Post-war Development Energy Scenarios for Ukraine

Olha Lukash and Vasyl Namoniuk

Abstract The systemic shock provoked by the Russian invasion created a radical discontinuity in the national development policies of Ukraine. This research examines the state of energy policy and the consequences of the ongoing war on plausible decarbonisation scenarios. Ukraine's commitment to decarbonization was firmly established before 2022, and the National Energy Strategy 2050 already aimed at a substantial 65% reduction in emissions of the economy in comparison to 1990. The war however, precipitated the need to adjust these targets and policy instrument to the current realities. For that, we conducted quantitative research to identify the most GHG intensive regions and sectors and related these to their Gross Regional Product and population. We found out that Zaporizhzhia, Dnipropetrovsk and Ivano-Frankivsk turn out be the most critical regions that require special consideration—so for the later region, we also identify particular decarbonization pathways. Our research shows that the Ukrainian war not only unveiled the inherent vulnerabilities of heavily centralised, carbon-dependent systems, but also can lead to the acceleration of non-linear structural low-carbon energy transformations more resilient to global change and systemic interdependences.

Keywords Decarbonization · Energy decarbonisation · Renewables infrastructure · Ukraine · Systemic shocks and discontinuities · Reconstruction

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Abbreviations

BuTPS	Burshtyn Thermal Power Station
CHP	Cohesion heating plants
CLD	Causal loop diagram
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
GRP	Gross regional product
GVA	Gross value added
IBS	The Institute for Structural Research
IPS	Integrated power system
KSE	Kyiv School of Economics
NPP	Nuclear power plant
TPP	Thermal power plant
TPS	Thermal power station
UN	United Nations
USD	United States dollar
USSR	Union of Soviet Socialist Republics

1 Introduction

Ruined Kakhovka Hydroelectric Station (Dnipro River, Kherson Region, Ukraine). Photo by MAXAR

Decarbonization of economies through structural and technological changes has become a global priority to tackle climate change and its impacts. The 2015 Paris Agreement saw nearly all of the 197 countries that are party to the agreement commit to developing national plans and strategies to transition towards low-carbon economies and cut greenhouse gas emissions (The Paris Agreement, n.d.). Decarbonization is expected to bring major social, economic and environmental benefits—spurring growth in renewable energy and high-tech industries, improving public health through reduced pollution, and increasing access to green products and services markets (Climate change…, 2022).

Ukraine had made decarbonization a key priority before the 2022 Russian invasion. The country's economy remains heavily reliant on fossil fuels, with the energy sector accounting for nearly 70% of Ukraine's greenhouse gas emissions (Kudyrko et al., 2022). Ukraine adopted an Energy Strategy to 2035 in 2017 aimed at transitioning towards carbon neutrality through modernizing infrastructure, phasing out coal, expanding renewables like solar and wind, and increasing energy efficiency. The strategy set targets to reduce the energy intensity of Ukraine's GDP by 50% and greenhouse gas emissions by 65% by 2030 compared to 2005 levels (Ministry of Energy and Coal Industry of Ukraine, 2017).

The systemic shock from Russia's 2022 invasion of Ukraine created a radical discontinuity, disrupting structural conditions underlying the nation's decarbonization ambitions. Ukraine's commitment to sustainable transition was firmly established pre-war, with policies targeting substantial emissions cuts. However, this progress now faces severe reversal amidst humanitarian crises, infrastructure destruction, and economic collapse.

Rebuilding after such an immense systemic disruption provides potential tipping points to fundamentally transform Ukraine's legacy fossil fuel dependence. Strategic integration of climate considerations during recovery can steer structural changes towards resilience and sustainability.

This chapter examines Ukraine's pre-invasion decarbonization goals and progress. We assess the shock's disruptive impacts across the energy system and economy. Finally, we explore leveraging prospective tipping points during reconstruction to balance immediate needs with catalyzing green transformation aligned with global climate objectives.

Opportunities exist amidst the challenges to develop a new energy system that addresses urgent humanitarian and infrastructure priorities while accelerating Ukraine's stalled decarbonization. Realizing this will require seizing potential windows for non-linear change during the rebuilding process. Our study intends to provide recommendations on navigating trade-offs and actualizing tipping points to emerge from crisis with enhanced sustainability and self-reliance.

A growing body of research examines how systemic shocks can catalyze sustainability tipping points when harnessed strategically. Lenton et al. (2022) synthesize theory and examples to provide guidelines on creating conditions to enable positive tipping points across socio-technical-ecological systems. Multiple potential interventions and actors can contribute to triggering them.

Literature on social tipping dynamics elucidates how small perturbations unlock rapid change by overcoming incumbent interests (Otto et al., 2020). This highlights the need for socio-political perspectives when considering nonlinear transformations.

According to Herrfahrdt-Pähle et al. (2020), socio-political shocks may constitute windows of opportunity for transforming natural resource governance regimes, and Ukraine should take advantage of this opportunity regardless of the depth of the negative impact of other factors. The authors also argue that successful transformation depends on a number of interacting factors across levels, such as the state of preparedness of the social-ecological systems, the enabling environment as well as the degree of change at the landscape level, the prevalence of visionary leadership, and the capacity to navigate each phase of the transformation. And it's a crucial factor for post-war Ukrainian situation.

Besides, some researchers (Tàbara et al., 2021) underline that embracing transformative change towards green transformations may entail adopting more diversified, self-defined complex forms of collective sense-making processes based on project identities. Such tipping points overlap well with the peculiarities of Ukrainian regional development.

Work on transformative climate science indicates conventional assessment methods have limitations in spurring systemic shifts. Instead, solutions-oriented processes that link adaptation, mitigation and development are required (Tàbara et al., 2019). This demands new interfaces supporting societal engagement and ownership.

The green economy discourse envisions transformations towards sustainability underpinned by policy, finance, technology, and governance innovations (Dogaru, 2021). However, equitable distributional aspects remain paramount.

Synthesizing these perspectives indicates Ukraine's rebuilding necessitates strategic governance to leverage disruptions in catalyzing sustainability tipping points across multiple dimensions. Despite the challenges, this moment offers unprecedented opportunities not previously feasible within the entrenched system.

2 The Energy Sector of Ukraine on the Eve of the War

2.1 Generating Capacities of the IPS of Ukraine

Ukraine's economy is characterised by its high energy intensity,[1] ranking among the highest globally. This legacy of inefficient infrastructure poses challenges but also opportunities to catalyze sustainability tipping points during reconstruction. The reference point for Ukraine's high energy intensity is IEA international comparison

[1] Energy intensity refers to the amount of energy consumed per unit of economic output, calculated as units of energy per unit of GDP. A high level of energy intensity indicates an economy is using energy inefficiently.

data (Ukraine energy profile, 2020). In 2019, Ukraine's energy intensity was 0.15 toe/thousand 2010 USD, over twice as high as Poland (0.07) or Germany (0.05). This means Ukraine consumed over twice as much energy for each unit of economic output compared to these European nations. This high energy intensity is attributable to factors such as Ukraine's industrial structure. Although some countries like Canada also exhibit high energy intensity, Ukraine's exceptionally low energy efficiency significantly contributes to its energy profile. Many industrial processes depend on outdated technologies, and energy efficiency in buildings is generally suboptimal. Equipment, including heating boilers, is antiquated and poorly maintained, restricting opportunities to enhance energy efficiency. Consequently, firms and individuals face substantial obstacles in making profitable energy-efficiency investments. The absence of affordable financing options and limited incentives due to historically regulated household energy prices exacerbate the situation, along with logistical and organisational issues for apartment building residents.

