Boston University Institute for Global Sustainability

Energy Security, Climate Change, and the Future of Ukraine Reconstruction

October • 2022

BOSTON UNIVERSITY

Authors

Darrick Evensen, Senior Research Scientist, Institute for Global Sustainability; Associate Professor, Department of Politics and International Relations, University of Edinburgh

Benjamin Sovacool, Director, Institute for Global Sustainability; Professor, Department of Earth & Environment, Boston University

Nate Dalton, Co-Founder and CEO, Sora Union

Kate Glebova, Localization Team Lead for Ukraine, Sora Union

Acknowledgments

Data and analysis contributing to this report were obtained from the Kyiv School of Economics' data collection on damage and reconstruction costs in Ukraine.

All results and any errors in this report are the responsibility of the authors.

Cover image: Dancing_Man/Shutterstock.com

Contents

Executive Summary

Russia's war against Ukraine has been ongoing for nearly eight months. Numerous reports, expert opinions, and commentaries have been written on Ukraine's approaches to recovery and reconstruction post-war. Herein we draw together key findings from these publications, particularly in the area of energy infrastructure. We do not assume we have the full contextual understanding to make specific recommendations for Ukraine's future; rather, we offer suggestions that Ukraine might consider as it further researches and hones its plans for recovery.

Key observations include:

- Many recovery cost estimates exist, generally in the range of 200 billion to 1 trillion USD.
- $349 billion (for reconstruction and recovery) and $750 billion (including costs for modernisation of assets not damaged) are two core, reputable estimates.
- Housing and transportation infrastructure account for by far the largest amount of current damage.
- Energy infrastructure itself sustained relatively little damage, compared to the sectors above, but massive investments of over $200 billion are required to finance a new approach to energy production, consumption, and security in the country.
- The greatest opportunity for change in energy systems likely lies in areas that have been most severely disrupted from Russia's war against Ukraine. This includes geographic regions and certain economic sectors and sub-sectors.
- A substantial shift to renewables is envisioned, with dramatic growth in wind and solar in Ukraine's southern regions, and increased potential for biomass production.

- Nuclear power will still be needed and is expected to grow in capacity over the next decade.

- Inefficient district heating and an old and poorly insulated housing stock are key challenges in Ukraine. Massive investments in energy efficiency and new approaches to heating – primarily heat pumps – are planned in response to these concerns.

- Ukraine sees a major role for hydrogen in its new energy system, although some concerns exist around the relative value and efficiency of such systems.

- Ukraine's big decisions going forward will be about what energy efficiency measures are promoted and adopted; the relative roles of nuclear, wind, solar, heat pumps, biofuels, and hydrogen; and where and when to make each of these shifts.

Recovery and Reconstruction in Ukraine

Since Russia invaded Ukraine on 24 February 2022, the way of life and the economy have been upended; lives and livelihoods have been constantly damaged, destroyed, and put at risk. Much of the destruction cannot be adequately measured in concrete monetary assessments – lives lost, families broken, futures devastated, important historical and cultural places decimated – nevertheless, numerous entities have sought to quantify a subset of the damage. They focus on the damage to physical infrastructure and the cost of replacing those pieces of physical capital. Some calculations also include estimates of economic cost due to lost productivity, although these estimates are normally accounted for separately.

Magnitude of damage and cost

A flurry of damage and reconstruction cost estimates emerged in the first months of the war. These culminated in the figure of $750 billion, first offered via the Ukraine National Recovery Plan, prepared by the Government of Ukraine, and presented at the Ukraine Recovery Conference[1] in Lugano, Switzerland, 4-5 July 2022. That estimate was still being used by Ukraine as of September 2022 for the cost of replacing lost physical capital according to 'building back better' principles, as well as 'needs for the recovery of the economy, and additional needs for the modernization of assets that have not suffered damage and destruction'[2]. Also in September 2022, the Government of Ukraine, in combination with the European Commission and World Bank, issued a report estimating the cost of reconstruction alone to be $349 billion[3].

Before Ukraine itself provided the $750b estimate, numerous other estimates – most on the same order of magnitude – were presented. Experts at the Wilson Center's Kennan Institute for research on Russia and Eurasia[4] (May 2022), and separately Werner Hoyer, chief of the European Investment Bank[5] (June 2022), both put forth a prospective estimate

[1] https://www.urc2022.com/
[2] https://kse.ua/about-the-school/news/due-to-the-last-estimates-damage-caused-to-ukraine-s-infrastructure-during-the-war-is-114-5-bln/
[3] Ukraine Rapid Damage and Needs Assessment, accessed from: https://www.worldbank.org/en/news/press-release/2022/09/09/ukraine-recovery-and-reconstruction-needs-estimated-349-billion
[4] https://www.wilsoncenter.org/blog-post/reconstruction-ukraine-three-experts-offer-priorities-future
[5] https://www.bloomberg.com/news/articles/2022-06-21/ukraine-reconstruction-may-cost-1-1-trillion-eib-head-says

of one trillion USD for the cost of reconstruction. This was the highest estimate offered. The Centre for Economic Policy Research's Blueprint for the Reconstruction of Ukraine[6] (April 2022) offered estimates in the range of $500-1000b.

