost completely phased out.

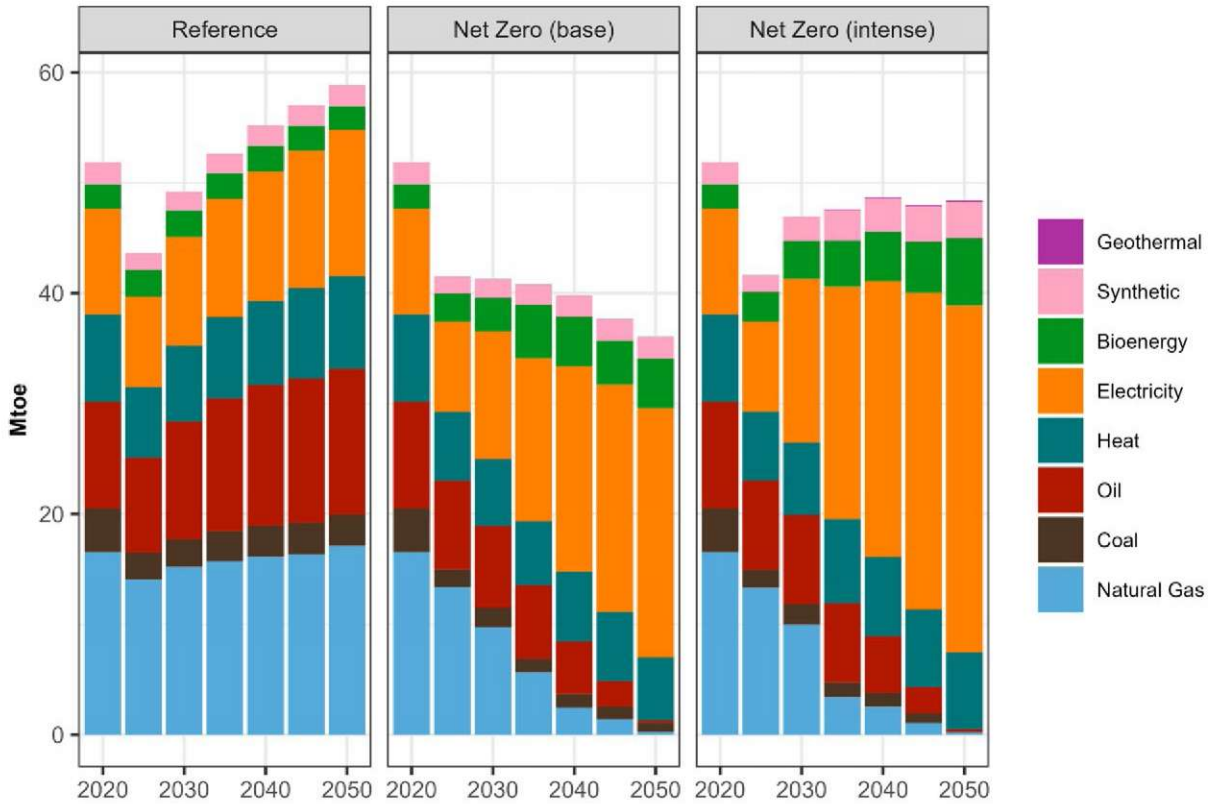

Figure 9. Total final consumption by fuel

In the Net Zero Intense scenario, with its greater end demand growth, total final consumption increases more rapidly after 2025 and levels off by 2050 at near 2020 levels. Electricity makes up two-thirds of the 2050 mix, and fossil sources are nearly eliminated. Synthetic fuels include bio- and synthetic methane and hydrogen.

GHG EMISSIONS

Figure 10 shows the GHG emissions resulting from the modeled shifts in the energy economy. In the Reference scenario, the sharp drop in emissions in 2025 is followed by a leveling out of total emissions. Decreasing emissions from electricity and heat production, as nuclear and renewable sources replace coal power, are balanced by increasing emissions from the industry and transport sectors. In the Net Zero scenarios, steep declines in emissions continue throughout the projection period.

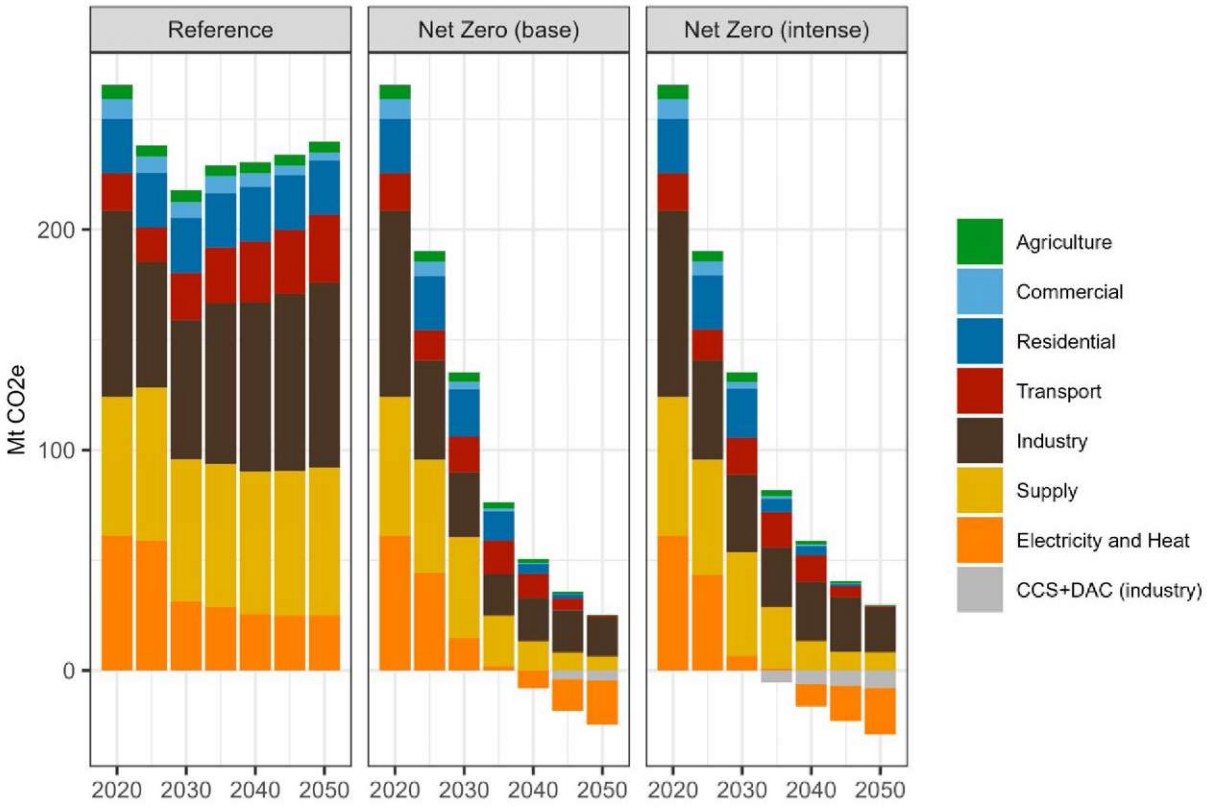

Figure 10. Ukraine's GHG emissions projections

The power sector is decarbonized and becomes net negative in 2040. The buildings sectors reach zero emissions by 2045. Negative emissions from the power sector with the help of CCS and direct air capture (DAC) balance small remaining emissions from the industry and supply sectors, achieving net zero in 2050. The negative 'wedge' for power and heat in the TIMES mode is all BECCS facilities. The timeline of total emissions is very similar between the Net Zero Base and Intense scenarios, despite the much greater energy consumption in the Net Zero Intense scenario, because they must both meet the same 2050 net zero target.