As of February 2022, Ukraine had extensive energy infrastructure and production capacity, positioning it among European leaders. However, the reliance on Russian gas imports vulnerable Ukraine's energy security. Accelerating renewables and efficiency represents a resilience tipping point. Specifically, Ukraine ranked in the top ten European nations in terms of installed electricity generation capacity, with a total of 55 gigawatts (GW) (Eurostat, 2022). The country was also one of Europe's largest natural gas producers, extracting over 20 billion cubic meters annually (Ukrainian energy …, 2022). Additionally, Ukraine possessed Europe's largest underground gas storage capacity, with around 31 billion cubic meters of storage spread across several facilities (Ukrainian energy …, 2022). This extensive infrastructure and Ukraine's role as a major producer and transit country for Russian gas gave it a strategically important position in Europe's energy system.

Ukraine's sophisticated and reliable gas, oil, petroleum product transportation, and electricity transmission systems connect the country with neighbouring EU nations and Moldova. Notably, around 70% of Ukraine's electricity was from low-carbon nuclear, hydro and renewables (Fig. 1). This is a strong foundation to build upon. Setting ambitious targets to expand renewables could act as a decarbonization tipping point.

As of December 31, 2021, the total installed capacity of power plants in the IPS of Ukraine, excluding the Crimean power system and the temporarily uncontrolled territory of the Donetsk and Luhansk regions, amounted to 56.247 GW. Thermal power plants (TPP), Cohesion heating plants (CHPs), and block stations accounted for 49.7% of the installed capacity, followed by nuclear power plants at 24.6%, hydroelectric power plants and pumped storage power plants at 11.2%, and renewable energy sources, such as wind farms, solar power plants, and bioenergy plants, at 14.5%.

Thus, phasing out coal reliance, while socially challenging, presents a major emissions reduction opportunity. Structural transitions to provide new economic opportunities in affected regions could make coal phase-out viable as a prospective tipping point.

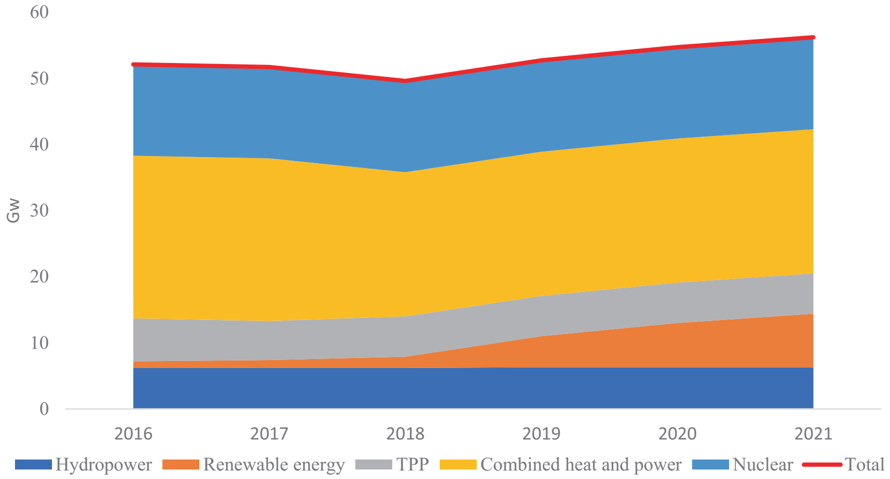

Fig. 1 Energy mix of Ukraine (Omelchenko, 2022)

2.2 *Russia-Ukraine War*

The Russian invasion severely disrupted Ukraine's legacy fossil fuel-dependent energy system. This jarring systemic shock provides opportunity to rebuild in a more sustainable manner, rather than reproducing outdated technologies and practices. Energy infrastructure facilities hold economic, humanitarian, and geopolitical significance, making them frequent targets of Russian aggression. Despite this, Ukraine's power grid has demonstrated remarkable resilience, with power engineers maintaining the stable operation of the industry during the hostilities. However, hostilities have destroyed 4% of the generating capacity, and an additional 35% of capacity is now situated in occupied territories.

The Russian invasion inflicted substantial damage to Ukraine's energy infrastructure, disrupting the nation's climate plans and exposing the vulnerabilities of its heavily fossil fuel-dependent power and industrial sectors. Ukraine's pre-war emissions landscape was characterized by a reliance on fossil fuels in power generation and heavy industry. Progress made toward decarbonization objectives was undermined by the war, as industrial activity declined due to the conflict, while emissions surged due to fires and ecosystem degradation. In the wake of the devastation, there emerges a critical juncture for Ukraine's energy future. Reconstruction offers a unique opportunity to rebuild in a more sustainable and resilient manner, emphasizing the importance of reaching tipping points in energy policy. However, this endeavour necessitates a delicate balance between addressing immediate energy security concerns and realizing long-term climate objectives. Proposed strategies to restart stalled sustainability momentum represent prospective tipping points. Expanding renewables, enhancing efficiency, integrating with EU grids and regulations, and securing external climate financing could drive transformation. Realizing

Ukraine's interconnectedness with European energy systems spotlights shared decarbonization tipping points. Collaboration and shared standards can multiply progress regionally.

Europe's largest nuclear power plant, the Zaporizhzhia NPP, operates within the Ukrainian power system and faces constant pressure from Russian occupiers. The plant has a production capacity of 6000 MW, equivalent to 43% of the total capacity of all Ukrainian nuclear power plants. Gas production has decreased by 10–12% since the full-scale invasion.

The KSE assessment (Report on the direct damage to the infrastructure from the destruction caused by Russia's military aggression against Ukraine a year after the start of the full-scale invasion, 2023) estimates the damages to Ukraine's energy sector at a minimum of $9.5 billion, including $8.1 billion in the energy sector and $1.4 billion in utility infrastructure (including district heating, water supply and drainage, and household waste management facilities).

According to the World Bank's Rapid Damage and Needs Assessment (2023), the damage to Ukraine's energy sector is estimated at $10.6 billion, including $6.5 billion in the power sector alone. The total needs for recovery and reconstruction of the energy sector are estimated at $47 billion.

It is worth noting that the actual damages and losses are likely to be higher, as complete information on Ukrainian facilities in the temporarily occupied territories is unavailable, and there is no publicly accessible information on the detailed damages inflicted on the country's energy infrastructure facilities.

The war has significantly affected energy demand, resulting in a substantial decrease of approximately 30–35% compared to the previous year's consumption. Additionally, the relocation of consumers to the western regions has led to a considerable shift in the consumption profile.

Presently, the annual electricity consumption by the population stands at around 32–33 billion kWh, marking a significant drop from the pre-invasion level of 38.6 billion kWh. Likewise, industrial consumption has experienced a considerable decline, dropping from fifty billion to approximately thirty-six billion kilowatt-hours.

Before the full-scale war, there were a lot of discussions about decarbonisation as a necessity in Ukraine. For example, the energy sector was the largest greenhouse gas emission before the war. It took two-thirds of these emissions in the whole volume. But after more than 1 year of severe war in Ukraine, the emissions volume from economic activity has significantly decreased. The main reasons for this are the outflow of the population, the destruction of industry, the closure of many enterprises, and so on. The occupation of Mariupol and the destruction of large metallurgical and other enterprises located in the Donetsk and Luhansk regions also significantly affected the change in the balance of greenhouse gas emissions in Ukraine. But at the same time, the number of emissions related to war is constantly increasing. Many burned oil depots, destroyed forests, fires, constant shelling, and bombing resulted in enormous environmental damage and emissions, the extent of which was even difficult to imagine until now. So, we face such negative balancing when emissions are increasing and decreasing parallel, and they both are the result of the war. According to Ministry of Environment data, Russia has already caused damage to the Ukrainian environment of 1373 billion hryvnias. Some ecosystems have been completely lost due to Russian aggression (Fig. 2).