This same Blueprint report offered analysis showing that previous examples of reconstruction aid could put the figure for Ukraine reconstruction in the $200-500b range. Nevertheless, this analysis of numerous reconstruction projects in the Middle East, and in Europe following WWII, cautioned that due to contextual differences across the countries in which reconstruction has been required, the best point of comparison (if any) is the post-WWII Marshall Plan. There are clearly still numerous concerns in applying reconstruction from 75 years ago to that needed from the current war. The Centre for Strategic and International Studies[7] (June 2022) offers the same $200-500b figure, whilst acknowledging that some reputable estimates do rise as high as the $1 trillion mark.

Beyond these one-time snapshot assessments of the magnitude of damage and the cost of reconstruction, a long-term data collection and analysis effort to chronicle damage due to Russia's war against Ukraine has been undertaken by the Kyiv School of Economics (KSE)[8] (in partnership with the Office of the President of Ukraine, Ministry of Economy of Ukraine, Ministry of Reintegration of Temporarily Occupied Territories of Ukraine, Ministry of Infrastructure of Ukraine, and Ministry for Communities and Territories Development of Ukraine). This research includes a citizen science data collection effort, with an online form[9] that can be filled out by anyone in Ukraine, to report damage to any physical object resulting from Russian attacks. People completing the form can write in details, characterise the damage via a number of drop-down menus, and upload photographic evidence. This project has been underway since February, and KSE provides updates of the overall damage incurred at least monthly. In addition to the number of items damaged or destroyed, the KSE researchers estimate the replacement cost; they are continually updating their methodology to reflect the reconstruction costs as accurately as possible. As of 5 September 2022, the total amount of damage, but not the higher costs associated with building back from the damage, stood at $114.5b (Figure 1).

[6] https://cepr.org/content/blueprint-reconstruction-ukraine
[7] https://www.csis.org/analysis/10-most-pressing-questions-ukraines-economic-reconstruction
[8] https://kse.ua/russia-will-pay/
[9] https://damaged.in.ua/

Figure 1 reveals that nearly half of the damage incurred in over seven months of war was sustained in the first two weeks (i.e., as of 10 March – the first date on which an estimate was provided). The figures are from press releases by KSE provided in real time as data collection continues. Throughout the weeks and months of updates from KSE, we observe periods of linear growth in damage and other instances of non-linear shifts. Additionally, due to constant updating of the methodology used to evaluate the replacement cost of the damage reported, there are occasional decreases in the total assessed damage (i.e., two in June).

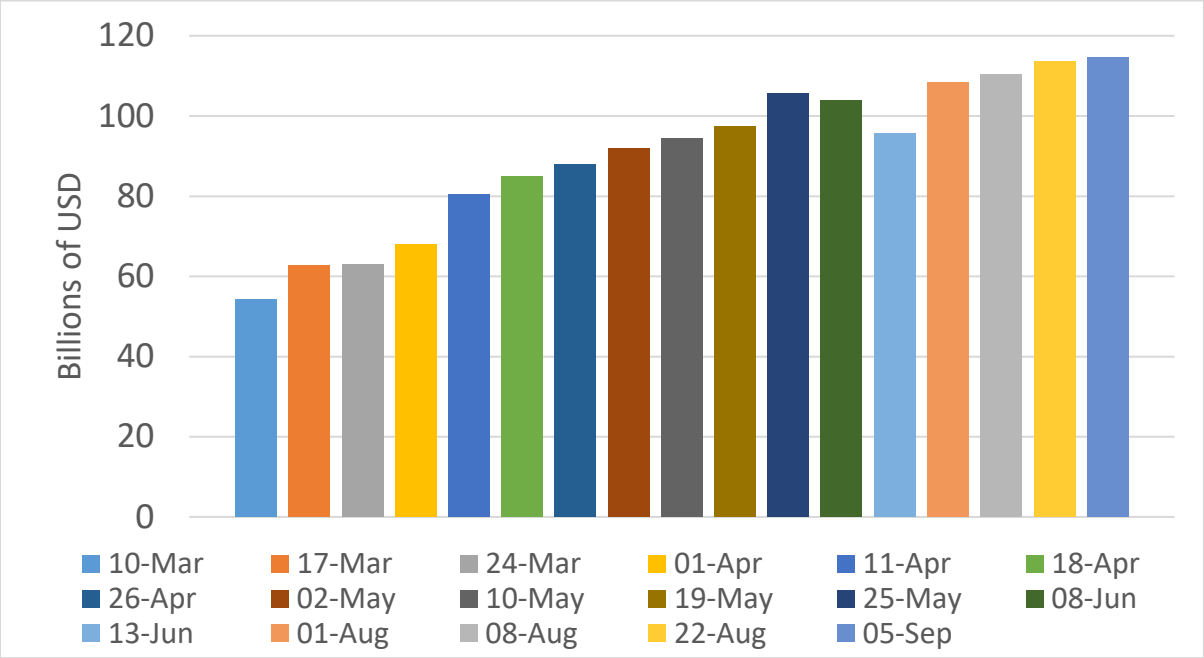


Figure 1. Total damages to physical objects in Ukraine from Russia's war (KSE data)

