CLIMATE DAMAGE CAUSED BY RUSSIA'S WAR IN UKRAINE

24 February 2022 – 23 February 2023

by Initiative on GHG accounting of war

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EPAIU is aiming at the civil society organizations development that act in the environmental field – institutionally capable, transparently governed, accountable and publicly recognized, and help improve the quality and inclusiveness of environmental policy making and implementation by means of strengthening inputs from civil society into designing, advocating, implementing and monitoring environmental policies and practices at all levels, and raising public awareness of, and demand for a problem-relevant, more inclusive, rights-based and conflict-sensitive approach to environmental policy and decision-making. The EPAIU has been implemented by the International Renaissance Foundation (IRF) with the financial support of Sweden.

The European Climate Foundation (ECF) is a major philanthropic initiative working to help tackle the climate crisis by fostering the development of a net-zero emission society at the national, European and global level. The initiative supports over 700 partner organisations to carry out activities that drive urgent and ambitious policy in support of the objectives of the Paris Agreement, contribute to the public debate on climate action and help deliver a socially responsible transition to a net-zero economy and sustainable society in Europe and around the world.

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Швеція
Sverige

LICENCE

In loving memory of Oleksii Khabatiuk

(19 September 1977 – 4 May 2023)

Ukraine's leading public energy and climate expert, Oleksii Khabatiuk devoted more than 20 years of his life to the development of Ukraine and the improvement of the Ukrainian energy sector. He was a power engineer who joined government to work on climate change and then joined Ukraine's largest energy company to work with government and the public on energy sector reform. He was one of the first GHG inventory experts in Ukraine and head of the national GHG inventory group in 2010-2012. In 2007, he led Ukraine's preparation for compliance assessment under the Kyoto Protocol, making it possible for the country to benefit from the Kyoto Protocol mechanisms.

Always prepared to engage in public debate, he made an invaluable contribution to the development of the state and democracy, international energy relations and climate education. With his personal example of small-scale solar production, he inspired many people to introduce energy innovations in Ukraine. He was extraordinarily gifted, kind, and a great patriot of Ukraine.

Oleksii joined the Armed Forces of Ukraine shortly after the start of Russia's full-scale invasion. He tragically lost his life on 4 May 2023 in the battle of Bakhmut. He leaves behind three beautiful daughters, and Olha, his wife for more than 20 years.

In civil and in military life, you were always the best.
You will forever stay in our hearts.

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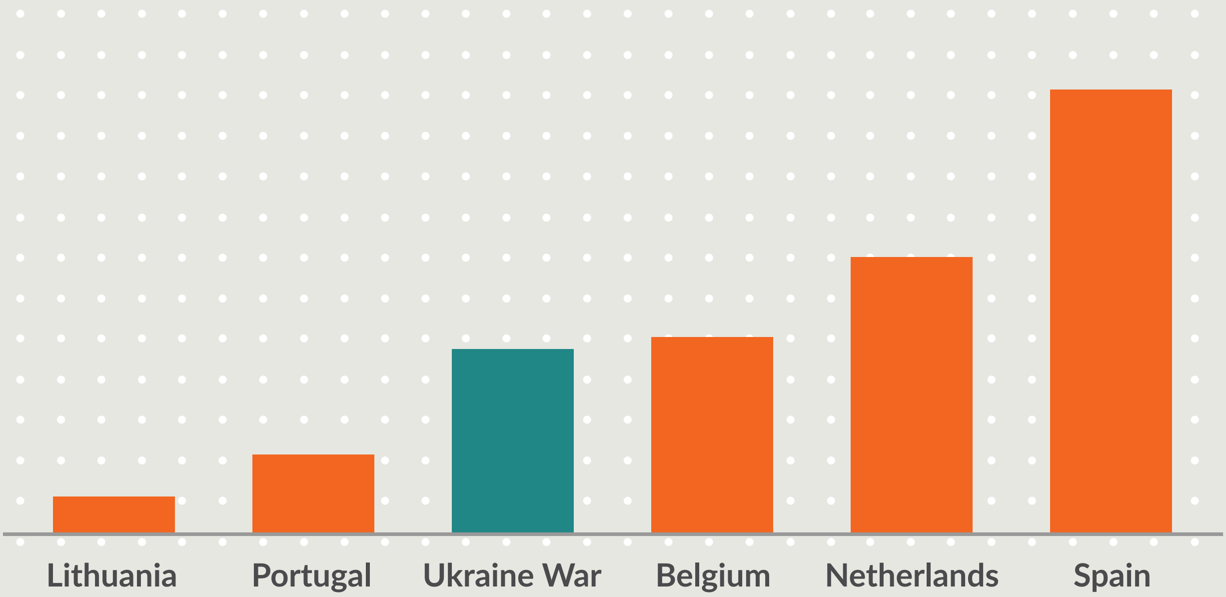
EXECUTIVE SUMMARY

The war in Ukraine has caused extensive devastation, including the destruction or damage of homes, schools, hospitals, and other critical public facilities, leaving citizens without essential resources such as water, electricity, and healthcare. The war has also led to significant environmental damage and had a detrimental impact on the global climate, resulting in the release of significant amounts of carbon dioxide and other greenhouse gases into the atmosphere.