During the war, many enterprises and infrastructure of cities and regions of Ukraine were destroyed or significantly damaged. And these destructions do not stop. Already now, it is necessary to start developing possible strategies for their renewal. But under these conditions, there may be several possible solutions. And it's important to look at all of them and analyse them from a carbon intensity perspective. In the process of reconstruction and restoration, the construction of roads, bridges, infrastructure, factories, and housing will take place. And this will also lead to a significant amount of greenhouse gas emissions. But there may be several options: to rebuild them, try to save everything that survived or create everything from zero. It is also clear that soon, Ukraine will try to maintain what it has—the infrastructure that remains in the energy sector, the remains of coal or gas-fired thermal power plants because there is nothing else yet. And it is also clear that essential investments are needed for any option of renovation, which could hardly be attractive in modern conditions of uncertainty.

The ongoing war on the territory of Ukraine has caused great damage to the economy and ecology of Ukraine. There is also a risk that Ukraine will not fulfil the already set climate goals, because the war is a contribution to climate change, and the recovery of the country will inevitably be accompanied by significant emissions of greenhouse gases. The lack of proper energy-efficient consumption, for example, or the failure to use the existing potential for the development and accumulation of renewable energy sources makes it impossible to compensate for the necessary "green effect" regarding the implementation of the Green Deal directives. It is important to have a plan for the reconstruction of the country now, long-term and

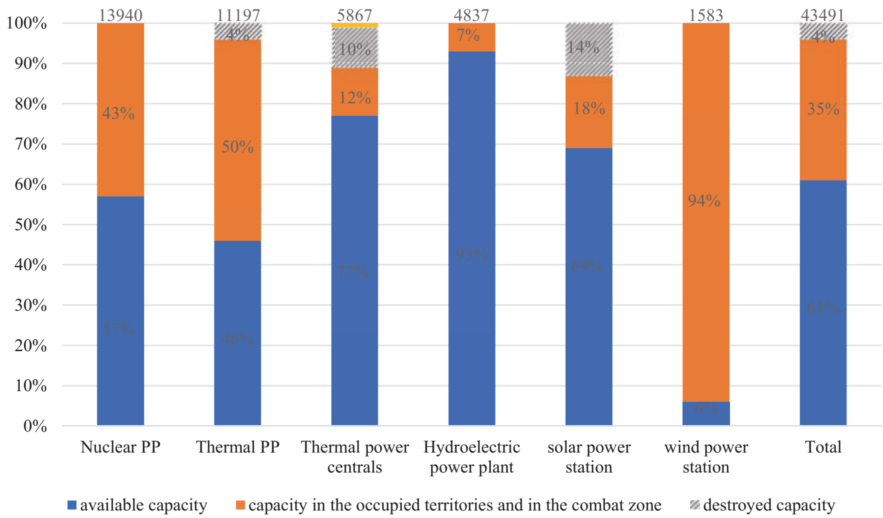

Fig. 2 Distribution of power generation facilities (Omelchenko, 2022)

high-quality solutions are needed that will ensure a balance between benefits for the economy, the environment, and society.

It is also worth focusing on the development of safer and more decentralized renewable energy. Nuclear and coal power is dangerous for the environment even in peacetime. The oil and gas sectors are also extremely vulnerable to several crisis phenomena (geopolitical, climatic, etc.) and are not a permanent solution for the recovery of Ukraine. Therefore, the reconstruction of the energy sector should focus on renewable energy sources that cause much less damage to the environment and people. Such a transition should be accompanied by an increase in energy efficiency and a fair transformation of regions dependent on traditional energy (How…, n.d.).

This infrastructure damage and disruption of the coal industry has led to significant declines in greenhouse gas emissions from the energy sector. With lower industrial output and coal use, Ukraine's CO_2 emissions dropped sharply in 2022 compared to pre-war levels. However, military activities have also caused substantial emissions through fires, combustion of fuels, damage to carbon-absorbing forests and lands, etc. Studies estimate the Russian invasion released over 67 million tons of CO_2 equivalent as of June 2022 (Bohdan, 2023).

Rebuilding damaged infrastructure once the war ends will necessitate increased emissions in the short term. But Ukraine also has opportunities to rebuild more sustainably and get back on track towards its decarbonization objectives. Seizing these tipping point opportunities requires assessing both the retrogression and possibilities created by war impacts. This analysis examines that tension.

2.3 Current Environmental and Energy Issues and Decarbonization in Ukraine

Ukraine's development trajectory over the past century has been intricately tied to environmental factors as part of the wider European region. Industrialization and economic growth have come at the expense of resource depletion, pollution, and rising carbon emissions. Addressing these environmental impacts while achieving sustainable growth will require economy-wide decarbonization. This transition brings immense challenges but also opportunities to modernize Ukraine's energy systems, attract investment, reduce imported fuel dependence, and increase integration with the European Union.

Major environmental challenges in Ukraine stem from several key factors:

– Unsustainable resource consumption practices including industrial deforestation, uncontrolled mining, and overexploitation of soils and fisheries. These practices supported heavy industrialization but with ecological consequences.
– Widespread industrial pollution across sectors like coal power, steelmaking, chemicals, and manufacturing. Lax pollution standards have led to severe air, water and soil contamination.

– Impacts of military conflict, especially the 2022 Russian invasion, which caused substantial ecosystem damage, industrial infrastructure destruction, landfill ruptures, and chemical/oil contamination.
– Insufficient waste management and regulatory oversight including uncontained municipal waste dumping and limited enforcement of environmental rules.
– Growing transportation emissions as private car ownership has risen without accompanying efficiency standards or electrification policies.
– Dependence on fossil fuel exports at the cost of domestic environmental health, as seen around sites like the Donbas coal mines.
– Overall lack of mainstreaming of environmental considerations into economic planning and behaviour, although awareness has expanded since independence.

Ukraine has taken steps to improve environmental policies since the 1990s, including developing standards aligned with the EU, promoting renewables, and reforming governance systems. However, the deeply entrenched legacy effects of unsustainable Soviet industrialization continue to pose major decarbonization challenges.

The energy sector is crucial for the decarbonisation of the Ukrainian economy. It accounts for two-thirds of greenhouse gas (GHG) emissions in Ukraine. Consequently, addressing this sector is vital for achieving meaningful progress in mitigating climate change and promoting green development in Ukraine after the war.

The energy sector contributes the most to GHG emissions in Ukraine. In 2021, this sector constituted approximately 64% of the emissions, excluding the Land Use, Land Use Change, and Forestry (LULUCF) sector. Around 76% of emissions in this sector are attributed to fuel combustion, which includes energy industries, manufacturing industries and construction, transport, other sectors, and other categories. Additionally, 24% of emissions are due to fugitive emissions from fuels.

The share of GHG emissions from fugitive emissions in the energy sector gradually increased from 1990 to 2000, reflecting the ageing infrastructure and industrial capital of the country. Since 2001, this proportion has steadily declined, reaching 24.0% in 2021 due to energy efficiency measures and the replacement of energy sources implemented in Ukraine.

The COVID-19 pandemic and subsequent measures against the disease decreased GHG emissions in the energy sector in 2020, particularly affecting energy industries, transport, and other sectors. The economic decline following the collapse of the USSR in 1991 resulted in a reduction in production, energy consumption, and, consequently, lower CO_2 emissions.