Key sectors affected

The Kyiv School of Economics database collects information on a number of sectors and sub-sectors of infrastructure that have been damaged and destroyed by Russian aggression. Sectoral data is reported in KSE's regular press release updates, although the categories presented change several times from one update to the next. The two areas most severely damaged are transportation infrastructure (highest until June) and housing (highest since June) (Figure 2). A major 244-page report on damage and reconstruction in Ukraine by the European Commission (EC), World Bank (WB), and Ukrainian Government confirms these two areas dominate in terms of damage sustained. The estimates in that report are

from the start of the war through 1 June 2022 and compare closely with the KSE estimates – $39.2b (EC/WB report) vs 39.4b (KSE) for housing, and $29.9b (EC/WB report) vs $31.6 (KSE) for transportation infrastructure.

Figure 2 reveals that damage to transportation infrastructure was extensive in the first month of the war (KSE issued the first sectoral damage report for damage through 24 March), and was primarily due to destruction of roads, although airports, seaports, and rail are also included. Very little has been added to this total damage since March. Conversely, the data reveal a steep and steady increase in damage to housing stock. As of 5 September 2022, KSE[10] reports that at least 115,900 homes and 15,300 apartments were damaged or destroyed. This, however, relies on individual direct reports of damage, and is a substantial underestimate. The EC/WB report estimates 816,000 housing units damaged (310,000 beyond repair), with 85% of these units being apartments. Damage is particularly acute in the regions of Donetska, Luhanska, Kharkivska, and Kyivska, where 82% of housing damage is projected to have occurred[11].

[10] https://kse.ua/about-the-school/news/due-to-the-last-estimates-damage-caused-to-ukraine-s-infrastructure-during-the-war-is-114-5-bln/
[11] European Commission, World Bank, and Ukraine Government. Ukraine Rapid Damage and Needs Assessment.