INVESTMENT NEEDS

Figure 11 presents the upfront investment needs for each scenario. In implementation, these amounts would ordinarily be financed and thus spread out over time, but viewing the upfront costs can help inform the timeline of investment and financing needs.

Modeled investments include all purchases of energy-producing, -transforming, and -consuming equipment, including power plants and industrial facilities, along with vehicles, cookstoves, refrigerators, and other energy-using appliances. Transportation dominates total investment needs in all three scenarios because vehicles have a much short lifetime than other technology types.

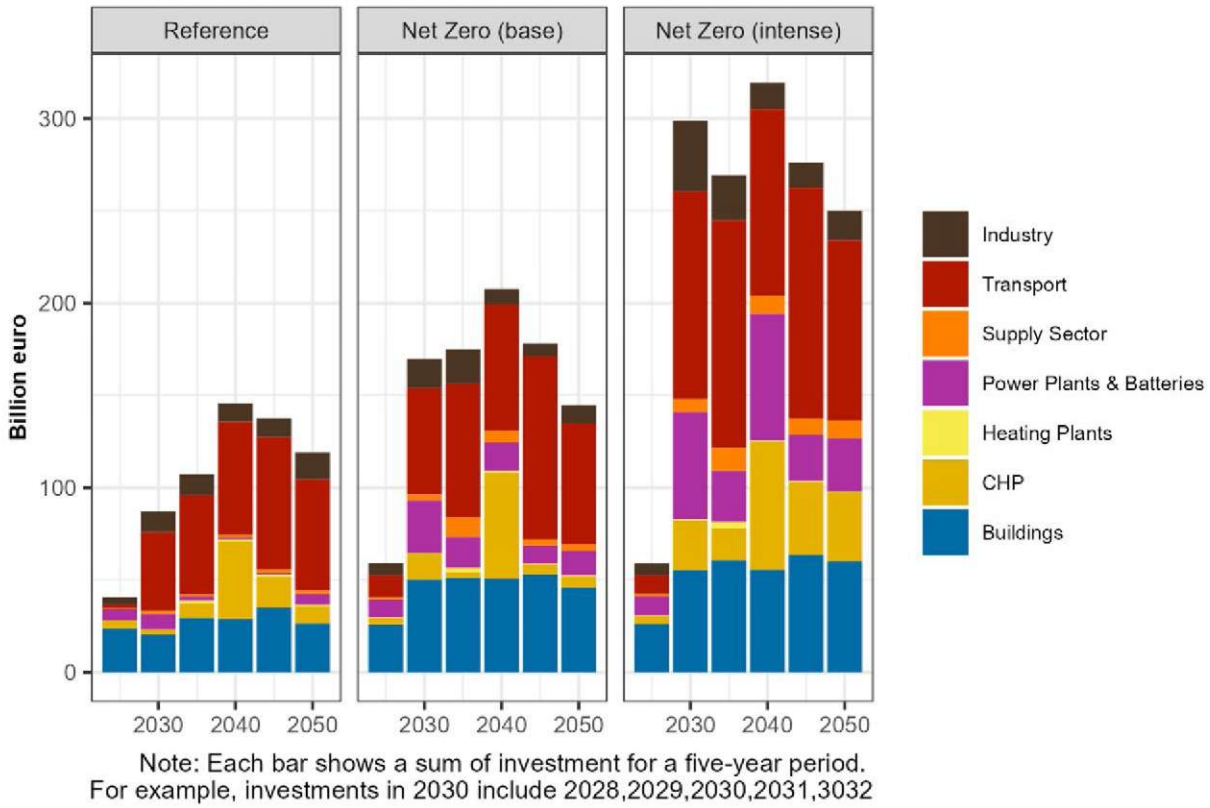

Figure 11. Total investment needs by sector

Cumulative investment needs in the Net Zero Base scenario are roughly 50% higher than in the Reference scenario. Major investments include electric and other clean-fueled vehicles, upgrades to buildings, the installation of clean heating systems, and new renewable and nuclear power plants. Investment needs to meet the much higher demand for energy services, industrial facilities, and clean power are significantly greater in the Net Zero Intense scenario, around 300 billion euro for the period of 2028-2032, although they fall gradually as the clean energy economy matures. Investments for clean heating, power, and CHP plants range between 60 and 150 billion euro per a 5-year period.

It is clear that upfront investment needs in the Net Zero scenarios are higher than in the Reference one. At the same time, the total energy system cost (investment, operation and maintenance costs, fuel expenditures, subsidies, etc.) for the Net Zero Base scenario is only 3% higher than the corresponding cost for the Reference scenario. In the case of a significant contribution of Ukraine to the decarbonization of the European continent, the total system costs in the Net Zero Intense scenario are 25% higher than in the Reference scenario.

INTERNATIONAL SUPPORT OF DECARBONIZATION PROCESSES IN UKRAINE

The section is based on the findings of the modeling approach, which aligns with the core principles of Ukraine's Energy Strategy. The interviews with key partner organizations supporting decarbonization projects in Ukraine offer valuable insights into their ongoing endeavors. While the discussions acknowledge certain challenges, these conversations reveal a mature and sophisticated approach to the complexities of sustainable development. The primary focus is on financial instruments provided or planned by key international donors and partners, their role in supporting Ukraine's energy decarbonization, and the promotion of innovative energy solutions.

CURRENT ACTIVITIES AND FOCUS SECTORS

Partner organizations are significantly invested in various decarbonization initiatives, with a pronounced emphasis on the energy sector. Their main thrust revolves around public energy infrastructure and private-sector green ventures. The multifaceted approach emphasizes the importance of both emergency support for immediate needs and sustainable project development for long-term recovery and development.

Emergency Support. Responding to the immediate impact of the war, there's a clear emphasis on rebuilding essential infrastructure, including repairing roads, bridges, utilities, and other damaged facilities, to swiftly restore essential services and connectivity in the affected regions. Another key area is ensuring energy resilience in regions affected by the war, involving the deployment of generators to maintain a stable power supply, with a notable focus on transitioning to more sustainable energy sources, such as solar, to reduce the environmental impacts. There is also a commitment to innovative solutions and technical support to enhance emergency response and recovery. This may involve leveraging technology and technical expertise to improve disaster management and recovery efforts.