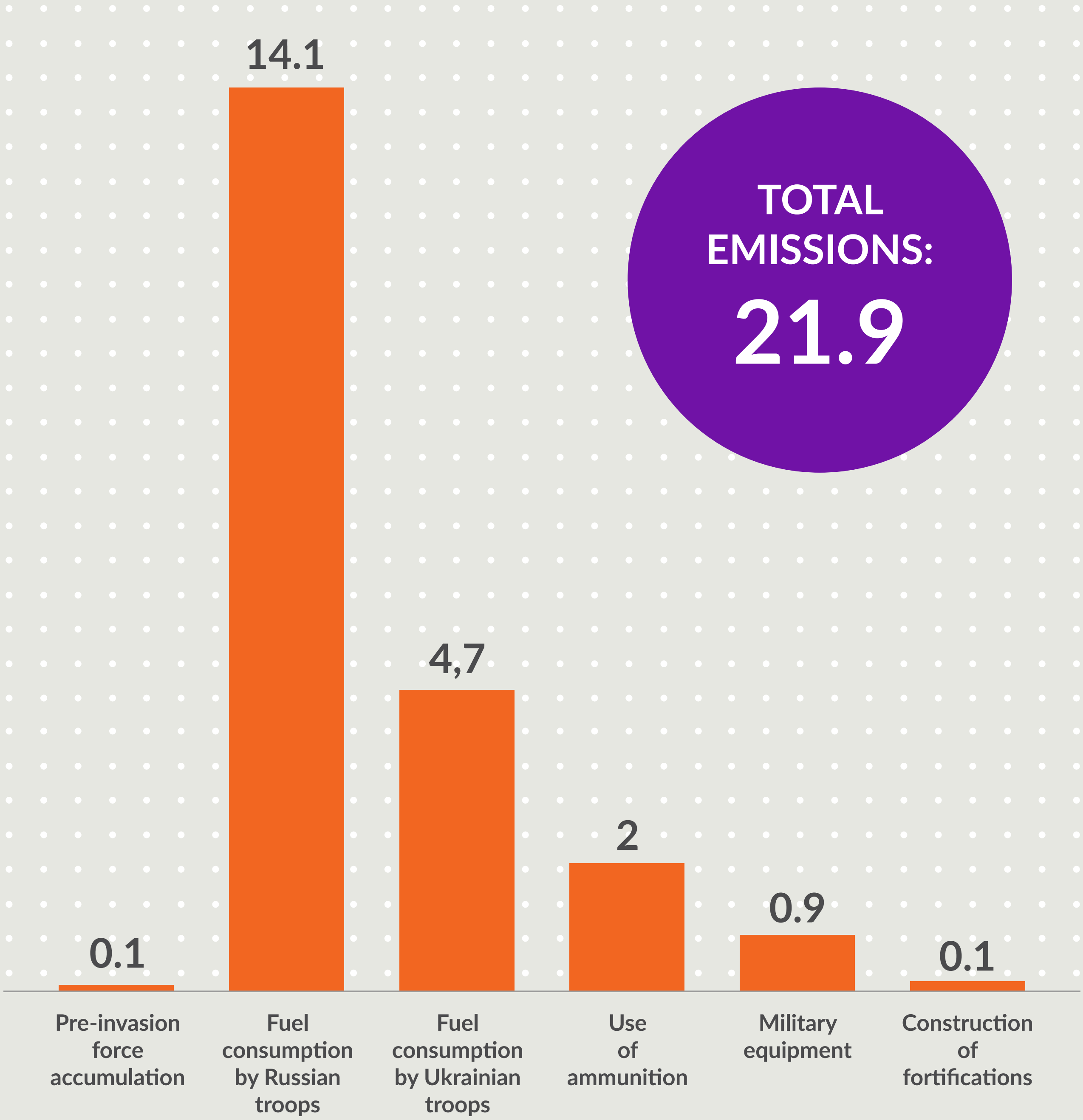
War emissions compared to emissions of European countries



This second interim assessment concludes that greenhouse gas emissions attributable to twelve months of the war totalled to 120 million tCO_2e. This is equivalent to the total GHG emissions produced over the same period in a country like Belgium. Compared to the first assessment, which covered seven months of the war, emissions did increase but did not grow at the same rate due to limited movement of the front line and winter conditions. Furthermore, the second assessment benefitted from additional insights into the situation in Ukraine, which allowed for some corrections to be made to the assessment.

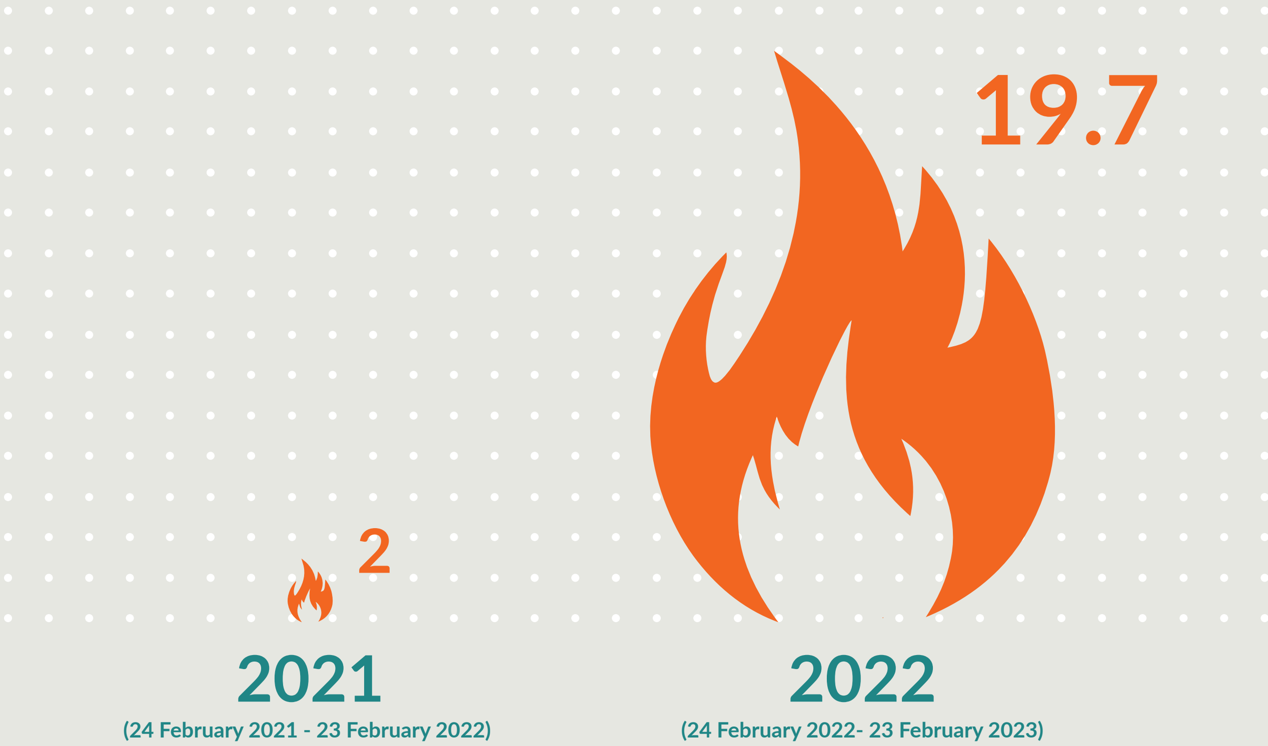
Despite not constituting the largest portion of emissions, emissions resulting from warfare persist unchecked. The consumption of fuel has risen steadily with each passing month of the war, while the large quantities of ammunition used have necessitated a significant increase in production in Russia, Ukraine, and elsewhere to replenish dwindling stocks. In anticipation of a potential counter-offensive by Ukraine, Russia has constructed kilometres of fortifications along and behind the front lines, using concrete as the construction material, resulting in more carbon emissions.