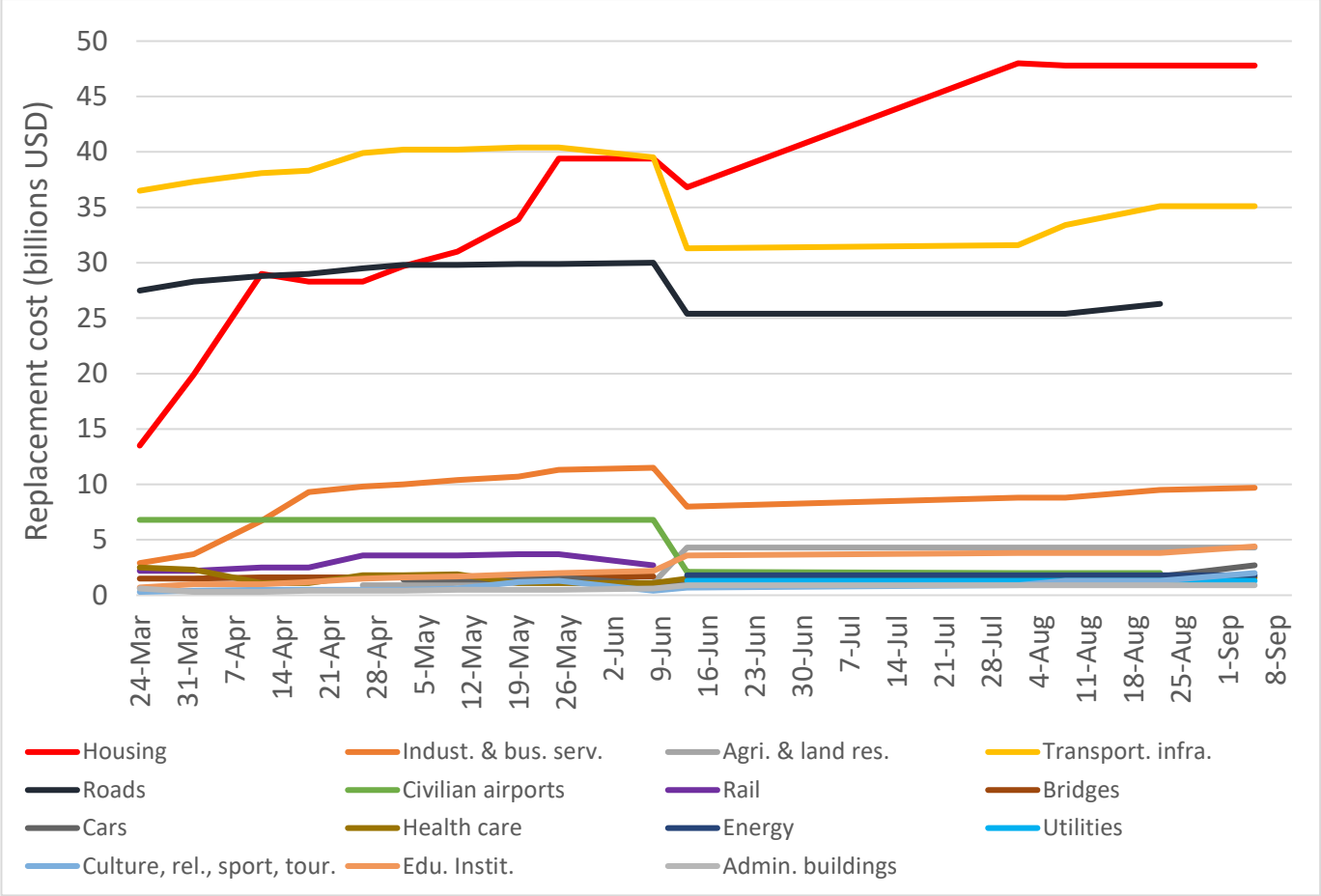


Figure 2. Damages to Ukraine's infrastructure and buildings over time (KSE data)

The damages to transportation infrastructure and housing clearly dwarf the total economic damage sustained in other sectors. To allow for a more nuanced view across sectors, Figure 3 presents the same data from Figure 2, but with the largest sectors and sub-sectors removed (i.e., housing, transportation infrastructure, roads, industry and business services, agriculture sector and land resources, and civilian airports).

The sectors and sub-sectors remaining in Figure 3 reveal continual increases in damages to schools and kindergartens, a recent increase in reported damages to cars, and notable fluctuation but little pronounced increase across several of the other sectors. Again, KSE consistently updates its methodology for assessing replacement costs and sometimes alters slightly what is included in each category. Damage in smaller sectors is also consistent between KSE and EC/WB estimates (e.g., $3.6b vs $3.4b respectively in education; $0.7b vs $1.1b in culture and tourism).