Sustainable Project Development. Sustainable energy solutions take precedence in discussions, with a strong emphasis on initiatives related to renewable energy sources. Solar and wind energy projects are prominently featured, with substantial investments and commitments to scale up their implementation in Ukraine. These investments typically amount to tens of millions of U.S. dollars, with specific projects covering the installation of solar panels, wind turbines, and related infrastructure to harness clean energy. Among the strategies for sustainability, discussions include projects focused on biomass and biofuels, such as support for companies aiming to scale up biomass-to-energy facilities, contributing to cleaner energy generation within the private sector. The anticipated results include reduced carbon emissions, increased reliance on renewable energy sources, and a transition to more environmentally friendly energy production methods. Alongside sustainable energy generation, there's an equally robust emphasis on upgrading energy grids and enhancing energy efficiency. The investments in this sector are considerable, covering the modernization of existing energy infrastructure, including transmission lines, substations, and grid management systems. These upgrades are intended to ensure reliability, reduce energy wastage, and make the entire

energy ecosystem more sustainable. The financial commitments here are substantial, often exceeding hundreds of millions of U.S. dollars to revamp and optimize the energy grid. The expected benefit is a more stable and efficient energy supply.

Large-scale contributions to sustainable development mainly come from public sector projects, including investments in state-owned enterprises with a focus on infrastructure development, ensuring the critical sectors of the economy are more environmentally responsible.

Sustainable project development extends to the private sector, with investments in private businesses oriented toward green projects with clearly defined environmental benefits, ensuring ecologically sustainable economic growth. Technical assistance plays a crucial role in developing sustainable projects, advocating for green taxonomy, and facilitating the transition to green bonds and other sustainable financial mechanisms.

AVAILABLE FINANCIAL INSTRUMENTS

Grants: These are a common financial instrument used for decarbonization projects. Grants often range from a few million to tens of millions of U.S. dollars, providing essential financial support for endeavors related to renewable energy, grid upgrades, and sustainability-focused initiatives in both public and private sectors. These grants serve as a catalyst for project initiation and implementation.

Loans: In addition to grants, loans play a crucial role in funding decarbonization projects. A notable feature is the strategic conversion of grants into loans in collaboration with international financial institutions (IFIs). While organizations might initially offer grants, they often work with IFIs to transform a portion of these grants into loans. This conversion allows for a more diversified financial approach, mitigating investment risks and making funds available for a broader range of projects. Loan amounts frequently exceed 10 million U.S. dollars.

Risk-Sharing Mechanisms: Collaborations with IFIs are at the heart of creating risk-sharing mechanisms and efficient financial structuring. The risk-sharing mechanisms often involve insurance-based instruments that protect investments in the event of project disruptions or economic uncertainties. The IFIs collaborate on various aspects of the projects, from technical assistance to investment guarantees, further enhancing the attractiveness of decarbonization projects to private investors.

Combination of Domestic and International Investments: While partner organizations allocate significant sums to support green initiatives, they recognize the importance of fostering collaboration with other international donors, investors, and financial institutions. It is important that decarbonization projects are financed through a combination of domestic and international funding. These collaborative financial strategies provide a more diversified funding base for decarbonization projects, ensuring their long-term sustainability and widespread success.

Innovative Financial Instruments: Partner organizations are actively exploring innovative financial instruments for green projects. These instruments go beyond traditional grants and loans and may include environmental impact bonds, green transition bonds, and climate-focused credit facilities. The exact nature and structure of these instruments are continually evolving and adapting to the specific needs of decarbonization projects. Their introduction is aimed at promoting a transition to more sustainable financial practices, driving the green agenda, and providing new avenues for investment in sustainable projects.

STRATEGY AND PLANS

The IFIs are looking to build partnerships that align with their long-term goals and strategies. While the organizations do have strategies in place, these tend to be focused on the mid-term (approximately 3 years). The organizations support a diverse range of sustainable projects and are open to cooperating with other donors. Looking ahead, the organizations are exploring innovative financial instruments, targeting green projects, and are eager to work with other stakeholders in Ukraine. Long-term financing is a goal, with a vision for its alignment with future reforms and conditions. In summary, the organizations anticipate a shift toward more long-term, sustainable support for decarbonization projects, but recognize the importance of international partnerships and cooperation.

There is unwavering commitment from various organizations to Ukraine's decarbonization efforts. While acknowledging the challenges they face, a prevailing atmosphere of determination, adaptability, and a shared vision of reshaping Ukraine's energy landscape in accordance with global sustainability objectives is evident. Their strategies are designed to provide enduring and sustainable support for decarbonization initiatives, with a forward-looking approach and a positive outlook on a promising future fostered through international collaborations in the fight against climate change.

CONCLUSIONS

The modeling results from this comprehensive study significantly contribute to a more detailed analysis of the National Energy and Climate Plan through 2030. At the Ukraine Recovery Conference in London, the G7 members collectively expressed a resolute commitment to catalyzing and maximizing investment in support of the National Energy and Climate Plan and Ukraine's National Recovery priorities [14]. The Ukrainian Government has clearly declared the foundational principles of climate neutrality and green transition as essential pillars toward Ukraine's recovery [15]. The Net Zero World team and the partners in Ukraine direct their efforts toward developing comprehensive scenarios, crafting pragmatic policy measures, and tangible implementation actions to advance Ukraine's reconstruction while addressing long-term decarbonization goals.

The G7 countries have notably expressed their appreciation for the united efforts of key financial institutions, including the World Bank Group, the EBRD, the EIB, and our Development Finance Institutions to establish the Support for Ukraine's Reconstruction and Economy Trust Fund at the Multilateral Investment Guarantee Agency. Simultaneously, they have shown strong support for the launch of the Ukraine Investment Platform, aimed at supporting Ukraine's recovery [16].

The current challenging and violent times, coupled with the damage and destruction, necessitate Ukraine's transformation, making it critical to rebuild the energy system. This highlights the importance of making the energy system green and decentralized to strengthen the country's resilience. Importantly, this transformation requires substantial funds and investments to not only repair but to "build-back-better" the energy system.

Investing in Ukraine's energy sector decarbonization and developing clean energy projects emerges as a pivotal opportunity. These investment opportunities allow us to achieve a clean, environmentally sustainable energy landscape, significantly reducing emissions not only in Ukraine but also in Europe and globally. This trajectory aligns with Ukraine's pursuit of reforms and creating a "success story" for Europe's green energy hub, particularly within the realm of European integration. The current landscape reveals unique and unparalleled opportunities for IFIs, lenders, and investors.

Ukraine's Clean Energy Roadmap provides comprehensive data and estimations, inviting global participation and encouraging others to join the transformation of Ukraine's energy sector toward a sustainable, decarbonized future. The adoption of the Energy Strategy of Ukraine through 2050 by Ukraine and the subsequent approval of the National Energy and Climate Plan should play an important role in determining the priority areas of cooperation between Ukraine and international partners and will be key guiding documents for the post-war recovery.