GHG emissions from warfare
($MtCO_2e$)



The number of fires larger than one hectare has increased 36-fold compared to the pre-war period of 12 months. These fires are primarily observed in close proximity to the front line, with many leading to the destruction of forested areas. While fires subsided during the winter, they are expected to intensify again as temperatures rise in the spring. **Total emissions: 17.7 million tCO_2e.**

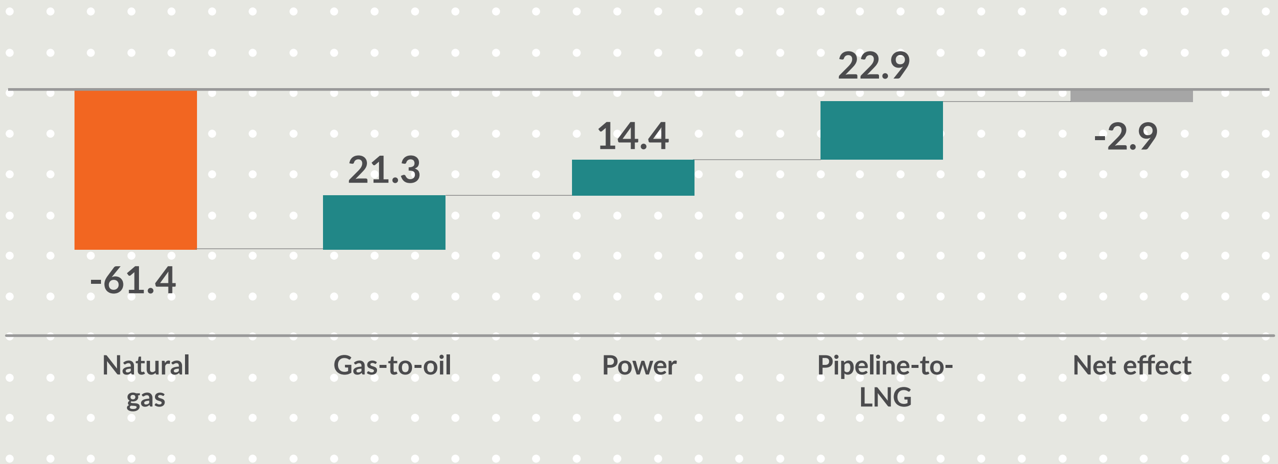
GHG emissions from fires
($MtCO_2e$)



In 2022, Europe experienced an unprecedented energy crisis that resulted in soaring prices for both natural gas and electricity. Although the energy market has since stabilized, the crisis prompted a range of interventions from governments and market actors. While not all of the causes of the crisis can be attributed to the ongoing war, this study argues that some of its effects have led to increases in carbon emissions in Europe, while others have contributed to emission reductions. However, the effect of these factors combined is negligible.

Looking to the long-term, the crisis has served as a catalyst for the transition to renewable energy in Europe. This trend is expected to continue not only in the European Union, but also in the post-war period of Ukraine's revival.