To foster sustainability, efficiency, and security, the reconstruction and modernisation of the Ukrainian energy system must adhere to EU standards. Adopting EU standards will provide a framework for creating a modernised and sustainable energy system in Ukraine, ensuring compatibility with European energy markets and enabling the country to benefit from regional energy trade.

There is a need for a green transformation of the Ukrainian electricity sector to align with international climate goals and European energy policies. By seizing the opportunity to rebuild and modernise its energy infrastructure, Ukraine can embark on a more sustainable and resilient energy system, better integrated with European markets and contributing to a greener future.

Ukraine's 2017 Energy Strategy established important tipping points for decarbonization across eight key pillars. The strategy's targets and policies aimed to transition Ukraine's energy system towards greater sustainability through 2050. However, Russia's invasion has severely impeded progress towards these envisioned tipping points. This comprehensive strategy delineates key policies and targets for transitioning towards greater energy sustainability through 2050. The plan aims to balance energy security and affordability with environmental goals while increasing self-sufficiency and aligning Ukraine's energy system with European markets.

The strategy identifies eight key pillars for energy sector transformation (Ukraine Energy Strategy, 2050):

- Modernizing energy infrastructure including thermal power plants, hydropower stations, nuclear generators, transmission grids, district heating systems and storage capabilities
- Expanding use of renewable energy sources such as solar, wind, small hydropower and bioenergy
- Substantially increasing energy efficiency and conservation across all sectors of the economy
- Reducing coal-fired power generation share by increasing nuclear, natural gas and renewables
- Boosting domestic oil and natural gas production from both conventional and unconventional sources
- Integrating Ukraine's energy markets with the European Union to increase trade and transparency
- Developing and expanding nuclear power generation as a zero-carbon baseload electricity supply
- Supporting alternative energy technologies including hydrogen, electrification, smart grids and distributed generation

Under this strategy, Ukraine set a target to reduce greenhouse gas emissions by 65% compared to 1990 levels by 2030. Multiple analyses indicate this goal is achievable through concerted efforts across the above decarbonization pathways. Key policies and measures to achieve this target include (Ukraine Energy Strategy, 2050):

- Increasing the renewable energy share in gross power generation to 25% by 2035 through large-scale deployment of solar, wind, small hydro and bioenergy
- Refurbishing and expanding hydroelectric power stations
- Continuing nuclear capacity additions and lifetime extensions to retain a 55% nuclear share in power generation through 2050
- Implementing demand-side energy efficiency improvements in buildings, district heating and industry
- Modernizing electricity transmission infrastructure and adopting smart grid technologies

- Electrifying rail-based transport networks
- Substituting natural gas for coal in thermal power plants
- Improving efficiency and reducing losses in gas production and distribution systems
- Developing onshore and offshore conventional and unconventional natural gas resources
- Implementing carbon capture on industrial facilities and gradually phasing out obsolete methane-intensive mines
- Expanding biofuel blending mandates to help decarbonize transport
- Impact of the 2022 Russian Invasion

While prudent when formulated, the realities imposed by the war now require re-evaluating timelines and approaches for reaching these tipping points. As Ukraine rebuilds, it must update strategies to seize new potential tipping points that can drive momentum towards a decarbonized and European-integrated energy system despite the ongoing conflict.

However, rebuilding after the war also provides an opportunity to construct back better. Ukraine can pursue more sustainable and resilient reconstruction strategies that restore self-sufficiency and prosperity while meeting climate goals. This will require substantial international support. Key principles for green reconstruction include:

- Prioritizing renewable energy systems and decentralized power generation to enhance self-reliance and minimize reliance on imported fossil fuels
- Building flexibility into new energy, transportation, water and waste management systems to improve climate adaptation and disaster resilience
- Leveraging reconstruction financing to implement clean technologies, electrification, smart grids, and efficiency upgrades
- Tightening environmental regulations on rebuilt infrastructure and restricting unsustainable resource extraction
- Mainstreaming sustainability and low-carbon development into national, regional and local planning
- Capacitating Ukrainian workers and institutions on green technologies and climate-aligned practices
- Collaborating with EU partners to align rebuilt infrastructure and governance frameworks with European sustainability standards
- Integrating climate resilience and risk reduction into new public service provision including healthcare facilities and affordable housing

Achieving deep decarbonization in Ukraine entails overcoming substantial environmental legacy challenges while also navigating the new obstacles imposed by conflict. But with prudent policies, external assistance, and integration of climate aims into recovery efforts, a transition to resilient and sustainable development is attainable. Ukraine established strong climate strategies pre-war, demonstrating rising ambition. Once humanitarian needs are met, Ukraine must leverage reconstruction to reach tipping points for a sustainable transition. The stalled green agenda underscored energy-climate-security connections. Strategically seizing this realization as a tipping point could catalyze climate action amid rebuilding. With diligent policies, recovery can set course for a decarbonized, resilient future.

2.4 Methods

This analysis utilizes a quantitative emissions data assessment to identify potential decarbonization tipping points by region and sector. Carbon dioxide emissions data from stationary sources was compiled from Ukraine's State Statistics Service for 2017–2021 (Tables 1 and 2). This established national totals and breakdowns by economic activity. Additionally, industry development metrics were collected on Gross Regional Product and sectoral contributions for the top five emitting regions (Tables 3 and 4). Leveraging this dataset, a benchmarking analysis was conducted. Emissions were recalculated on a per capita and per GDP basis for the priority regions (Tables 5 and 6).

This multi-dimensional perspective aimed to reveal areas of disproportionate impact beyond absolute totals. The goal was elucidating where targeted interventions could induce sustainability tipping points. This quantification of priority sectors and regions provides an analytical foundation. It enables developing tailored policies and strategies to restart stalled decarbonization momentum through reconstruction tipping points.

The integrated data assessment offers robust evidence-based identification of decarbonization priorities. This can inform strategic rebuilding aligned with climate objectives.

Table 1 Carbon dioxide emissions from stational pollution sources by regions (top five regions), thsd. t

Region	2017	2018	2019	2020	2021
Donetsk	22,879.8	25,143.4	23,528.1	22,258.3	22,699.5
Dnipropetrovsk	26,072.6	23,620.7	23,496.6	20,474.8	22,321.8
Zaporizhzhya	14,047.4	14,614.1	13,663.3	12,979.6	12,935.8
Ivano-Frankivsk	11,965.1	13,763.2	12,898.9	10,207.1	12,067.1
Kharkiv	5765.5	7281.4	7595.8	7789.6	6173.3
Ukraine	**124,217.9**	**126,378.3**	**121,282.9**	**109,079.4**	**111,854.2**

Based on Carbon… (2023)

Table 2 Quantity of carbon dioxide emissions in Ukraine from stational pollution sources by types of economic activity, thsd. t

Type of economic activity	2017	2018	2019	2020	2021
A—Agriculture, forestry and fisheries	1099.8	1174.0	1162.2	1187.5	1461.7
B—Mining and quarrying	3365.2	3892.2	3105.0	2119.7	2448.9
C—Manufacturing	49,085.4	47,877.4	48,782.3	46,868.1	51,132.4
D—Electricity, gas, steam and air conditioning supply	63,865.2	68,464.0	63,274.0	56,262.1	51,997.5
F—Construction	52.8	57.0	38.0	48.9	67.3
G—Wholesale and retail trade	110.5	88.4	76.4	68.6	159.0
H—Transportation and storage	4393.3	3749.2	3703.9	1588.6	1687.2
Selected activity (A+B+C+D+F+G+H)	*121,972.2*	*125,302.2*	*120,141.8*	*108,143.6*	*108,954.1*
Ukraine (total)	**124,217.9**	**126,378.3**	**121,282.9**	**109,079.4**	**111,854.2**

Based on Air… (2023)

Table 3 Gross regional product (for selected five regions), mln. USD

Region	2017	2018	2019	2020	2021
Donetsk	6239	7065	7928	7653	10,383
Dnipropetrovsk	11,788	13,579	15,102	14,791	21,343
Zaporizhzhya	4895	5406	6003	6205	8389
Ivano-Frankivsk	2399	2884	3354	3353	4386
Kharkiv	7040	8576	9580	9563	11,720
Ukraine (GDP)	**112,091**	**130,891**	**153,883**	**156,618**	**199,766**

Based on Gross… (2022)

2.5 Basic Conditions for Analysis

For our research, we focused on basic data about carbon dioxide emissions (Tables 1 and 2) and industry development level (Tables 3 and 4) for the period 2017–2021 (Lukash & Nikulina, 2023).