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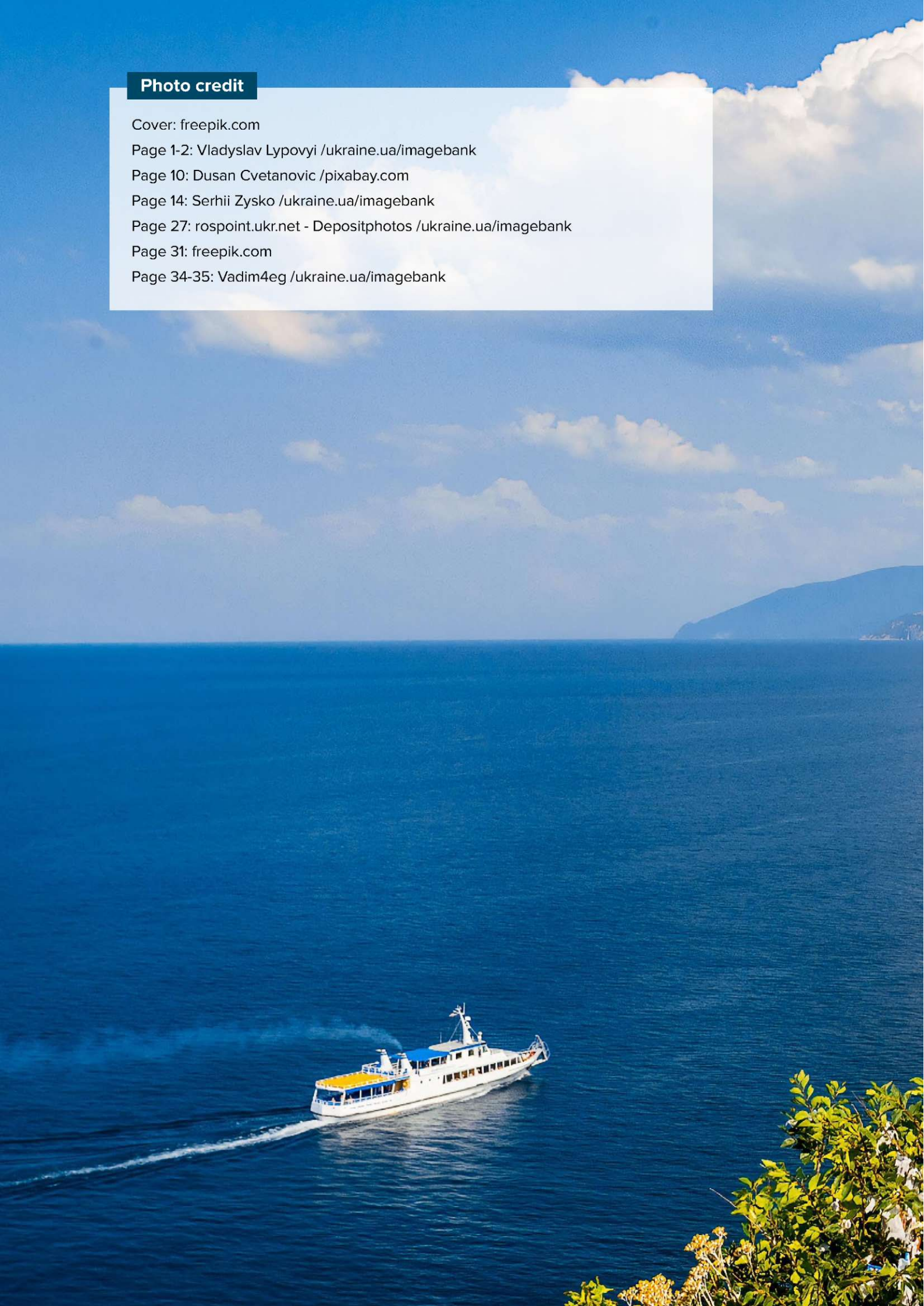

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ANNEX

DESCRIPTION OF THE TIMES-UKRAINE MODEL AND KEY ASSUMPTIONS

General background of TIMES-Ukraine model

The modeling team used the ***TIMES-Ukraine model***, developed by the Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine, and improved in 2023 under the Net Zero World Initiative.

The TIMES-Ukraine is a linear optimization energy system model of the MARKAL/TIMES model family (IEA-ETSAP) that provides a technology-rich representation of the energy system (bottom-up framework) of Ukraine for the long-term estimation of the energy dynamics (Loulou et al., 2016; Podolets and Diachuk, 2011). For more details see https://iea-etsap.org/.

The Ukrainian energy system is divided into seven sectors in the model (Figure A1): energy supply sector, power and heat generation, industry, transport, residential, commercial and agriculture (including fishing).