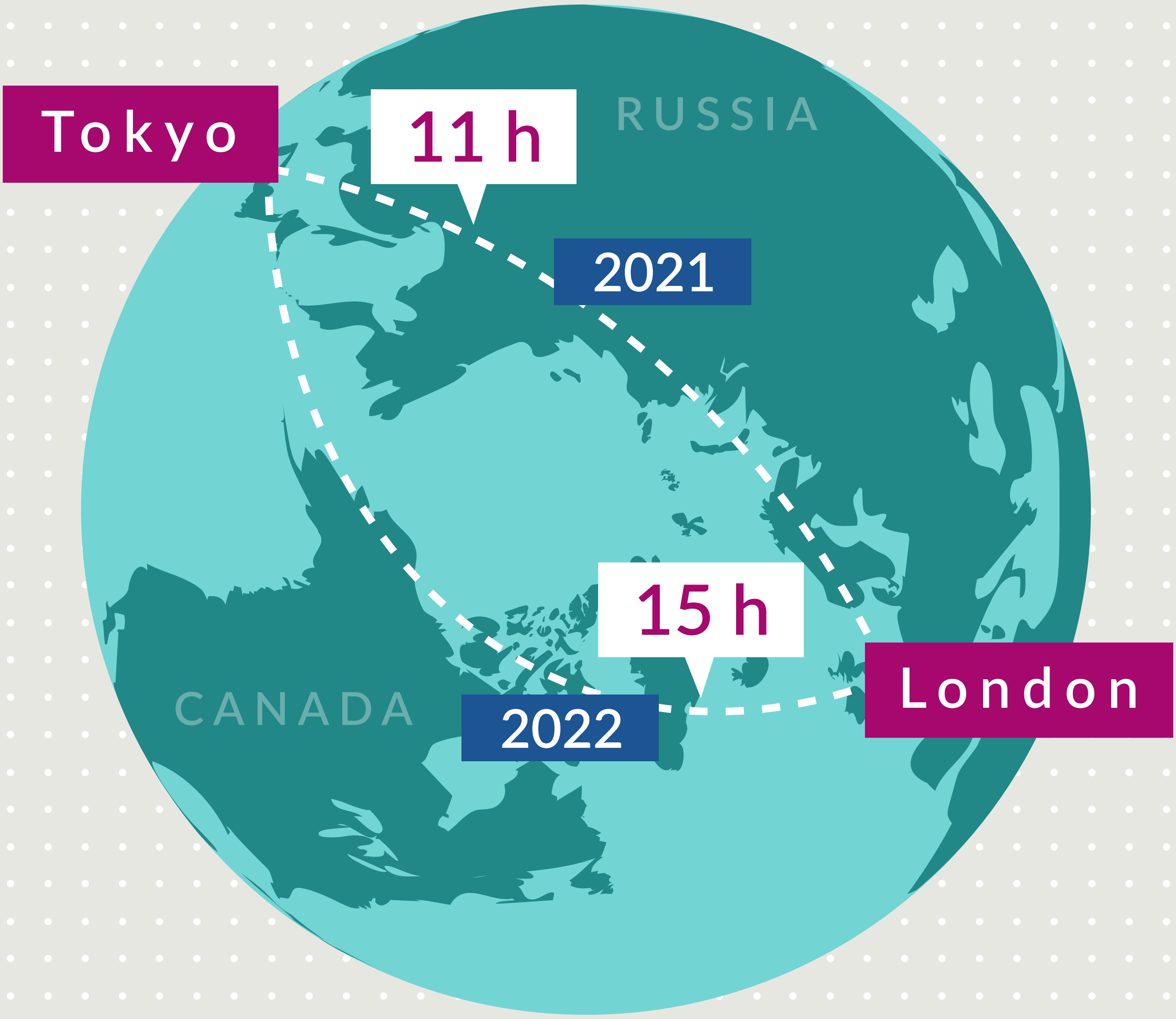
Year-on-year change in EU energy sector attributed to the war ($MtCO_2e$)



The ongoing war in Ukraine caused the country's economy to contract by almost 30% in 2022, resulting in a corresponding reduction in emissions. However, it is expected that the reduction in emissions are less than the decline in GDP. Nonetheless, these reductions were significant, but this report contends that most of the emissions reduction has simply been displaced outside Ukraine. Millions of refugees have been forced to flee the war, taking their carbon footprint with them to Europe and other parts of the world. In addition, due to energy shortages, disrupted supply lines, and destruction of factories, the production of consumer goods has shifted from Ukraine to other parts of Europe, resulting in increased emissions in those regions. Furthermore, in the highly globalized iron and steel market, competitors have taken over dwindling production, thereby increasing emissions in their respective regions. Thus, the reductions in emissions in Ukraine have largely been offset by increased emissions elsewhere, providing no meaningful relief to the climate.

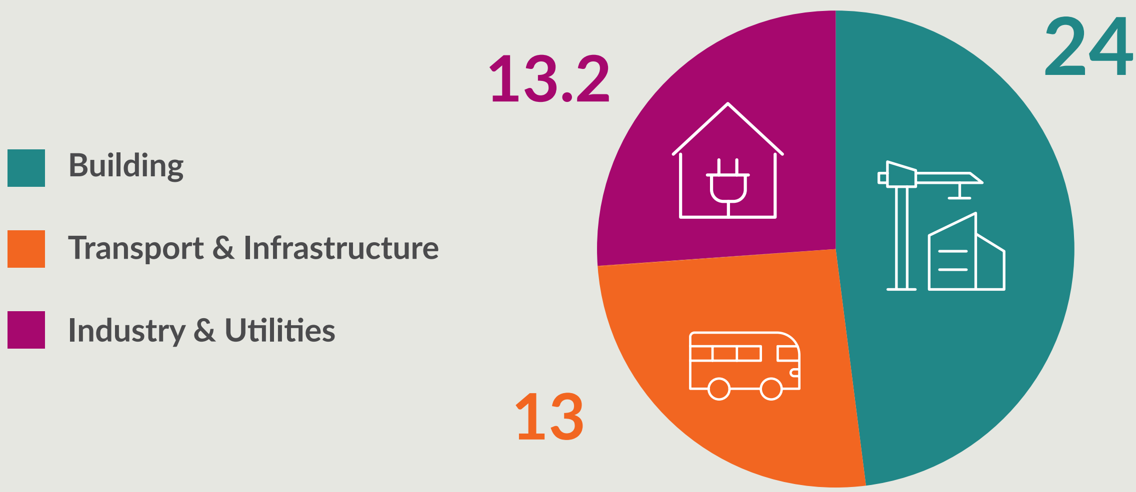

EUROPE
UKRAINE
THE WORLD

The various airspace bans issued by Western countries and Russia have cut important east-west airways between Europe and Asia for many Western carriers. Carriers were forced to take detours on routes to East and Southeast Asia resulting in longer flight times, as well as added fuel costs and higher greenhouse gas emissions. **Total emissions: 12 million tCO_2.**



The post-war reconstruction of damaged and destroyed civilian infrastructure constitutes the largest source of emissions. As noted in our previous assessment, the reconstruction of buildings and other infrastructure is highly carbon-intensive, especially given the significant damage sustained during the war. Although the frontline has remained relatively static in recent months, the total damage to buildings continues to increase, albeit at a slower rate compared to earlier stages of the war. Notably, attacks on energy infrastructure during the winter months have considerably increased emissions associated with reconstruction in this sector. Meanwhile, industries and business services have also been severely impacted, further exacerbating emissions from reconstruction efforts in those sectors. **Total emissions: 50.2 million tCO_2e.**