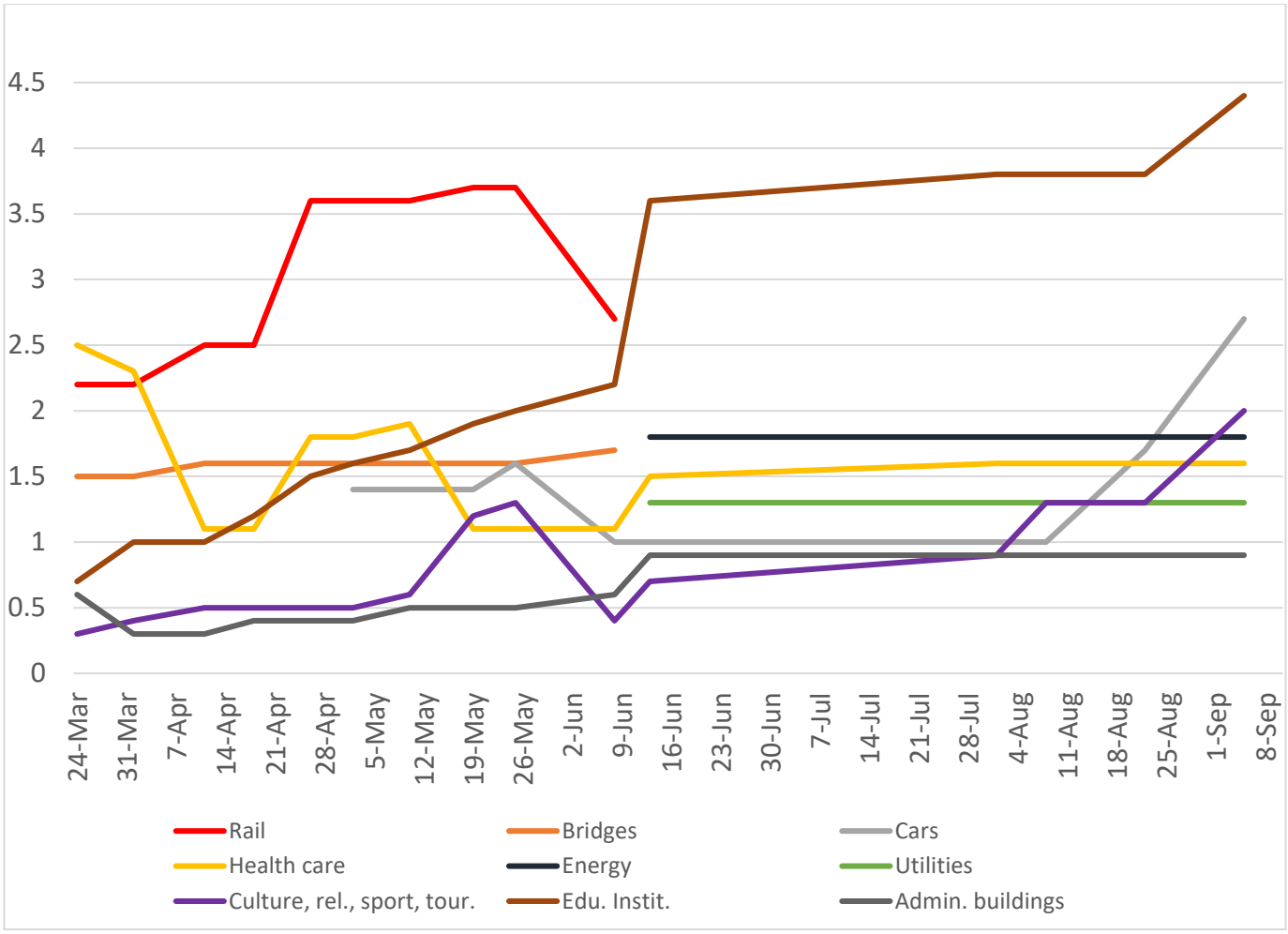


Figure 3. Damages to Ukraine's infrastructure and buildings, smaller sectors (KSE data)

Energy

One sector that seems at first glance to have sustained relatively minor costs is energy. The category KSE labels 'energy' is constant at $1.8b from when it was first included in KSE updates on 13 June, through the last update on 5 September. Likewise, 'utilities' remains constant during that same period, at $1.3b. It is possible that these numbers seem rather low due to under-reporting – because much of the data to chronicle replacement costs comes from the citizen science effort of individuals reporting damage they observe, personal rather than societal infrastructure and objects might be more reflected in reports submitted to KSE. Nevertheless, the combined total of $1.8b + $1.3b in June 2022 matches exactly the EC/WB report estimate of $3.1b in damage within the energy sector – split out

as $1.4b damage to the power sector, $0.7b to district heating, $0.5b to gas infrastructure, and $0.4b to infrastructure for transportation fuels.

An important proviso when discussing damage is that assessed damage is not the same as cost of reconstruction and recovery needs. The EC/WB report assesses these needs at $10.4b ($2.4b for the power sector, $1.35b for district heating, $5.85b for gas, and $0.8b for oil). Furthermore, the cost for recovery from damage to the energy sector specifically will also depend in large part on what choices are made for the reconstruction of energy infrastructure. Ukraine has consistently expressed its desire to 'build back better' following the war[12], both to improve the lives of its people and to align itself with European Union visions and plans – due to Ukraine's current candidate status for becoming an EU member state[13].

Beyond specific damages sustained to infrastructure and the $5b estimated for replenishment of natural gas stocks, a sizable price tag could accompany modernisation, a shift to increasingly low-carbon energy production, and energy efficiency measures (e.g., smart grids, digitisation, and green building practices). Ukraine's National Recovery Plan projects that work in these areas will cost over $200b – out of the total recovery estimate of $750b.

Approaches to recovery in the energy sector

Myriad commentaries have been published on how to enhance, modernise, and decarbonise the energy industry in Ukraine following the war. The essential point of departure and initial baseline for all such assessments should be the status of energy systems in Ukraine before the war, and the extent and distribution of damage to these systems resulting from Russia's war against Ukraine. A detailed understanding of what was present and what functionality has been destroyed can offer insights into approaches to recovery.

Due to relying heavily on Soviet-era infrastructure, Ukraine's housing stock was highly inefficient in relation to energy use prior to the war. For example, approximately 40% of residential heating in Ukraine is provided via district heating systems[14]; yet, these systems

[12] Lugano Conference, Ukraine's National Recovery Plan, and Ukraine Rapid Damage and Needs Assessment
[13] Ukraine National Recovery Council. 2022, July. Ukraine National Recovery Plan. Accessed from: https://www.urc2022.com/urc2022-recovery-plan.
[14] https://keepwarmeurope.eu/countries-in-focus/ukraine/english/

require 250-400 kWh per m^2 per year, compared to less than half that in Scandinavia (150 kWh) and one-fourth the amount in buildings with energy efficiency measures (60-80 kWh)[15]. District heating has been substantially affected during the war, particularly in Donetska, with over $0.5b in estimated damage and nearly $1b in recovery needs in Donetska alone. Ukraine's National Recovery Plan estimates $11b for modernising district heating across Ukraine. Separately, the Plan predicts $59b will be required for residential energy efficiency programmes, with an additional $29b for energy efficiency in social infrastructure.

In relation to electricity, the majority of Ukraine's electricity produced prior to the war was generated by nuclear (51.4% in 2020)[16]. Renewable sources contributed marginally to domestic electricity production, with 5.1% of production in 2020 from hydropower, 4.0% from solar, 2.2% from wind, and 0.5% from other renewables. An attractive feed-in-tariff programme in Ukraine saw the share of wind and solar in the energy mix increase notably over the last few years[17], but the financing for such a programme would be in question following the economic fallout from the war. During the war, new installation of renewable energy generation has understandably stagnated. Further, some estimates suggest that 30-40% of utility scale solar power installations have been damaged[18], whilst others project that 1 GW of installed capacity (about 15% of solar capacity) has been destroyed[19]. Power transmission infrastructure has also suffered considerable damage, especially in Zaporizhzhia, where the Ukraine Rapid Damage and Needs Assessment evaluates requirements for power recovery in this region alone at $0.5b.