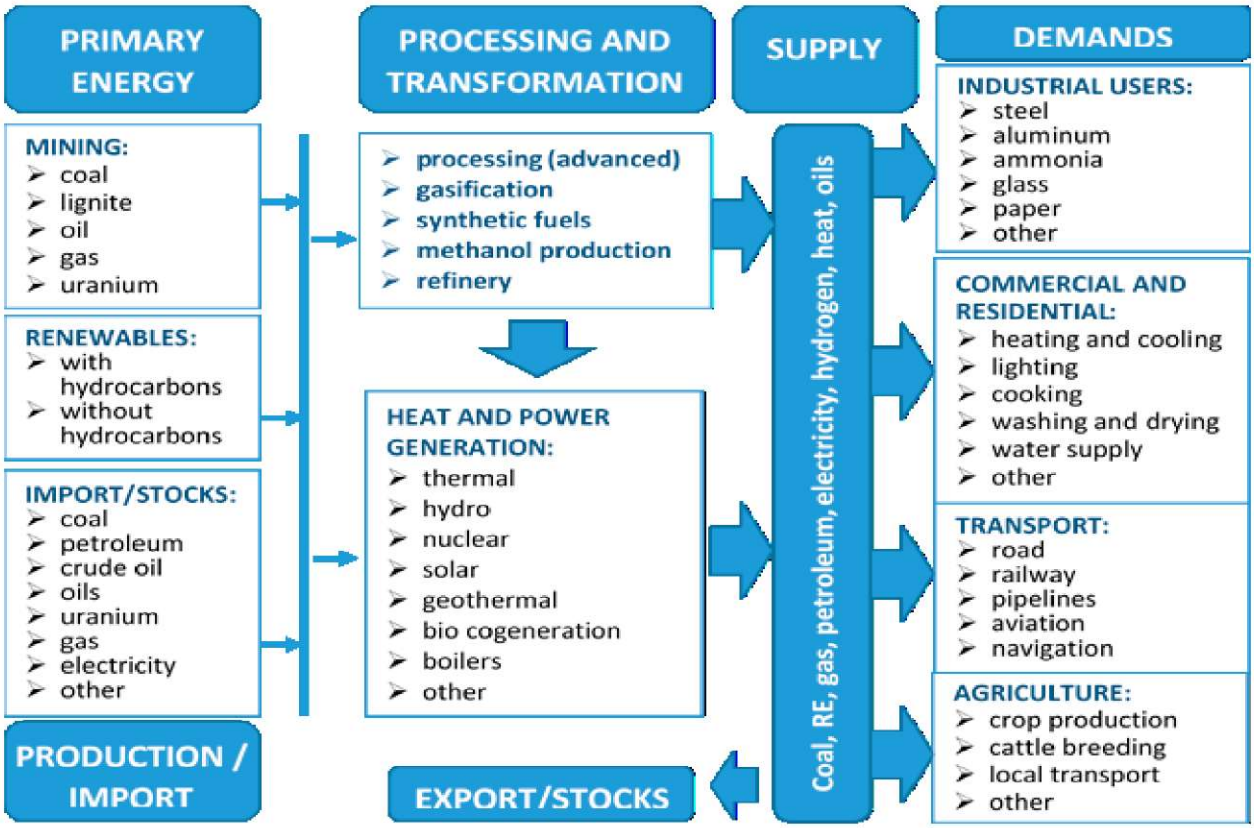

Figure A1. Representation of the energy system in the TIMES-Ukraine model

Industrial users are disaggregated into two categories depending on the level of their energy intensity. Energy-intensive subsectors are represented by product-specific technologies. For other industrial subsectors, a standard representation is adopted according to the four types of general processes: electric engines, electrochemical processes, thermal processes and other processes. Energy consumption by households and the commercial sector is determined by the most energy intensive categories of consumer needs, such as heating and cooling of dwellings, water heating, lighting, cooking, refrigerating, clothes washing and drying (ironing), dishwashing etc. The transport sector is represented by the types of transportation: road, railway, pipelines, aviation and navigation. The energy services, which are provided by technologies of road and rail transport, are transportation of passengers and freight. The agriculture sector is divided into crop production, cattle breeding, local transport and other.

The structure of the model is harmonized with Eurostat and International Energy Agency methodology with approximately 2050 technologies. The runs till 2060 and every year comprises 96 time slices, representing 4 seasons and 24 hours.

The model database is filled with economic and energy available data for 2005-2023. The database of the TIMES-Ukraine model includes data from several sources, including, the State Statistics Service of Ukraine, the Ministry of Energy, Ministry of Economy, Ministry of Environment and Natural Resources, Ministry of Internal Affairs, Ministry of Communities, Territories and Infrastructure Development, and many others. Energy data is gathered from the IEA, OECD, IAEA, and others. Long-term macroeconomic development indicators are based on data from the IEF NASU, IMF, World Bank, National Bank of Ukraine and Ministry of Economy.

The database of the TIMES-Ukraine model contains the data of the following origin:

- statistical observations of the State Statistics Service of Ukraine;
- data of the Ministry of Energy and Coal Industry; Ministry of Economy, Ministry of Environment, Ministry of Internal Affairs, Ministry of regional development, construction and housing and communal services, SAEE, power generating and supply companies, etc.;
- data from the IEA (in particular ETP, E-TechDS), DIW Berlin, IAEA, OECD, DEA and others (used to identify promising energy technologies and their technical and economic characteristics);
- data from specialized associations (Bioenergy Association of Ukraine, Ukrainian Wind Energy Association, Ukrainian Association of Renewable Energy Sources and other) and companies (Energoatom, Ukrenergo, DTEK, Naftogaz, etc.);
- the structure of demand in the end-use sectors (corresponding to the models structure of other European countries);

- long-term macroeconomic development indicators that are based on data from the IEF, international financial, rating agencies and other organizations (IMF, World Bank, Standard & Poor's, etc.), as well as data of the Ministry of Economic Development and Trade;
- forecast of prices for the main energy resources (based on IEA and World Bank data);
- forecasts of demographic dynamics in Ukraine (based on data from the Institute of Demography and Social Research of the National Academy of Sciences of Ukraine and the Department of Economic and Social Affairs of the United Nations).

GHG emission factors (based on the National Inventories data on anthropogenic emissions from sources and removals by sinks of greenhouse gases in Ukraine).

The TIMES-Ukraine model was used for preparation of the lot of energy and climate strategic documents, which adopted by the Government of Ukraine in 2016-2021. For example:

- the National Energy Efficiency Action Plan for period 2019-2030 (2021)[1];
- the Updated National Determined Contribution of Ukraine to Paris Agreement (2021)[2];
- the Low Emission Development Strategy under Paris Agreement (2018)[3];
- the Intended National Determined Contribution of Ukraine (2015)[4];
- the National Action Plan on Energy Efficiency through 2020 (2015)[5].

The model has been used in projects by USAID, EBRD, World Bank, UNDP, IAEA, IIASA, GIZ, DEA, European Union, Energy Community and many national projects, including projects of the National Academy of Sciences of Ukraine.

Macroeconomic projections

The modelling scenarios are based on macroeconomic projections to 2060 (Table A1), which include the occupied territories of Ukraine, and the assumption that these territories will be returned to the control of the Government of Ukraine no later than 2025. This assumption is in line with the official domestic and foreign policies of Ukraine and is used for many international studies in Ukraine, including the EBRD project on updating NDC of Ukraine, Energy Community project on developing the National Energy Efficiency Action Plan for period 2019-2030.

We analyzed two macroeconomic scenarios that correspond to the Base and Intense recovery scenarios described in this report. Base recovery scenario is aligned with economic projections used

[1] https://www.kmu.gov.ua/news/skorotiti-na-223-pervinne-spozhivannya-energiyi-peredbachaye-nacionalnij-plan-z-energoefektivnosti-do-2030-roku
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in the Energy strategy of Ukraine by 2050, while Intense recovery scenario additionally assumes extension of production and export of "green commodity" export, such as green steel, green ammonia etc. The main parameters of these economic scenarios are presented in Tables A2- A4).

Table A1. Projection of the GDP of Ukraine, bln USD 2015

	2020	2025	2030	2035	2040	2045	2050	2055	2060
Base recovery	98.1	81.8	111.5	131.8	149.2	166.3	183.6	202.8	223.9
Intense recovery			138.4	171.6	198.5	223.5	246.8	272.5	300.9

Source: IEF NASU

Table A2. Projection of the GDP grows rates, %

	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Base recovery	-3.6	6.4	3.4	2.5	2.2	2.0
Intense recovery		11.1	4.4	3.0	2.4	2.0

Source: IEF NASU

29.1% drop in 2022, followed by +2.9% in 2023, +3.5% in 2024, and +6.8% in 2025 as suggested by the National Bank. For the long-term projections in Base recovery scenario, macroeconomic assumptions are aligned with the Energy Strategy by 2050, which assumes 65% increase of GDP in 2032 comparing to 2023 (5.4% annual growth), and 148% increase in 2050 comparing to 2023 (2.3% annual growth for 2033-2050).

Table A3. Projection of the structure of Ukraine's economy, Base recovery, %

	2022	2023-2030	2031-2040	2041-2050
Industry, *growth rate in %, average for period*	-37.9	3.6	1.3	2.0
Mining and querying, *growth rate in %, average for period*	-32.2	0.9	-9.0	-1.0
Manufacturing, *growth rate in %, average for period*	-43.1	4.0	3.0	2.2
Construction, *growth rate in %, average for period*	-67.6	18.5	7.3	2.7
Services, *share in GDP, average for the period, %*	61.2	61.1	61.2	61.1
Agriculture, *share in GDP, average for the period, %*	12.6	12.5	13.0	12.9

Source: IEF NASU

*Table A4. Production of main goods of heavy industry, Base recovery, million tones**

	2020	2030	2040	2050
Iron steel	10.3	4.4	5.3	5.7
Cement	9.7	14.4	19.5	22.6
Ammonia	2.8	3.3	3.7	3.8

** Production volumes may not coincide with data from other sources due to different nomenclature.*

Source: IEF NASU

Figure A2 shows the structure of Ukrainian GDP by sector under Base recovery scenario over modelling horizon in selected years. No specific sectoral policy was assumed in a long run, instead assuming inertial socially-orientated development based on recovery of damaged facilities.