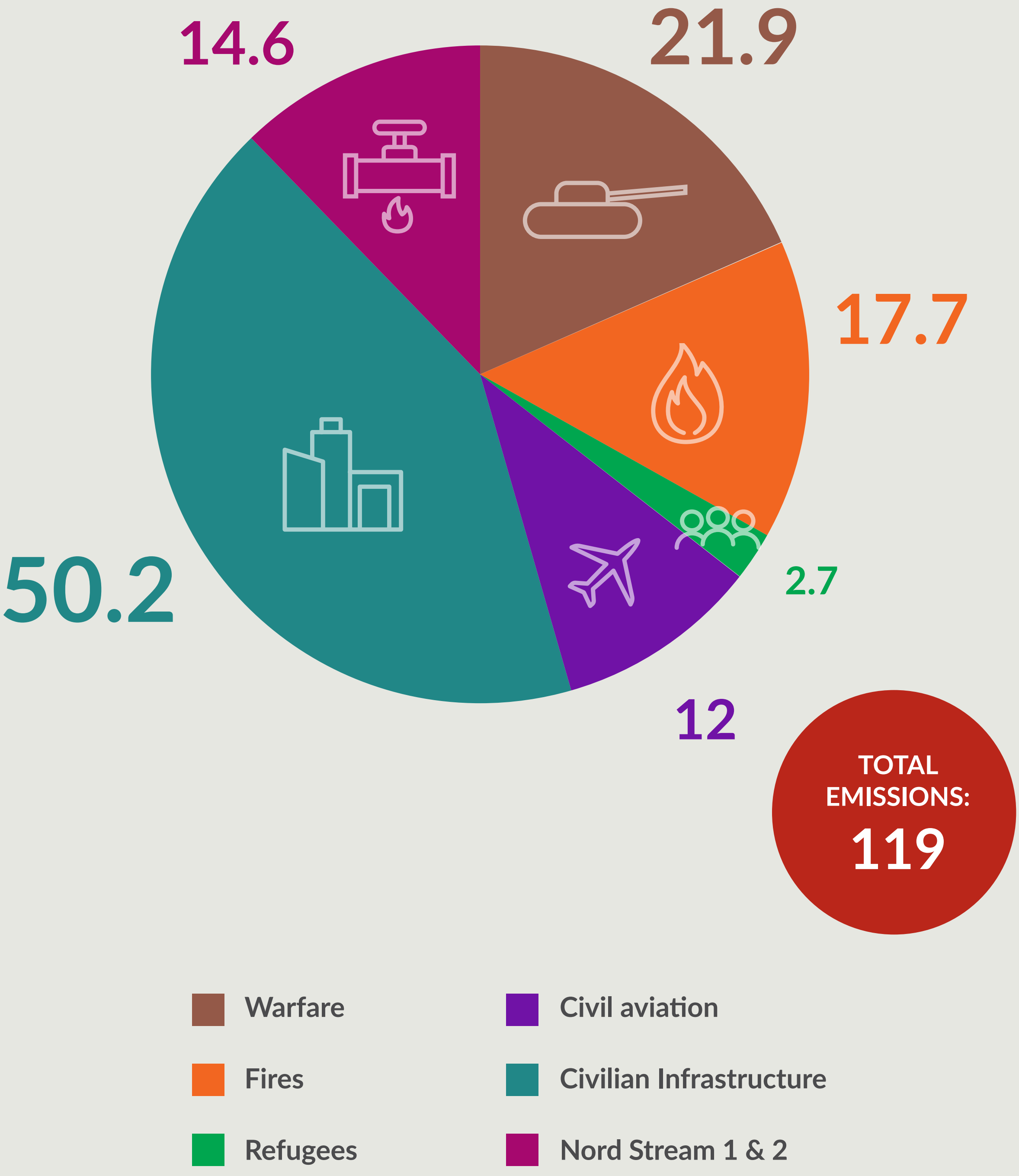
GHG emissions of the reconstruction of civilian infrastructure ($MtCO_2e$)



The ongoing war has led to a significant deterioration of the security situation in Europe. In the short run, the production of ammunition has increased to supply Ukraine and to replenish depleted stocks in Europe and other parts of the world. However, in the long run, Europe will have to maintain higher military spending levels to invest in the new equipment and cover the increased operational costs necessary to deter further acts of aggression by the Russian Federation.

Unfortunately, militaries are only beginning to consider decarbonization, and much work needs to be done in this area. The rearmament of Europe and other parts of the world is not good news for the climate and is likely to increase those emissions in the years ahead.

Total GHG emissions over the various sectors ($MtCO_2e$)



1. INTRODUCTION

On 24 February 2022, the Russian Federation launched an unprovoked, large-scale invasion of Ukraine and the war has been dragging on for almost 1.5 years, causing a humanitarian crisis with many people perishing, getting injured, or having to flee their homes. The war has also damaged or destroyed civilian infrastructure including buildings, factories, and roads. The war, other than overturning people's lives, has destroyed natural ecosystems and polluted the environment. Each explosion of a missile or projectile causes pollution of the air, water, and land with toxic substances. Many industrial installations have been hit, leading to uncontrolled chemical releases. Forests and natural reserves have been damaged.

Many initiatives have been launched to keep track of environmental damage. The Ministry of Environmental Protection and Natural Resources of Ukraine has launched a website[1] aggregating damage to the environment based on reports from local governments and civilians, who can report damages through an application. The Conflict and Environment Observatory and the Zoï Environment Network release regular briefings to assess different environmental types of damages like radiation risk, water pollution, or industry[2]. Data about local pollution incidents is collected by civilians and processed by the Center for Environmental Initiatives Ecoaction together with Greenpeace using an interactive map[3].

Besides environmental pollution and degradation on the territory of Ukraine, the war has caused significant emissions of greenhouse gases (GHG) into the atmosphere. While the world is struggling to drastically reduce GHG emissions to limit the average global temperature increase to 1.5^{0}C, these extra emissions caused by the war make it even more difficult to reach the goals of the Paris Agreement. The war also undermines climate mitigation activities in Ukraine as it is redirecting financial flows to reconstruction and, on the European continent, to security and defence.