The abovementioned data reflects the current state of issue carbon dioxide emissions and industry development level for five chosen regions chosen by the highest level of carbon dioxide emissions from stational pollution sources. Further, we will use these official data for in-depth analysis.

3 Results and Discussions

3.1 Pre-war Situation

In the first stage of decarbonization analyses, we suggest an overview of the current situation with carbon dioxide emissions (for 2017–2021) from stational pollution sources as one of the most significant problems for Ukraine. Firstly, this analysis

Table 4 The share of GVA by types of economic activity in the total amount of regional GVA in 2021 (for selected 5 regions), %

Region	A	B	C	D	F	G	H
Donetsk	8	28	15	3	3	10	5
Dnipropetrovsk	8	22	24	4	2	8	3
Zaporizhzhya	13	5	26	10	1	11	4
Ivano-Frankivsk	13	6	15	6	4	9	8
Kharkiv	11	8	12	3	3	15	5
Ukraine	**13**	**8**	**12**	**4**	**3**	**16**	**6**

A, agriculture, forestry and fisheries; B, mining and quarrying; C, manufacturing; D, electricity, gas, steam and air conditioning supply; F, construction; G, wholesale and retail trade; H, transportation and storage
Based on Regional… (2023)

Table 5 Carbon dioxide emissions from stational pollution sources by regions (top five regions), per capita (t/person)

Region	2017	2018	2019	2020	2021
Donetsk	5.4	6.0	5.7	5.4	5.6
Dnipropetrovsk	8.1	7.3	7.4	6.5	7.2
Zaporizhzhya	8.1	8.5	8.1	7.7	7.8
Ivano-Frankivsk	*8.7*	*10.0*	*9.4*	*7.5*	*8.9*
Kharkiv	2.1	2.7	2.8	2.9	2.4
Ukraine	**2.9**	**3.0**	**2.9**	**2.6**	**2.7**

can help us find weaknesses and the most problematic Ukrainian regions in the sense of high carbon dioxide emissions in relative measurement (per capita and GRP). Secondly, based on this analysis, we can develop a target policy for decarbonization. In the first stage, based on official statistical information, we choose the top five Ukrainian regions by carbon dioxide emissions (Table 1) (Carbon…, 2023). These regions (Donetsk, Dnipropetrovsk, Zaporizhzhya. Ivano-Frankivsk, and Kharkiv regions) in total cover 68.1% of carbon dioxide emissions in Ukraine in 2021. But the main task for us is not only to find the most significant carbon dioxide pollution sources but to identify regions where such emissions cause the highest social and economic issues.

For this purpose, we recalculated carbon dioxide emissions on two variants: per capita for selected regions (Table 5) and compared with Gross Reginal Product (GRP) (Table 6). Both calculations based on (Gross …, 2022; Population…, 2022) clarified the regional situation in more detail and significantly changed the ranking of the top five most problematical regions.

This multi-dimensional analysis elucidated priority decarbonization zones based on holistic environmental, social (Table 4), and economic (Table 5) considerations. The aggregated results definitively spotlight Ivano-Frankivsk Oblast as the highest leverage region for interventions that can catalyze sustainability tipping points.

Indexed analysis of emissions trajectories over the examined period indicates substantive intensity reductions. On a per capita and per unit GDP basis, all focus

Table 6 Carbon dioxide emissions from stational pollution sources by regions (top five regions), t / 1 mln USD GRP

Region	2017	2018	2019	2020	2021	2021/2017
Donetsk	3667.3	3559.1	2967.9	2908.4	2186.1	**–40.4%**
Dnipropetrovsk	2211.7	1739.5	1555.8	1384.3	1045.9	**–52.7%**
Zaporizhzhya	2869.8	2703.4	2276.0	2091.9	1542.0	**–46.3%**
Ivano-Frankivsk	*4987.2*	*4772.7*	*3846.1*	*3043.9*	*2751.2*	***–44.8%***
Kharkiv	819.0	849.0	792.9	814.5	526.7	**–35.7%**
Ukraine	**1108.2**	**965.5**	**788.1**	**696.5**	**559.9**	**–49.5%**

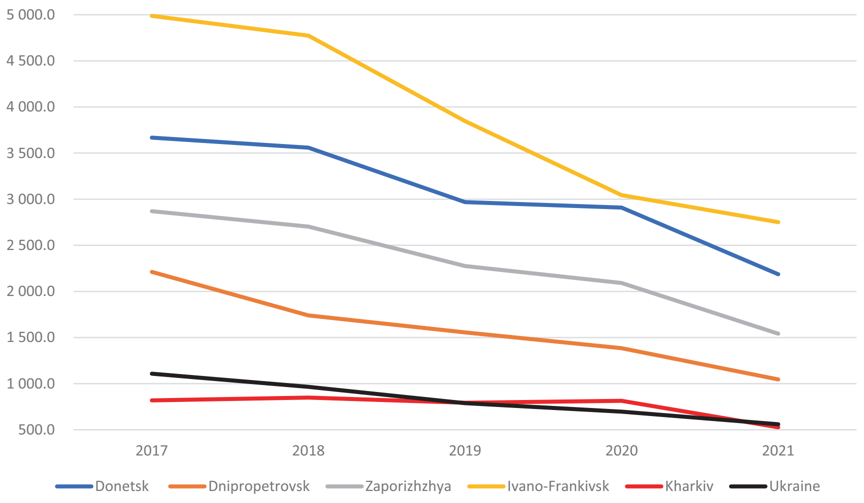

Fig. 3 Carbon dioxide emissions from stational pollution sources by regions (top five regions), t/1 mln USD GRP (Lukash & Nikulina, 2023)

oblasts exhibited downward emissions trends, signifying economy-wide decoupling of pollutive externalities from growth. Almost a 50% decrease for all Ukrainian regions and an even higher reduction for some of them (Dnipropetrovsk region) during the last 5 years, see Fig. 3. This momentum provides a strategic platform to launch targeted policies that can induce tipping points across both legacy and emerging industries.

A pivotal research inquiry is delineating high-impact decarbonization pathways for the Ivano-Frankivsk region. This region constitutes a priority area based on disproportionate emissions contributions relative to economic and demographic factors. The predominant source of Ivano-Frankivsk's elevated emissions profile is the lignite-fired Burshtyn Power Plant. This facility not only ranks among the most carbon-intensive generators in Western Ukraine, but exerts outsized environmental externalities nationally.

Targeted interventions centered on Burshtyn could catalyze a regional tipping point with national ramifications. Retiring a share of its capacity in favor of renewable energy installations, while providing transition assistance for affected workers, could spur momentum. Moreover, complementary strategies like distributed solar and wind, efficiency upgrades, and electrified transport can compound sustainability benefits. If underpinned by appropriate finance and policy frameworks, Ivano-Frankivsk could pioneer decentralized low-carbon development, creating demonstration effects to accelerate national progress.