Today, solar installations are most represented in Odesa, Mykolaiv, Zaporizhzhia, Kherson, and Dnipro; this is where the best prospects for solar PV production exist[20]. These same five regions in southern and central Ukraine have the highest potential for onshore wind energy installations; there are also prospects for up to 250 GW capacity for offshore wind in Ukraine[21]. Ukraine's National Recovery Plan predicts need for $15b to fund 5-10 GW capacity of renewable energy generation and an addition 3.5 GW of hydropower and

[15] Ukraine Rapid Damage and Needs Assessment
[16] BP (2021). BP Statistical Review of World Energy, July 2021, 70th edition. Retrieved from: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.
[1717] https://www.trade.gov/energy-resource-guide-ukraine-renewable-energy
[18] https://statensolar.com/2022/07/01/ukraine-powering-forward-with-solar/
[19] https://www.pv-tech.org/ukraines-solar-pv-sector-grinds-to-a-halt-with-15-of-installed-capacity-lost/
[20] https://www.trade.gov/market-intelligence/ukraine-renewable-energy-market
[21] https://www.globsec.org/publications/renewable-energy-in-ukraine-a-solution-for-european-energy-security-and-for-shifting-the-eu-gnd-eastward/#_ftn4

pumped hydro storage. Beyond solar and wind, Ukraine sees a role for biomass in its energy future, with an estimated $4.2b required for developing biofuels from agricultural products and residues. Some commentary has suggested strong opportunities in the area of biomass, due to Ukraine's status as a major agricultural producer[21].

No conversation about energy in Ukraine can avoid the role of nuclear. Russian forces have attacked nuclear power plants and held them hostage during the war. Despite this, the plants have largely continued to produce electricity, and due to severely decreased demand during the war and the March 2022 connection of Ukraine to ENTSO-E (the European electricity network), Ukraine has been an electricity exporter during the war. Prior to the war, Ukraine was entirely dependent on Russia for imports of nuclear fuel.[22] Ukraine estimates a need of $14b for expanding nuclear capacity post-war.

Although extensive conversations exist about the shift to low-carbon solutions and futures in Ukraine, the country also needs to consider the role of fossil fuels in the short and medium terms. Ukraine generated 26% of its electricity from coal and 10% from gas in 2020. Further, gas and coal are used to generate the energy for the aforementioned inefficient district heating systems in Ukraine. Prior to the war, Ukraine imported 31% of its gas needs[23], leading to the National Recovery Plan identifying approximately $18b needed for expanded development of domestic gas fields, including tight/unconventional resources.

Ukraine clearly envisions a future for gas in its energy mix, but also has ambitions to replace some gas use with hydrogen. The National Recovery Plan identifies 30+ GW capacity from renewable energy being needed to power green hydrogen production, costing $38b, with a separate $7b for 15 GW of electrolyser capacity and $2b for hydrogen transport infrastructure. Green hydrogen – produced from renewable electricity – could be used to decarbonise residential and district heating and/or for industrial decarbonisation.

[22] Ukraine Rapid Damage and Needs Assessment
[23] Ukraine Rapid Damage and Needs Assessment

Rebuilding and Enhancing Energy Infrastructure

The Ukrainian Government, numerous international organisations, and energy experts have offered advice on how to build back better following the end of the war in Ukraine. We summarise and expand upon those analyses and recommendations here.

Challenges before the war

To reprise some of the context associated with energy systems in Ukraine from above, we distil several key challenges and constraints on Ukraine's production and provisioning of heat and electricity:

- Severe constraints on reducing energy use, due to energy inefficiency – particularly in (district) heating
- Old, inefficient, and poorly insulated housing stock
- Energy security concerns: reliance on Russia for nuclear fuel and gas, use of Ukrainian nuclear power plants as instruments of war, lack of decentralised electricity production
- Limited renewable energy production
- The vast majority of solar and wind energy production potential lies in areas occupied by Russia and illegally claimed by Russia; this also restricts offshore wind opportunities, at least in the near-term[24]
- General concerns about transparency, corruption, and energy market structure in Ukraine, constraining opportunities for reform

Opportunities following the war

Despite the foregoing concerns, substantial opportunities exist for improving the energy systems in Ukraine, both in the short- and long-term. We separate these out according to several economic sectors and sub-sectors.

[24] https://www.csis.org/analysis/opportunities-and-challenges-renewable-energy-generation-ukraine

Housing

Housing is the sector that has sustained the greatest damage, at over 800,000 units and nearly $50b in replacement cost alone. It is also likely the sector with the greatest capacity for improvement in relation to energy. In regions with particularly high damage - Donetska, Luhanska, Kharkivska, and Kyivska – energy efficiency measures can be targeted particularly effectively. Donetska is also the region with by the highest level of damage to district heating. Once this area is no longer under Russian control, it could become a demonstration site for energy efficient buildings employing advanced heating systems (via heat pumps).