In this report, we want to create awareness that Russia's act of aggression is not only impacting Ukrainian citizens and the Ukrainian environment, but is affecting the rest of the world through enhancing emissions and making the efforts to halt global heating more difficult. Secondly, GHG emissions related to the military and conflicts have often been overlooked, omitted, or underreported by both the military and the climate change community. This war puts the limelight on this overlooked issue and recently, many publications have appeared in the public domain[4].

1. https://ecozagroza.gov.ua/en
2. Conflict and Environment Observatory (http://www.ceobs.org/publications/) and Zoï Network (https://zoinet.org and https://ecodozor.org/index.php?lang=en).
3. https://en.ecoaction.org.ua/warmap.html and https://maps.greenpeace.org/maps/gpcee/ukraine_damage_2022/
4. For example: Low-carbon warfare: climate change, net zero and military operations, https://academic.oup.com/ia/article/99/2/667/7024982

Thirdly, the Russian Federation shall be held accountable for its act of aggression, foremost for the crimes against humanity. Russia should compensate all damages caused, including those to the environment and the climate. Registering those damages is a first step in this process. Finally, this study aims to provide a clear insight in future emissions during the reconstruction phase. Awareness of the amount of these emissions provides an opportunity to minimize them.

The first assessment of climate damage[5] was presented at the Climate Conference COP27 in Sharm-el-Sheik, Egypt on 9 November 2022[6], covering the first seven months of the war. The estimate included four sectors: emissions from the movement of refugees, emissions from warfare, uncontrolled fires in forests and cities, and future emissions from the reconstruction of damaged and destroyed buildings, roads, and factories.

This second assessment of climate damage updates these four emission causes, covering the first 12 months of the war, i.e. from 24 February 2022 to 23 February 2023. In addition to these sectors, we have looked at additional sectors impacted by Russia's act of aggression. These sectors include the European energy sector, the rerouting of flights due to airspace closures, and the country-wide impact in Ukraine. This report covers the period until 31 December 2022 for these additional emission sources.

In this report, greenhouse gas emissions have been derived from data sources like fossil fuel consumption and the number of damaged apartment blocks. The war is still going on and many data sources are not available or their access has been restricted for security reasons. Visual inspection is often not possible due to safety issues, qualified staff being mobilized to defend the country, or the territory being occupied. Hence, remote sensing through satellites is often the only available option. Estimations rely on many assumptions, which are subject to revisions in due course as more information becomes available. Only after hostilities have ceased, i.e. when the war is over, assumptions can be verified.

In preparing the analysis, we have relied on open source information, including social media, scientific studies and open-source intelligence (OSINT) analysts, interviews with experts, industry reports, government publications, peer-reviewed articles, and other available sources of information. Acknowledging uncertainty of the estimates, we have relied on conservative assumptions, multiple sources of information, and comparing results from several alternative approaches, where possible. Mapping carbon emissions of a major conflict has never been done before, let alone of an ongoing conflict, and a methodology is emerging as we work. This does not mean Climate Damage is not happening, it is just work in progress. We are grateful to all experts, who have participated in the calls and discussions on various topics covered by the report, providing useful ideas and references. We also invite all interested parties to contribute to the process of climate damage assessment by providing industry insights and suggestions on activity data collection and GHG emissions estimation.

5. Climate Damage caused by Russia's war in Ukraine. English: https://en.ecoaction.org.ua/climate-damage-caused-by-russias-war.html. Ukrainian: https://ecoaction.org.ua/vplyv-ros-vijny-na-klimat.html
6. The recording of the side-event: https://www.youtube.com/watch?v=ynQbzwxTnBw

Some of the emissions that are presented in this report have taken place on the territory of Ukraine, either under control of the Ukrainian government or in occupied territories, while others have occurred elsewhere. Some of the emissions have already occurred while others will happen in the future (e.g. reconstruction emissions). From a climate damage perspective, the geographical location of emissions is not relevant: each tonne of CO_2e emitted, wherever in the world, contributes to climate change equally.

2. WARFARE

There are no reliable estimates on GHG emissions caused by the military around the world while initiatives to increase the transparency and assess data on the climate impact of armed forces have only started to gain attention[7].

Nevertheless, modern armies are known to be large consumers of fossil fuel even during peace time due to the operation of high-tech equipment employed (planes, helicopters, ships, tanks, and armed vehicles) and various ancillary infrastructure (airstrips, roads, and supply vehicles). Energy consumption of the military is high due to the prioritization of superior combat performance of equipment, the need for rapid movement of troops, overall high-tech militarization of the armed forces, and increasing their size rather than energy efficiency[8].

An overview of the studies on military GHG emissions in various countries (see the Annex) helps to understand the scale and composition of the military-related greenhouse gas emissions, which contribute at least 1% to the total national GHG emissions. Analysis of these studies results in the following observations.

First of all, assuming the conservative 1% share of the military's operational emissions in national inventories, during peace time, Russia's military would likely be responsible for the emissions of about 20 million tCO_2e[9], while Ukrainian military – for approximately 3 million tCO_2e. According to some estimates, Russia has committed 80% of its ground forces to the war in Ukraine, while Ukraine has obviously committed all available and additionally mobilized resources to resist Russia's invasion. During the war, the level of emissions would certainly be significantly higher and most likely would be increased manyfold due to the mobilization of manpower, more intensive use of fuel, construction of fortifications, and extended supply chains.

Secondly, fuel consumption is the most significant single source of GHG emissions associated with the operation of the military and warfare. During peace time, fuel consumption could be responsible for up to one third of total emissions or for a considerably higher share if calculated including operational emissions only (i.e. without considering supply chain emissions). Consumption of fuels significantly increases during active military activities and

7. See, for instance: A framework for military GHG emissions reporting, https://ceobs.org/report-a-framework-for-military-greenhouse-gas-emissions-reporting/; Climate of Change - Reshaping Military Emissions Reporting (2022), https://www.osce.org/secretariat/529068; and Submission to the UNFCCC Global Stocktake: military and conflict emissions (2023), https://thefivepercentcampaign.files.wordpress.com/2023/02/gst-submission-military-emissions.pdf
8. Brett Clark, Andrew K. Jorgenson & Jeffrey Kentor (2010), Militarization and Energy Consumption, International Journal of Sociology, 40:2, 23-43, DOI: 10.2753/ IJS0020-7659400202
9. This estimate would be in line with some scarce earlier data on annual fuel consumption by Russia's military in 2016 in the amount exceeding 2 million tonnes per year, of which approximately two thirds were used by aviation (see https://tass.ru/armiya-i-opk/4031315), assuming that fuel consumption is responsible for approximately one third of total emissions.

warfare and the rate of increase depends on the share of forces committed to military action. The highest volume of fuel consumption is typically associated with jet fuel use for aviation, which could represent more than two thirds of total fuel consumption, and diesel fuel, which could represent about 20% of total fuel consumption. The ratio between jet fuel and diesel fuel will depend on the types of operations the military is performing as well as aviation use intensity during the warfare, which could be relatively low in some cases.