BuTPS generation is very important for the entire region. The installed electrical capacity is 2400 MW (this is the second-largest TPS in Ukraine). BuTPS is the basis of the Burshtyn Energy Island (part of the energy system of Ukraine, on which BuTPS electrical networks are located, together with the adjacent power grid and its electricity consumers within Transcarpathian and partially Ivano-Frankivsk and Lviv regions). Unlike the rest of Ukraine's power grids, the Burshtyn Energy Island was connected to the power grids of EU countries and allowed to export Ukrainian electricity abroad since July 1, 2002. On February 26, 2022, it was connected to the Ukrainian energy system. On March 16, 2022, Ukraine joined ENTSO-E and the Burshtyn Energy Island ceased to exist.

The main technological fuel of BuTPS is coal, and the auxiliary fuel is natural gas and fuel oil. For the BuTPS, the problem of storage and processing of solid waste—fuel slag and ash—which remains after burning coal in the furnaces of the BuTPS is extremely relevant.

As of the beginning of 2022, the BuTPS was producing about 1000 MW. The share of BuTPS in the industry of the local region exceeds 20% (by revenue in 2021). About 2500 employees work at the enterprise. The station covers domestic consumption (where approximately three million people live) and transfers up to 645 MW of energy for export.

Reduction of emissions is possible due to the replacement of BuTPS capacities, but this is a rather difficult issue. There are several main reasons for this:

1. The relatively low current cost of generation, which makes the export of BuTPS electricity very attractive
2. A sufficiently large number of workers who will not be able to find alternative jobs in such a small region
3. The difficulty of introducing alternative generation into the outdated energy supply system, which will require significant investment and time

3.2 *Ukrainian Energy Strategy: Actual Challenges and Issues During Wartime and After*

Modernization and decentralization represent prospective tipping points to transform Ukraine's energy system beyond merely rebuilding the legacy fossil fuel dependence. The scale of reconstruction also enables non-linear expansions of renewables, efficiency improvements, and interconnections with the EU grid that can catalyze decarbonization. These goals are planned to be achieved through the development of modern and safe nuclear generation, renewable energy sources, and the modernization and automation of transmission and distribution systems. According to the developed strategy, by 2050, the energy sector should be as close as possible to climate neutrality, which means the availability of clean energy, overcoming energy poverty, development of an innovative and decentralized energy system, the full functioning of national energy markets and their integration into international ones (Energy…, 2023).

Ukraine's energy system suffered significant damage and destruction because of military operations. And now it needs restoration. But this reconstruction will not be done only through repairs; it will include modernization. Increased deployment of distributed energy resources and smart grids constitutes a pivotal tipping point for flexibility and resilience. Transitioning towards decentralized renewable energy can dramatically improve Ukraine's self-sufficiency. It is planned to introduce energy storage facilities that accumulate it. One of the essential elements of decentralisation should be encouraging Ukrainians to install solar panels and individual energy storage installations. The use of microgrids and smart grid technology is also expected. This should provide better control of the load on the power system and respond more effectively to modern challenges. The third direction of the Strategy is the continuation of the integration of the Ukrainian energy system with the European one. Of course, the Ukrainian energy system is already a part of the European one, but certain actions still need to be completed before full integration. These actions include the implementation of EU directives, the development of market mechanisms that would ensure a transparent and fair approach, as well as the increase of physical opportunities for the export and import of electricity with EU countries. Ukraine has enormous potential in this area, and the Ukrainian government believes that energy will be one of the drivers for the future recovery and growth of the Ukrainian economy. Among the important directions of the strategy is the development of "green" energy. For this purpose, the government is developing effective tools to stimulate and support green generation: auctions, certificates of origin and other tools to increase the share of green generation in Ukraine. The war continues and a separate important task is operational preparation for the autumn-winter period. The government is preparing for various scenarios: damaged ones are being repaired, new ones are being built, energy resources are being accumulated, and assistance from international partners is being mobilized for all these purposes (Cabinet…, 2023). Strategic leveraging of prospective tipping points is imperative amidst reconstruction, given heightened energy security needs. International climate financing will prove critical in catalyzing investments that can achieve sustainability tipping points domestically.

The new Ukrainian Energy Strategy envisages Ukraine achieving carbon neutrality in the energy sector by 2050 and considers:

- The consequences of the full-scale war of the Russian Federation against Ukraine, strengthening the role of energy security and strengthening the stability of the energy system
- The results of joining the UES of Ukraine to the European network of electricity transmission system operators (ENTSO-E) and deepening the integration of Ukraine's energy system into the European one
- The availability of the latest technologies (in particular, the production and use of hydrogen for energy purposes, small modular nuclear reactors, and energy storage facilities), technical changes in the energy sector, world trends and innovative solutions, requirements for environmental safety by EU regulations and accepted obligations of Ukraine
- Ukraine's international obligations regarding energy efficiency, use of RES, and reduction of greenhouse gas emissions
- decentralization of electricity generation throughout the country to improve the stability and reliability of energy supply (Ukraine…, 2023)

3.3 Possibilities and Consequences of Phasing Out Coal in Ukraine

For several decades, the coal sector has been an integral part of the Ukrainian electricity system. But the fact that it needs to be modernized for many reasons becomes obvious. Among these reasons are outdated infrastructure, significant emissions of carbon dioxide, and military actions on the territory of Ukraine, which create security for the entire energy system. Several conducted studies indicate the technical and economic possibility of gradually abandoning the use of coal, which should create an ecological and economic effect, reducing the need for subsidies to support the coal industry.

Based on the results of a study conducted in the period from October 2020 to April 2021 by the Aurora Energy Research company, a transition scenario was simulated, which provided for the linear closure of all 17 GW of coal-fired power in Ukraine in the period 2021–2030. According to this scenario, with the closure of coal-fired power plants, we get a tripling of the parallel installed power generation capacity from renewable sources, which reaches 35 GW of wind, solar, hydro- and bioenergy power by 2030. However, other capacities, particularly nuclear generation, remain unchanged in this scenario. Therefore, the results of this study confirmed that it is possible to guarantee the security of the electricity supply under the condition of gradual abandonment of the use of coal. In addition, researchers' hourly simulation of electricity production showed that renewable energy sources could occupy an increasingly large share of electricity production.

In the developed transition scenario, electricity production from coal decreases from 28% in 2020 to its gradual abandonment in 2030, and renewable energy sources occupy an increasingly large share of the structure of the electricity industry. In 2030, they can provide more than half of electricity generation. Electricity production from wind farms accounts for the largest share of electricity generation from all renewable energy sources, and under this scenario, in 2030, it should make up 25% of all generation. Photovoltaic electricity generation almost triples its share, from 4 to 11% in 2030. By 2030, nearly 14 TWh of electricity will be produced with the help of biomass, which is 8% of the entire generation. The transition scenario calls for significantly more gas-fired capacity to provide the necessary flexibility, with existing combined-cycle gas turbines replacing coal-fired generation during semi-peak load and adding new open-cycle gas turbine units to the system. Thus, the results of this study prove that the main challenge for the Ukrainian electricity system is flexibility and not a lack of renewable capacity (The consequences…, 2022).