The Ukraine Government has identified both heat pumps (up to $29b for their application for individual and district heating) as well as hydrogen (at least $47b for production and transmission) as novel technological energy system needs moving forwards. Although governments including the EU and the UK have advanced hydrogen as a beneficial transition fuel, particular concerns have emerged from recent studies of the cost competitiveness of hydrogen gas for heating and hot water[25]. If renewable capacity is to be expanded substantially for the purpose of generating green hydrogen, it may be more efficient to use that renewable power to run heat pumps. Although heat pumps lose efficiency in particularly cold winters, it is notable that the southern regions where the highest potential for renewable energy production from wind and solar exists are also the warmer regions where heat pumps would perform with highest efficiency. Hydrogen could still have a role in decarbonising heavy industry (e.g., metallurgy, green steel), but should be viewed cautiously and in light of trade-offs for other ways in which renewable electricity for hydrogen production could be used.

Renewable energy production

Although some expansion of renewable energy might be able to advance in the short-term, much will need to wait until Russia no longer occupies the regions in the south – Odesa, Mykolaiv, Zaporizhzhia, Kherson, and Dnipro – with greatest potential for wind and solar development. About 12% of Ukraine's electricity was produced from renewable sources in

[25] Rosenow, J. (2022). Is heating homes with hydrogen all but a pipe dream? An evidence review. *Joule.* https://www.cell.com/joule/fulltext/S2542-4351(22)00416-0

2020; before the war, in 2021, Ukraine set a goal for 25% of all of its energy used (not just production and not just electricity) to come from renewable sources by 2035[26]. Due to its relatively large land mass for Europe, Ukraine has substantial potential for wind, solar, and biomass production. Furthermore, Ukraine's aspirations to convert its EU candidate status to that of a full member state incentivise Ukraine contributing to EU low-carbon and net-zero goals. The recent connection of Ukraine to ENTSO-E offers a means for renewable electricity exports simultaneously to generate export revenue and to lower EU carbon intensity.

Important when considering Ukraine's energy systems post-war is that no single option will emerge as a panacea. Wind and solar have considerable capacity, but this is mainly confined to a few regions that are currently heavily occupied by Russia. Heat pumps have substantial potential, especially when combined with energy efficiency and insulation upgrades, but they become less efficient in areas with the coldest winters. Biomass can emerge as a supplemental energy source, but conversion of food crops to energy crops must be pursued cautiously and deliberately to not exacerbate or continue the global food shortage concerns that have emerged since the start of the war in Ukraine. No single panacea also indicates that nuclear and fossil fuels will continue to play a role in the energy system. That role must be deliberate, by design, and not by default.

Nuclear power

Ukraine's National Recovery Plan includes a vision to expand nuclear production by over 38% in 2032, from 2019 levels. Ukraine clearly has interest in expanding overall production of energy, to reduce reliance on imports, to allow for the economic benefit of exports to the EU, and to reduce carbon intensity for Europe broadly. Therefore, whilst some expert commentaries on energy transitions in Ukraine post-war have cautioned against large-scale nuclear due to security concerns, such as those arising from the Russian attack on and capture of the Zaporizhzhia nuclear power plant, Ukraine clearly view it as a necessity, alongside expanded renewable generation capacity.[27] Perhaps the future of nuclear energy in Ukraine should focus on ways to make it as safe and secure as possible, as opposed to whether to include it in the energy mix or not. Conversations could examine geographical

[26] https://www.trade.gov/energy-resource-guide-ukraine-renewable-energy
[27] https://news.climate.columbia.edu/2022/03/14/ukraine-demonstrates-the-problem-with-nuclear-power/; https://www.nature.com/articles/d41586-022-02239-0

siting of such plants, and type and scale of the installations – perhaps delving into conversations about molten salt reactors and small modular reactors.[28]

Gas, oil, and coal

Gas will be an essential component of Ukraine's energy systems in the short- and medium-term to provide for heating needs, in direct relation to the speed at which Ukraine is able to modernise its heating systems. Having gas to provide for immediate heating needs is clearly a major energy security objective and imperative. At only 10% of electricity production in 2020, gas for electricity is not a major concern. Therefore, to transition away from gas, energy efficiency improvements and heat pumps become the favoured approach in the realm of housing, and some level of green hydrogen production allows for reduced gas use in heavy industry.

Exploiting new gas fields, however, is a long-term project and long-term investment. Particularly if Ukraine is seeking to expand into unconventional/tight formations, this will require foreign technical expertise and extensive exploration. Time horizons for when commercial production could realistically occur will need to be considered carefully alongside Ukraine's visions for how long it expects gas to play a considerable role in its energy mix.

Oil plays a very small role in electricity production in Ukraine (1% or less); it is predominantly used in the transport sector. Ukraine's National Recovery Plan has a clear vision to shift away from oil use through expanded electrification (of transport), substitution of hydrogen where relevant, and construction of better connectors to the EU. Coal will still play a role in the energy system in the near- and medium-term due to 80% of thermal power plants currently being coal-fired. Nevertheless, two coal-fired power plants and three coal mines have been substantially damaged in the war already and need not be replaced. Ukraine seeks to remove coal as quickly from its energy mix as it can, with an expectation in the National Recovery Plan of going from 18% in 2019 to 2% of the energy mix in 2032. Nuclear and biogas/methane are expected to fill this gap.