Thirdly, fuel consumption represents only a fraction of the total climate impact that occurs in the course of day-to-day activities of the armed forces, force mobilization, and military warfare. Other impacts combined, including embodied carbon in materials used for manufacturing of equipment and ammunition, construction materials and activities, as well as procurement of various goods and services, would most likely outweigh the impact of fuel consumption. Supply chain emissions could be two to five times higher than operational emissions of the military. Having in mind that in the course of the war stocks accumulated during many years, and even decades, are being used and depleted, the impact of such upstream emissions could be even higher.

Finally, due to the complexity of supply chains and secrecy of information, especially during an ongoing war, it is not possible to track all climate impacts and high-level assumptions with the focus on the most significant sources of GHG emissions (e.g. jet fuel in case of fuel consumption, artillery shells in case of ammunition, etc.) should be applied.

Besides, the impact of Russian aggression falls far beyond the direct emissions from fuel and energy consumption or even emissions associated with the supply chain. Analysts use a concept of total, global, and hybrid war to describe hybrid warfare tactics, including cyber, economic, informational, and covert operations, which are considered as much a part of Russia's approach to war as conventional warfare. Examples of such tactics include weaponization of energy, blockades of grain and other food items from Ukraine through the Black Sea, and even weaponization of environment to influence the public opinion of allies and the international community[10]. Impacts of such hybrid warfare practices should be also analysed as a part of other indirect GHG emissions linked to the military and warfare.

The current assessment focuses on Scope 1 emissions (e.g. fuel combustion, use of ammunition and explosives), other Scope 3 emissions (e.g. embodied carbon of military equipment and fortification structures), and a broad range of other indirect GHG emissions linked to the military (Scope 3 plus emissions). Scope 2 emissions from purchased energy are not covered by the assessment since they are considered to be not impacted by warfare.

10. War changes everything: Russia after Ukraine, edited by Marc Ozawa, https://www.ndc.nato.int/news/news.php?icode=1798

GHG emissions from fossil fuel combustion

Fossil fuels are essential for military activities and are used by tanks and armed vehicles, aircrafts, other military vehicles, as well as by logistic vehicles used for the transportation of ammunition, fuel, soldiers, food, medicines, and other cargo. Fuel is used during the mobilization of forces, operational movements, relocation, and even during stand-by. In addition, fuel is used by civilian vehicles involved in war-related activities: emergency services, medical vehicles, movements related to evacuation, rebuilding supply chains, operation of "tractor troops" recovering abandoned and damaged equipment, etc. Fuel storage facilities are also often targeted by missile or drone attacks to undermine the ability to sustain military operations.

The most visible equipment using fossil fuels include aircrafts and main battle tanks along with other armoured equipment, but the largest share of fuel consumption during the warfare is likely associated with the less obvious fuel consumers behind the frontlines. To deploy tanks and other armoured vehicles on the battlefield, a huge military machine operates on the background and requires even higher volumes of fuel and energy. This includes heavy vehicles transporting military equipment, cargo helicopters and planes, forward bases support activities, generators used at command posts and temporary bases, as well as other logistic required to move people and cargo to the area of operations and throughout the theatre of military actions. Reliance of Russia's logistic on the rail network, destruction of forward fuel and ammunition deposits by Ukrainian Armed Forces, and the risk of attacks by long-range artillery and drones resulted in the need to truck fuel and other cargo from the railheads located at the distance of 100 km or more from the frontlines[11] or even from the territory of Russia. This also means that there are significant volumes of fuels consumed even during the period when the operational pauses occur at the battlefield.

Large amounts of fuel consumption led to significant greenhouse gases emissions and war-related climate change impact. Quantification of fossil fuel consumption is very complicated though, due to limited data availability and high uncertainty levels. A bottom-up approach for quantification requires numerous data and assumptions about the number of vehicles involved in military operations and logistics, characteristics of various vehicle types, transportation distances and distance during the operational movement of the troops, supply chain structure, etc. Such military-related data are rarely available during peacetime and almost impossible to obtain during the war. Fuel consumption data are also rarely available at the disaggregated level disclosing fuel consumption for military purposes. Only indirect proxy indicators could be used to understand the scale of the fuel consumption during the war using a top-down approach.

11. See, for instance, analysis of logistic networks in Luhansk region of Ukraine, https://twitter.com/NLwartracker/status/1627047617938223106

Estimating fuel consumption by Russian forces

In general, the following approaches could be used for assessing the fuel needs during the warfare and associated GHG emissions, all of which face challenges in terms of data availability:

- tracking total fuel supply for military purposes (based on official data or proxy estimates);
- using benchmarks from previous studies and conflicts (e.g. fuel consumption per typical division per day or fuel consumption per soldier per day);
- tracking activity data for key fuel consuming equipment and machinery.

Fuel use based on fuel supply estimates

There are no official data for fuel supply for military purposes in Russia and only proxy estimates, such as an increase in fuel delivery to the regions near the frontlines, could be applied.