Agriculture, Manufacturing, Transport and Services develop with relatively identical growth rates, although with some structural shifts within sector. Mining & Utilities show moderate growth in absolute values, but their share in GDP is push out by Construction.

No new production facilities (after destructions during war) in Metallurgy and Chemical industry, while existing capacities are upgraded and fully loaded. Energy demand in Industry is driven by internal demand on construction material, and also by F&B and Machinery.

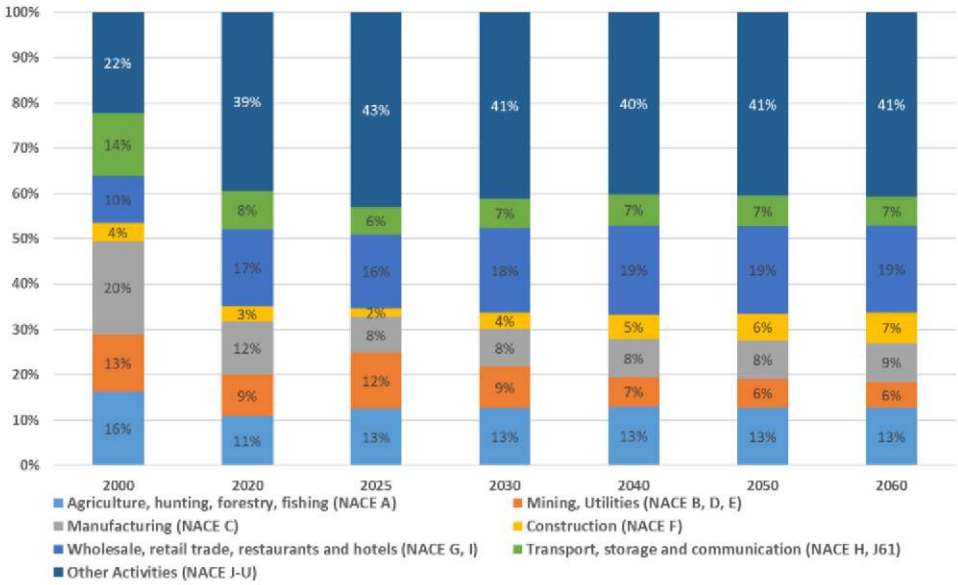

Figure A2. GDP by Sector, Base Recovery

The Base Recovery consider Services as the main economy driver. GVA structure shown on Figure A3.

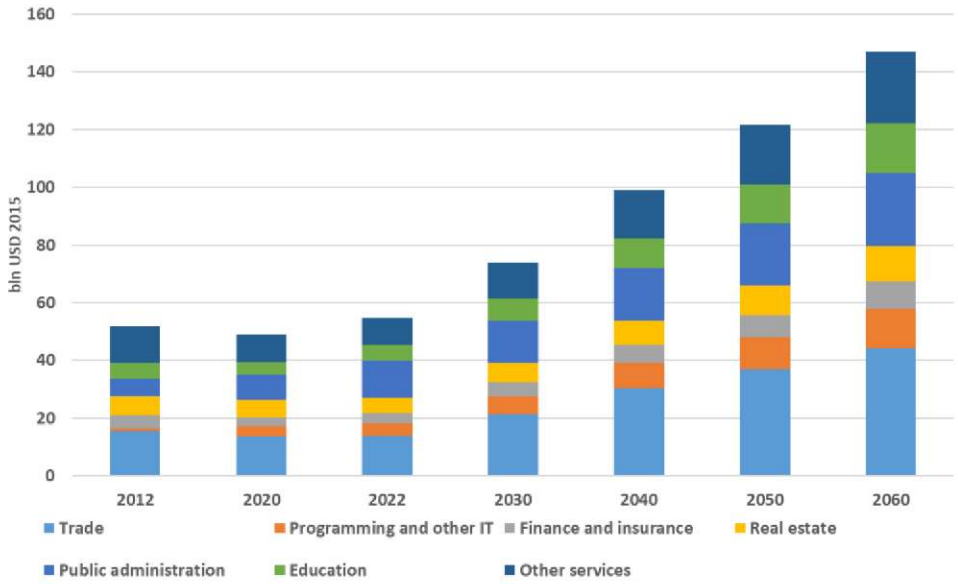

Figure A3. Dynamics of GVA in Services, Base recovery

It is assumed that 6.4% of residential and commercial buildings were destroyed in 2022. Moderate increase in household incomes will ensure the harmonization of household spending and results in a stable share of the Services in GDP. The largest growth among Services during 2023-2050 will be observed in Computer programming, Consultancy and related activities: these will grow in average 4% annually resulting in 3 times increase over the period and almost doubling if their share in GDP. Dynamics of GVA in Manufacturing is also shown on FigureA4.

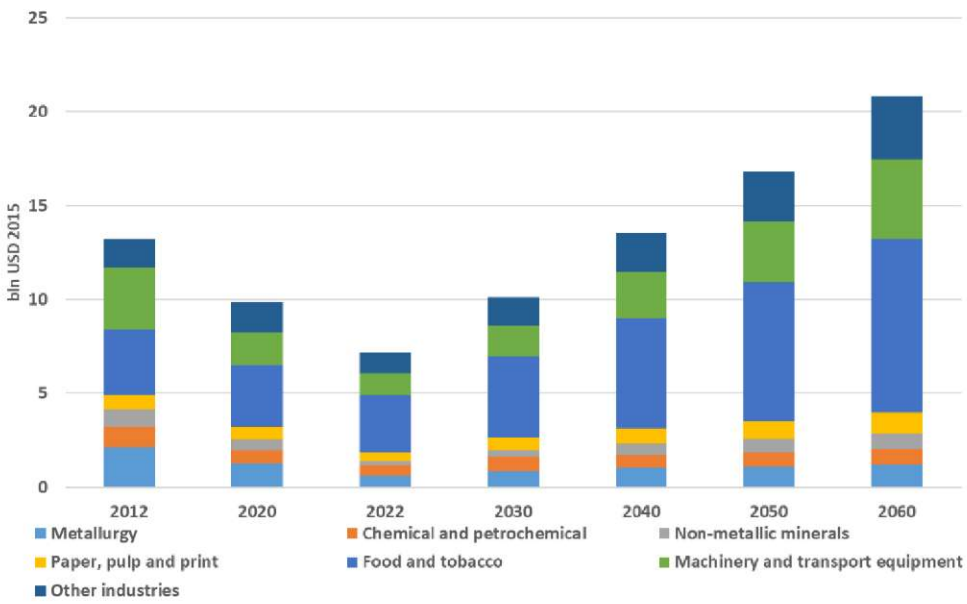

Figure A4. Dynamics of GVA in Manufacturing, Base recovery

As of May 23, 2023, 5.4 million refugees fled Ukraine and recorded across Europe, although 77% of them intend to return. War victims and internal migration are not counted, occupied territories are considered starting from 2025. Projection after 2025 is based on 2020 estimation of the Institute for Demography and Social Studies, NASU as follows: Medium fertility – Medium life expectancy – Medium net migration (e.g. positive migration after 2025 of 50-60 thousand annually); average age increases from 40.1 up to 45.6 years; average life expectancy increases to 68 years for men and 77 for women; share of working-age population drops to 47%. The figure and table below present the IDSS demographic projection based on above listed assumptions (Figure A5 and Table A6).