In 2019, Ukraine entered the top 10 countries in the world regarding renewable energy development rates due to the increase in total renewable energy capacity of 61.6% in 1 year (IRENA, 2020). In 2020—in the TOP-5 European countries in terms of solar energy development rates due to the increase in total solar energy capacity of 266.0% in 2 years (IRENA, 2021). In 2021, the share of electricity generated from RES reached 8.1%, of which 56% came from solar radiation, 33% came from wind energy, almost 8% came from burning biomass and biogas, and 3% came from small hydropower. It is worth noting that in 2021, an active pace of development was observed in the segment of domestic SPPs, which in 2021 was 36.4% of the new RES capacities put into operation in 2020. Most renewable energy facilities currently installed in the country are concentrated in Ukraine's southern and south-eastern regions, where active hostilities have been ongoing for more than a year. According to various experts' estimates, 30–40% of RES power plants in these regions have already suffered in one way or another.

Russia's full-scale war against Ukraine brought an unprecedented social and humanitarian catastrophe, which affected all spheres of activity, including the economy, energy, and ecology. It is currently quite difficult to fully assess the consequences of this war crime, just as it is difficult to predict the further development of events and their consequences. But, considering the experience of the post-war recovery of European countries, for the economic recovery of Ukraine, it is worth choosing a course of carbon neutrality in energy to achieve annual GDP growth of 4% by overcoming import dependence through the availability of the best technologies, diversification, decentralisation and digitalisation. Thus, it is recommended to continue the process of diversification of sources of supply of energy resources, in particular nuclear fuel for nuclear power plants, at the expense of expanding own resource base of uranium, mastering the production of zirconium alloys and creating capacities for its fabrication in cooperation with global manufacturers. The further development of the alternative energy sector and the evolution of the power system is only possible with the reconstruction of substations and digitalisation. Therefore, it is suggested to move first to the operation of modular and unified structures of substations, as well as to equip the switching equipment with electric drives with the function of remote control and monitoring of their technical condition. Given the emphasis on decentralising the national energy system, it is essential to implement a distributed energy resource management system that includes a virtual model, active networks and microgrids. To complete the process of decentralisation of the energy system, it is necessary to develop and implement local programs for the modernisation of thermal energy infrastructure to optimise local energy systems by considering the potential of local types of fuel, supply logistics, regional and national energy infrastructure (A new…, 2022).

Analysing the Energy Strategy of Ukraine 2050, it should be noted that not all representatives of the authorities optimistically perceive the reality of implementing this strategy. Critics of this strategy have the most doubts about the announced plans for developing RES. They insist that the strategy should also include a conservative scenario of a protracted war. Experts, who do not share the optimistic views of the supporters of the Strategy, believe that at the first stage, the primary attention should be paid to gas generation, which is a relatively simple solution so that it can be quickly implemented. Gas generation and nuclear generation should become the basis for the development of Ukraine’s energy system because it can balance unstable renewable energy sources in the future.

Even before the war, the shortage of balancing capacities reached 2 GW, which led to the emergence of the infamous “green-coal” paradox, in which, to balance the “clean” and “green” generation, “Ukrenergo” was forced to turn off the sides of the NPP and balance the system with “dirty” coal blocks TPP (The energy…, 2023).

The green-coal paradox is the need to significantly increase electricity production at coal-fired thermal power plants, which have harmful emissions, with many “clean” wind and solar power plants in Ukraine’s energy system. At the same time, it is also necessary to reduce the base load of nuclear power plants, which, unlike coal-fired thermal power plants, do not emit harmful emissions into the atmosphere. This situation is caused by a significant shortage of power for manoeuvring in the energy system of Ukraine. In other words, there is a paradoxical component in Ukraine’s energy system—an increase in the number of wind turbines, and SPPs leads to an increase in carbon and other harmful emissions (Paradox…, 2018).

Of course, solar and wind energy must be developed. However, the development of wind turbines in the coming years is a big question since the most attractive regions for this are either in the occupation zone or very close to the front line, making implementing such projects problematic. Regarding SES, the situation is a little better, but it is challenging to discuss implementing large new projects in the current unstable situation. Only the domestic SPPs segment continues to develop actively, where the main driving force is the consumer’s desire to provide himself with the most stable energy supply.

The common and indisputable opinion of supporters and critics of the Strategy is the need to decentralise the energy system. The energy transmission system must become more decentralised to reduce dependence on the central power transmission systems under constant enemy attacks (The energy…, 2023).

4 Conclusions

The 2022 Russian invasion of Ukraine created a radical discontinuity in prevailing energy policies and starkly exposed the weaknesses and inherent vulnerabilities of Ukraine's heavily centralized, carbon-intensive energy systems. However, amidst the challenges and destruction wrought by the war, there emerges a unique window of opportunity to reshape Ukraine's energy landscape along a green and sustainable path.

The war's impact on Ukraine's energy infrastructure, while devastating, underscores the urgency of adopting a new approach. These changes, precipitated by the conflict, align with the global imperative to address vulnerabilities related to climate change and improve the quality of life.

Before the invasion, Ukraine had made significant progress in decarbonization, but the path forward was marred by the legacy of Soviet-era industry and centralized energy systems. The destruction of critical infrastructure, including coal and gas plants, created a paradox of reduced emissions in the short term but with the need for increased emissions during reconstruction.

To navigate this predicament successfully, Ukraine must strike a delicate balance between immediate energy security needs and long-term sustainability goals. This necessitates a strategic approach, combining prudent policies and external support.

Rebuilding damaged infrastructure represents a tipping point opportunity to modernize towards sustainability, if climate considerations are integrated into planning. Prioritizing decentralized renewables, aligning grids with the EU, and tightening regulations could serve as positive tipping points driving a resilient, low-carbon energy future.

While coal may remain important in the short term for specific applications, a managed transition to alternative energy sources, including solar, wind, biomass, and nuclear, is imperative for achieving affordable, low-carbon electricity. Enhancing grid flexibility will be essential to accommodate a higher share of variable renewables.

Strategic partnerships and targeted assistance will play a pivotal role in advancing Ukraine's energy security and climate ambitions. The mobilization of substantial financial resources and technology transfer will be key. Integrating climate resilience and energy efficiency considerations into the reconstruction process is essential for sustainable recovery.

This analysis underscores the importance of adopting a prudent strategy to advance Ukraine's energy security and climate aspirations during the recovery period. While significant challenges persist, a commitment to sustainable energy can bolster resilience and prosperity in Ukraine, ensuring that the post-war era represents a turning point toward a greener and more self-sufficient energy landscape.

Significant differences in the socio-economic development of the territory of Ukraine and peculiarities of regional, cultural and ethical perceptions of the importance of changes inevitably leave an imprint on the strategy of further action on the way to decarbonization. On the other hand, such tipping points can contribute to faster practical implementation of sustainable policies for some regions (Ivano-Frankivsk, as shown in our research) and become an essential driving force and example for others. The war is an incredible and unpredictable stress and test for all branches of politics. Still, it is necessary to use the opportunity for fundamental changes whose time has long come.

In conclusion, Ukraine faces major challenges balancing immediate needs and long-term vision. Yet strategic policies and investments during reconstruction could serve as tipping points for transformational change. Despite difficulties, leveraging this opportunity can catalyze Ukraine's stalled sustainability ambitions. With prudent planning, the recovery period can pave the way for a decarbonized, European-aligned economy in Ukraine.