[28] https://world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx; https://www.energy.gov/ne/advanced-small-modular-reactors-smrs

Synthesis and Recommendations

Hundreds, if not thousands, of pages have been written on Ukraine's approaches to recovery and reconstruction post-war. Our object here was to draw together key findings from this extensive work, particularly in the area of energy infrastructure. Importantly, we base our recommendations on the clear goals that Ukraine sets out for itself in its National Recovery Plan. We explicitly eschew any attempt at academic imperialism; any suggestions we offer are focused on topics that Ukraine might consider further as it hones its plans for recovery, rather than outside perspectives on specific actions that are best for their country.

Our first observation is that the greatest opportunity for change lies in areas that have been most severely disrupted from Russia's war against Ukraine. This includes geographic regions, for example the four regions sustaining 82% of damage to housing, as well as economic sectors and sub-sectors acutely affected – residential heating in Donetska, power transmission infrastructure in Zaporizhzhia, and coal mines and coal power plants that have been damaged beyond repair.

Any major disruptive event can incentivise non-linear shifts in technological and economic decision-making[29]. The need to massively rebuild transportation infrastructure, predominantly roads, could help facilitate Ukraine's goals of electrification of transport to reduce dependence on oil (85% imported prior to the war). Bringing life back to agricultural production following the war could offer opportunities to re-envision the extent to which a role exists for biofuels, and how to balance these with food needs. Other changes, such as increasing solar and wind installations, could create opportunities to co-locate crops with energy projects.

The destruction of considerable housing, especially in the south, where solar potential is highest might create opportunities to assess potential for rooftop solar to be included in building plans. Because roof space and building orientation are central to rooftop installations, such projects can be much more promising on new builds than for retrofits[30].

[29] Kivimaa, P., Laakso, S., Lonkila, A., & Kaljonen, M. (2021). Moving beyond disruptive innovation: A review of disruption in sustainability transitions. *Environmental Innovation and Societal Transitions*, *38*, 110-126. https://www.sciencedirect.com/science/article/pii/S221042242030143X

[30] Schneider Electric. 2022. Towards net-zero buildings: A quantitative study. https://www.se.com/ww/en/insights/sustainability/sustainability-research-institute/towards-net-zero-buildings-a-quantitative-study.jsp

Ukraine sees clear potential for a move towards hydrogen – viewing this as an opportunity to reduce reliance on gas and oil and to use relatively cheap renewable electricity to allow for excess production and hydrogen exports. This could strengthen the economy and energy security. At the same time, Ukraine envisions substantial investment in heat pumps. We recommend a thorough analysis of the extent to which 30+ GW of added renewable electricity would be more effectively and economically directed to powering heat pumps or creating hydrogen. There may be differing energy security implications as well, based on which energy sources are being replaced.

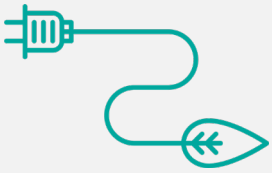
The role of nuclear requires detailed consideration as well, due to security concerns with nuclear plants being used by Russia as instruments of war. A low-carbon shift and phrasing out of coal require more added capacity than renewables alone can provide. If nuclear is to fill this gap, citing of plants, and potential technological innovations that can protect the plants from disaster are essential. If Ukraine foresees substantial expansion in large-scale nuclear, this further highlights the value of added wind and solar, particularly rooftop solar and community wind. Throughout the war, small-scale decentralised power generation has been an important lifeline and energy security backup when communities have become disconnected due to destroyed infrastructure[31].

A final recommendation relates to additional data and research needs. The European Commission and World Bank's 'Ukraine Rapid Damage and Needs Assessment'[32] makes clear that substantial data gaps and broad assumptions affect the estimates of damage to date and reconstruction and recovery needs. Nevertheless, whilst it is important to know the full extent of the damage, the much larger question – both economically and politically – is how the energy system will be structured post-war.

The damage to Ukraine's energy sector from Russia's war is currently estimated at $3b, with around $10b required for recovery. Ukraine[33] identifies a need for well over $200b to finance a new approach to energy production, consumption, and security in the country. The big decisions will be about what energy efficiency measures are promoted and

[31] https://www.pv-magazine.com/2022/05/02/ukraine-is-there-a-pessimistic-solar-scenario-no/
[32] https://www.worldbank.org/en/news/press-release/2022/09/09/ukraine-recovery-and-reconstruction-needs-estimated-349-billion
[33] Ukraine National Recovery Plan, https://www.urc2022.com/urc2022-recovery-plan

adopted; the relative roles of nuclear, wind, solar, heat pumps, biofuels, and hydrogen; and where and when to make each of these shifts.


Darrick Evensen, Benjamin Sovacool, Nate Dalton, and Kate Glebova, 2022. *Energy Security, Climate Change, and the Future of Ukraine Reconstruction.* (Published by Boston University Institute for Global Sustainability, Boston, MA, USA). Available at bu.edu/igs.

Boston University Institute for Global Sustainability