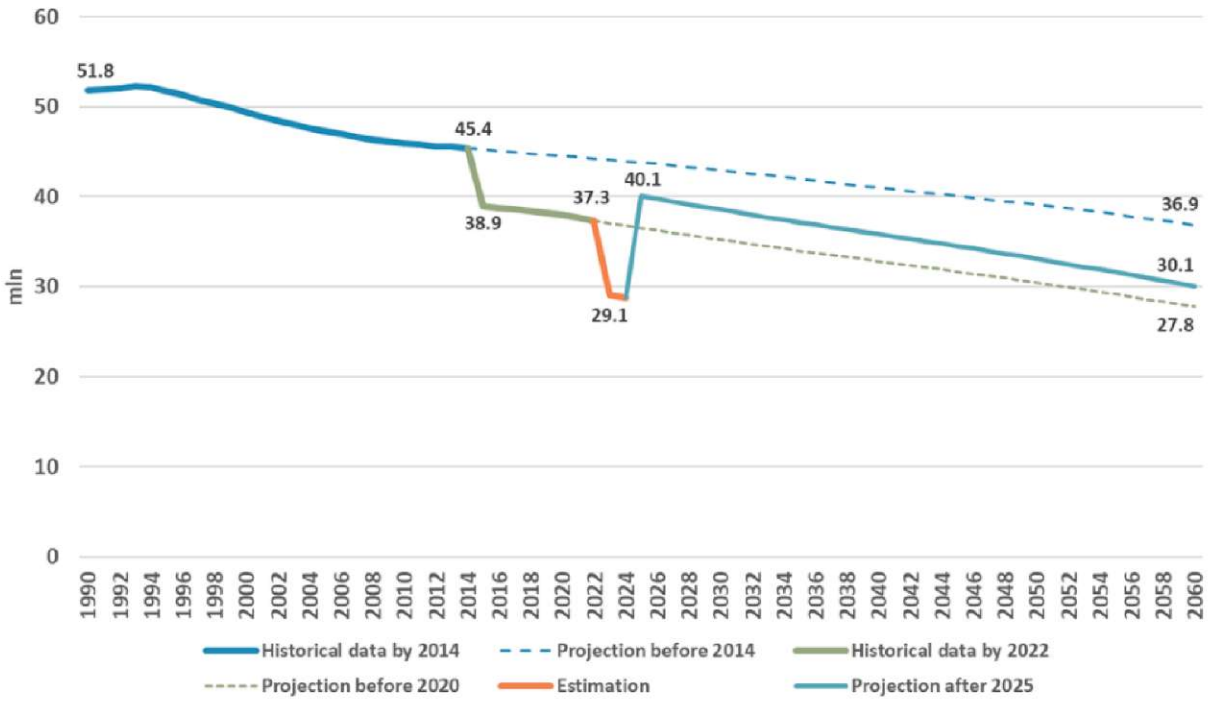

Figure A5. Projection of population in Ukraine, million

Table A6. Projection of population in Ukraine, million

	2020	2025	2030	2035	2040	2045	2050
Base recovery	38.0	40.1	38.6	37.2	35.8	34.5	33.1
Intensive recovery		40.4	39.7	39.2	39.0	39.0	39.0

Source: Institute of Demography and Social Studies NASU, IEF NASU

The forecast of energy prices for the main energy commodities for Ukraine until 2035 is based on the World Bank Commodities Price Forecast[6] and has been extended by 2050 with the IEA projection (World Energy Outlook 2021, Announced Pledges Scenario) (Table A7).

Table A7. Commodities Price Forecast

Commodity	Unit	2015	2020	2022	2023-2030	2031-2040	2041-2050
Coal, Europe	$/mt	60.2	61.4	250	106,7	63,3	58,3
Crude oil, avg	$/bbl	50.8	41.3	100	74,2	65,9	64,7
Natural gas, Europe	$/mmbtu	6.8	3.2	34	14,1	6,6	6,5

Source: World Bank, IEF UNAS

[6] https://thedocs.worldbank.org/en/doc/ff5bad98f52ffa2457136bbef5703ddb-0350012021/related/CMO-October-2021-forecasts.pdf

The short list of technologies used in the TIMES-Ukraine model

Technologies	*Overnight Capital Cost (CAPEX), €/ kWe*							*Efficiency (Electric), %*	*Availability factor, %*	*Lifetime, years*	*Heat Rate*
	2020	2025	2030	2035	2040	2045	2050				
Thermal Power Plants (TPPs) and Combined Heat and Power Plants (CHP)											
Nuclear											
New Large Units	4400							33	88	60	0.03
Extension of the operational life of existing units of NPPs	254							33	80	30	0.04
New small nuclear reactors (160 MW)	4400							32	90	80	0.04
Nuclear Very High Temperature reactor with Hydrogen production	7650-6885							33	94	60	0.1-0.12 (H2)
Gas											
Combined cycle TPPs	1000							60	50	35	0.15
Combustion turbine TPPs	600							40	50	30	0.15
Steam turbine TPPs	920							42	50	30	0.15
Fast Start Engine TPPs (only as balancing technologies)	1000							50	1.5	35	–
Combined Cycle + Carbon Capture and Storage TPPs	2450							51	50	35	0.05
Combustion turbine + Carbon Capture and Storage TPPs	2050							34	50	30	0.05
Combined cycle CHPs	800							50	50	35	0.84
Combustion turbine CHPs	920							45	50	35	0.95
Extension of the operational life of existing CHPs	280-650							19-43	50	15	1.1-3.0
Combined Cycle + Carbon Capture and Storage CHPs	2250							45	50	35	0.84
Coal											
Integrated gasification combined cycle (IGCC) TPPs	1800							46	50	35	0.15
Supercritical parameters TPPs	1300							43	50	40	0.15
Subcritical parameters TPPs	1600							39	50	35	0.15
Circulating Fluidized Bed TPPs	1700							43	50	35	0.15
Joint combustion of coal and biomass (subcritical parameters) TPPs	2050							33	50	35	0.15
Extension of the operational life of existing Coal TPPs	950							33-40	34-62	20	0.01-0.19
IGCC + Carbon Capture and Storage TPPs	4400							39	50	35	0.15
Supercritical + Carbon Capture and Storage TPPs	3900							37	50	35	0.15
Subcritical + Carbon Capture and Storage TPPs	4650							33	50	35	0.15
Circulating Fluidized Bed + Carbon Capture and Storage TPPs	4300							28	50	35	0.15
Combined cycle CHPs	1200							40	50	35	0.84
Combustion turbine CHPs	1100							35	50	35	0.90
Combined cycle+ Carbon Capture and Storage CHPs	2650							35	50	35	0.84