References

Air emissions and greenhouse gases from stational pollution sources. State Statistic service of Ukraine. Retrieved March 8, 2023, from https://www.ukrstat.gov.ua/operativ/operativ2018/ns/vzap/arch_vzrap_u.htm

A new energy profile in the context of decarbonisation and post-war reconstruction of Ukraine. (2022, May 18). Razumkov centre. https://razumkov.org.ua/statti/novyi-profil-energetyky-v-konteksti-dekarbonizatsii-ta-pisliavoiennogo-vidnovlennia-ukrainy

Bohdan, T. (2023, March 31). *Financial and economic consequences of the war*. https://lb.ua/blog/tetiana_bohdan/550614_finansovoekonomichni_naslidki.html (in Ukrainian)

Cabinet of Ministers named the key directions in the development of the energy system. (2023, April 21). UNIAN. https://www.unian.ua/economics/energetics/u-kabmini-nazvali-klyuchovi-napryamki-u-rozvitku-energosistemi-12228363.html

Carbon dioxide emissions from stational pollution sources by regions. State Statistic service of Ukraine. Retrieved March 8, 2023, from https://ukrstat.gov.ua/operativ/operativ2020/ns/xl/vdv_v_stas_dj_04-20ue.xlsx

Climate change 2022: Mitigation of climate change. (2022). IPCC. https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/.

Decarbonization of the economy: Ministry of Energy and Energy presented the concept of green energy transition. (2020, February 11). Glavcom. https://glavcom.ua/new_energy/news/dekarbonizaciya-ekonomiki-minekoenergo-prezentuvalo-koncepciyu-zelenogo-energetichnogo-perehodu-658848.html

Dogaru, L. (2021). Green economy and green growth—Opportunities for sustainable development. *Proceedings, 63*(1), 70. https://doi.org/10.3390/PROCEEDINGS2020063070

Energy strategy of Ukraine until 2050. (2023, April 21). https://zakon.rada.gov.ua/laws/show/373-2023-%D1%80#Text, https://mev.gov.ua/reforma/enerhetychna-stratehiya

Eurostat. (2022, December 7). Electricity and heat statistics. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_heat_statistics

Gross regional product. (2022). State Statistic service of Ukraine. Retrieved March 8, 2023, from https://ukrstat.gov.ua/operativ/operativ2021/vvp/kvartal_new/vrp/VRP_%20reg_04_20_II_ue.xls

Herrfahrdt-Pähle, E., Schlüter, M., Olsson, P., Folke, C., Gelcich, S., & Pahl-Wostl, C. (2020). Sustainability transformations: Socio-political shocks as opportunities for governance transitions. *Global Environmental Change, 63*, 102097. https://doi.org/10.1016/j.gloenvcha.2020.102097

How to rebuild the country better than it was—advice from. (n.d.). Ecodia. https://ecoaction.org.ua/vidbuduvaty-krainu-krashchoiu.html?gclid=CjwKCAjw4JWZBhApEiwAtJUN0PYSAnlzexqbCyli6xcow2LDobeMB6KNwkGKvN3jpZ8uGOAXUK1YABoCyG0QAvD_BwE

IRENA. (2020). *Renewable energy statistics 2020.* The International Renewable Energy Agency. https://www.irena.org/publications/2020/Jul/Renewable-energy-statistics-2020

IRENA. (2021). *Renewable energy statistics 2021.* The International Renewable Energy Agency. https://www.irena.org/publications/2021/Aug/Renewable-energy-statistics-2021

Kudyrko, L., Korohod, A., & Buonocore, M. N. (2022). Renewable energy of the EU countries in the context of risks of import dependence. *Foreign Trade: Economics, Finance, Law, 123*(4), 17–28. https://doi.org/10.31617/3.2022(123)02

Lenton, T. M., Benson, S., Smith, T., Ewer, T., Lanel, V., Petykowski, E., Powell, T. W. R., Abrams, J. F., Blomsma, F., & Sharpe, S. (2022). Operationalising positive tipping points towards global sustainability. *Global Sustainability, 5*. https://doi.org/10.1017/sus.2021.30

Lukash, O., & Nikulina, M. (2023). Decarbonization of the Ukraine economy: situation and issues. In *Mechanisms for combating modern challenges and threats: Lessons from the EU for Ukraine (conference proceedings)* (pp. 32–34).

Ministry of Energy and Coal Industry of Ukraine. (2017). Ukraine 2035 energy strategy.

Omelchenko, V. (2022, November 11). *Renewable energy sector of Ukraine before, during, and after the war*. Razumkov Center. https://razumkov.org.ua/statti/sektor-vidnovlyuvanoyi-energetyky-ukrayiny-do-pid-chas-ta-pislya-viyny

Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A. K., Hewitt, R. J., Lucht, W., Rockström, J., Allerberger, F., McCaffrey, M., Doe, S. S. P., Lenferna, A., Morán, N., van Vuuren, D. P., & Schellnhuber, H. J. (2020). Social tipping dynamics for stabilizing earth's climate by 2050. *Proceedings of the National Academy of Sciences, 117*(5), 2354–2365. https://doi.org/10.1073/pnas.1900577117

Paradox for 55 billion hryvnias. Why the rapid development of green energy will cost consumers dearly. (2018, May 25). Kontrakty.ua. https://kontrakty.ua/article/118732

Population by region. (2022). State Statistic service of Ukraine. Retrieved March 8, 2023, from https://ukrstat.gov.ua/operativ/operativ2022/ds/kn/arh_kn2022_u.html

Rapid damage and needs assessment, February 2022–February 2023. (2023). World Bank. https://documents1.worldbank.org/curated/en/099184503212328877/pdf/P1801740d1177f03c0ab180057556615497.pdf

Regional statistics. Comprehensive regional statistics. Regions of Ukraine in 2021 (2023). State Statistic service of Ukraine. Retrieved March 8, 2023, from https://www.ukrstat.gov.ua/druk/publicat/kat_u/2022/zb/12/Reg_21_doc.zip

Report on the direct damage to the infrastructure from the destruction caused by Russia's military aggression against Ukraine a year after the start of the full-scale invasion. (2023). https://kse.ua/wp-content/uploads/2023/03/UKR_Feb23_FINAL_Damages-Report.pdf

Tàbara, J. D., Jäger, J., Mangalagiu, D., & Grasso, M. (2019). Defining transformative climate science to address high-end climate change. *Regional Environmental Change, 19*(3), 807–818. https://doi.org/10.1007/S10113-018-1288-8

Tàbara, J. D., Lieu, J., Zaman, R., Ismail, C., & Takama, T. (2021). On the discovery and enactment of positive social-ecological tipping points. Insights from energy systems interventions in Bangladesh and Indonesia. *Sustainability Science*. https://doi.org/10.1007/s11625-021-01050-6

The consequences of the gradual refusing of coal in Ukraine until 2030. Infographics. (2022, August 10). Ecopolitic.com.ua. https://ecopolitic.com.ua/en/news/nazvani-naslidki-postupovoi-vidmovi-vid-vugillya-v-ukraini-do-2030-roku-infografika-2/

The energy of Ukraine: objective reality against the 2050 strategy. (2023, February 20). Ekonomichna Pravda. https://www.epravda.com.ua/columns/2023/02/20/697207/

The Paris Agreement. (n.d.). United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/process-and-meetings/the-paris-agreement

Ukraine energy profile. (2020). IEA. https://www.iea.org/reports/ukraine-energy-profile

Ukraine is the energy hub of Europe: the government approved the Energy Strategy until 2050. (2023, May 1). UNIAN. https://www.unian.ua/economics/energetics/uryad-shvaliv-energetichnu-strategiyu-do-2050-roku-shcho-vona-peredbachaye-12240660.html

Ukrainian energy sector evaluation and damage assessment—I (as of August 24, 2022). (2022). Energy Charter. https://www.energycharter.org/fileadmin/DocumentsMedia/Occasional/20220829_UA_sectoral_evaluation_and_damage_assessment_final.pdf.