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Technologies	Overnight Capital Cost (CAPEX), €/ kWe							Efficiency (Electric), %	Availability factor, %	Lifetime, years	Heat Rate
	2020	2025	2030	2035	2040	2045	2050				
Bioenergy											
Wood biomass TPPs	2800	2750	2700	2650	2600	2550	2500	24	50	30	–
Biomass from waste TPPs	2900	2850	2800	2750	2700	2650	2600	23	50	30	0.3
Biogas TPPs	3200	3200	3200	3200	3200	3200	3200	42	50	30	–
Energy crops TPPs	2900	2850	2800	2750	2700	2650	2600	24	50	30	–
Wood biomass+ Carbon Capture and Storage TPPs	3650							24	50	30	–
Biogas + Carbon Capture and Storage TPPs	5350							42	50	30	–
Energy crops + Carbon Capture and Storage TPPs	3750							24	50	30	–
Wood biomass CHPs	3400	2850	2800	2750	2700	2650	2600	20	50	35	2.0
Biomass from industrial waste CHPs	3400	2950	2850	2850	2900	2750	2700	19	50	35	1.9
Biomass from municipal waste CHPs	5400	2950	2900	2850	2800	2750	2700	25	50	35	1.2
Energy crops CHPs	3400	3150	3100	3050	3000	2950	2900	20	50	35	2.0
Wood biomass + Carbon Capture and Storage CHPs	4450							20	50	35	1.5
Energy crops+ Carbon Capture and Storage CHPs	4450							20	50	35	1.5
Wind											
Onshore Wind Power Plants	1100	1075	1050	1000	950	900	850	–	32	30	–
Offshore Wind Power Plants	2120	1960	1800	1700	1680	1660	1640	–	42	30	–
Solar											
PV Plant size (without tracker)	750	725	700	630	560	510	475	–	12.5	25	–
PV Plant size (with tracker)	920	850	800	720	645	590	540	–	14.7	25	–
PV Roof panel	900	875	850	800	750	700	600	–	13.5	25	–
Geothermal											
Geothermal Power Plants	4300-3600							–	35-55	25	–
Hydro											
Small Hydro Power Plants	3250-3080							–	30	40	–
Large Hydro Power Plants	3300-3100							–	33-36	60	
Pump Storage	610							80	27	60	–
Storage technologies, EUR/kWh											
Electric Battery Storages	1042	832	622	508	394	324	255	92	33	10	–
Hydrogen Underground Storage Large	980	750	700	650	600	550	500	100	100	30	–
Hydrogen Tank Storage Large	4600	3600	3400	3200	3000	2800	2500	100	100	22	–
Hydrogen Tank Storage Small	2650	2075	1900	1800	1700	1600	1500	100	100	22	
Seasonal Heat Storage	2700	2600	2562	2434	2312	2197	2087	70	50	20	–
Fuel Cells (Hydrogen)											
Fuel Cells Power Plants	2530	1125	1125	844				50	85	10	–
Fuel Cells Combined Heat and Power Plants	2530	1125	1125	844				50	60	10	0.64
Heat plants											
Hard Coal District Heating Plant	600							40	50	35	–

Technologies	Overnight Capital Cost (CAPEX), €/ kWe							Efficiency (Electric), %	Availability factor, %	Lifetime, years	Heat Rate
	2020	2025	2030	2035	2040	2045	2050				
Anthracite District Heating Plant	600							40	50	35	–
Lignite District Heating Plant	700							40	50	35	–
Gas District Heating Plant (with availability of bio or synthetic methane)	300							71	50	40	–
Wood biomass District Heating Plant	145	142	140	138	136			64	50	35	–
Biomass from industrial waste District Heating Plant	350	320	300	280	270	260	250	62	50	35	–
Electric District Heating Plant	350							90	50	40	–
Air-sourced Heat Pump District Heating Plant	1100							250	50	25	–
Hydrogen District Heating Plant	390							64	50	35	–
Generic boilers											
Gas/Coal Generic industrial boiler plant (bio&synthetic methane ava-le)	59	59	58	58	57	56	56	90	60	40	–
Wood biomass Generic industrial boiler plant	145	142	140	138	136	134	134	83	60	40	–
Biomass from Industrial Waste Generic industrial boiler plant	270	260	250	240	230	220	220	80	60	40	–
Hydrogen Generic industrial boiler plant	145	142	140	138	136	134	134	81	60	35	–
CHP autoproduction											
Hard Coal CHP autoproduction	3600							3-15	15	35	2.7-18
Gas CHP autoproduction (with availability of bio or synthetic methane)	1080							3-15	15	35	4.4-20
Coke Oven Gas CHP autoproduction	1080							3-15	15	35	3.3-26.7
Blast Furnace Gas CHP autoproduction	1080							3-15	15	35	3.3-21
Heavy fuel oil CHP autoproduction	1080							3-15	15	35	20
Municipal Waste CHP autoproduction	2500							3-15	15	35	4-25
Industrial Waste CHP autoproduction	3500							3-15	15	35	12
Wood biomass CHP autoproduction	3500							3-15	15	35	14
Heat utilization and Separate boilers											
Generic Heat utilization	20							11-100	76-100	40	–
Separate steam boilers in Industry	500							81	1	40	–
Other technologies											
Chemical Absorption Direct Air Capture, electric	2.32	2.05	1.86	1.8	1.7	1.6	1.5	0.014-0.007 PJ/kt CO_2	90	25	–
Chemical Absorption Direct Air Capture, gas	2.32	2.05	1.86	1.8	1.7	1.6	1.5	0.014-0.007 PJ/kt CO_2	90	25	–
Methanation	600	500	450	400	350	300	250	75-83 (H2)	95	25	–
Hydrogen DRI production	360	355	350	345	340	333	324	17 PJ H2/Mt DRI	85	40	–

Technologies	*Overnight Capital Cost (CAPEX), €/ kWe*							*Efficiency (Electric), %*	*Availability factor, %*	*Lifetime, years*	*Heat Rate*
	2020	2025	2030	2035	2040	2045	2050				
Low carbon Iron ore concentrate production	96							64-75	1	30	–
Electrolyzer Alkaline, *€/ kW*	650	500	450	375	300	275	250	67-75	97	25-35	–
Electrolyzer PEM, *€/ kW*	925	800	650	550	450	425	400	58-71	97	20-30	–
Electrolyzer SOEC, *€/ kW*	4500	3200	1900	1620	1340	1060	780	77.5-83.5	91	10-20	–
Steam methane reforming Large	10.6							77	90	20	–
Steam methane reforming Small	22							69	80	20	–
Solar Methane Steam Reforming Large	9.8							120	90	20	–
Solar Methane Steam Reforming Small	27							60	90	20	–
Biomass Gasification to H2 Large			63.4	47.6				50	90	20	–
Biomass Gasification to H2 Small			111	95				33	71	20	–
Ethanol steam reforming	234							67	90	20	–