Even before the invasion, analysts indicated the build-up of fuel stocks in the Russian and Belarus regions bordering Ukraine. According to Russian rail shipments data analysed by Energy Intelligence, fuel shipment to seven regions bordering Ukraine and the south of Belarus significantly increased in January and February 2022. The daily volumes of fuel supply – primarily jet fuel and diesel, but also some gasoline – were 4 to 5 times higher than the average values reported for 2021. The data covered deliveries to Russia's Defence Ministry in seven regions in the southwestern part of the country (Bryansk, Belgorod, Voronezh, Kursk, Rostov, Krasnodar, and Smolensk), as well as occupied Crimea[12].

According to Bloomberg's calculations made in October 2022 based on a similar analysis of railway data, supply of gasoline, diesel, and jet fuel to the Russian Defence Ministry's units in six regions bordering Ukraine as well as occupied Donetsk and Luhansk regions rose about three times in 2022: from 0.465 million tonnes of fuel during 9 months of 2021 to 1.431 million tonnes of fuel during the same period of 2022[13]. Again, up to a fourfold increase in shipments has been recorded compared to the values observed in 2021.

The figures reported by Bloomberg include deliveries to the four major airports in Russia's southwest, where civilian flights have been banned since the first day of the invasion at the end of February.

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12. Russia Boosts Flow of Fuel to Troops at Border, https://www.energyintel.com/0000017f-0ebd-dfa7-a5ff-9fbf3c920000
13. Calculated based on the data reported by Bloomberg: Russia Sends More Fuel to Army In Ukraine Amid Mobilization, https://www.bloomberg.com/news/articles/2022-10-12/russia-sends-more-fuel-to-army-in-ukraine-amid-mobilization

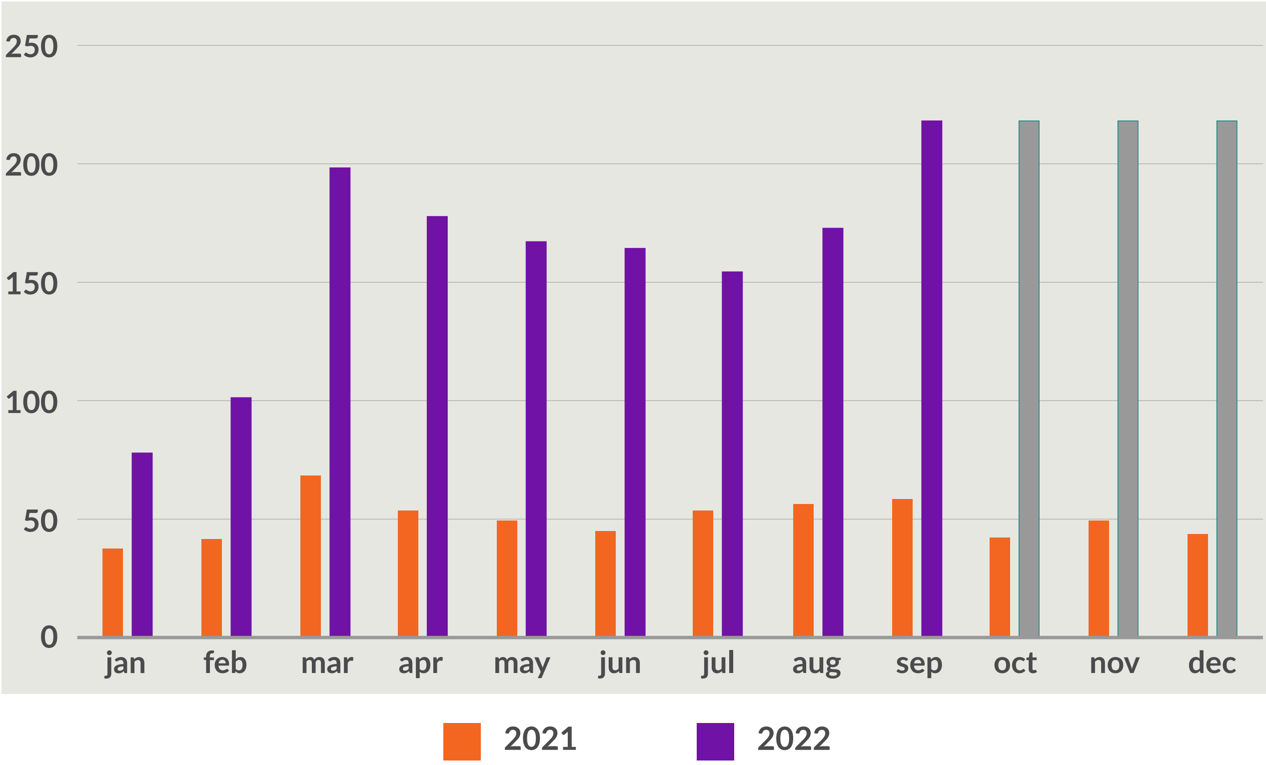

Fig. 1. Increase in fuel supply to the regions bordering Ukraine, by months, 1000 t (supply in Q4, 2022 is assumed based on the data for September and marked grey; this is a conservative estimate taking into account mobilization of additional manpower and resources)

The estimates based on railway supply data do not represent a complete picture since additional fuel could be supplied via maritime shipments to Crimea, oil products pipeline operated by Transneft in Voronezh and Belgorod regions bordering Ukraine, supplies to other parties that could be involved in military activities, and supplies from Belarus to the north of Ukraine during the initial phases of the war. For the purpose of analysis, an assumption about 30% of additional fuel supply via other routes has been applied.

PARAMETERS	Value, 1000 t
Reported additional fuel supply by railway during the 9 months of 2022	966
Estimated additional fuel supply by railway during 2022	1,483
Assumed fuel supply via other routes	30%
Estimated total fuel consumption due to the war in 2022	1,927
Estimated monthly average fuel consumption due to the war in 2022	161
Estimated monthly average fuel consumption due to the war (Sep-Dec 2022)	220
Estimated total fuel consumption due to the war – up to Feb 2023	2,367

Table 1. Data and parameters used for supply-based estimation of fuel consumption

An estimated increase in fuel supply by railway along with assumed supplies by other routes have been used as a proxy for fuel supply for the war needs. However, due to the suspension of civil aviation operation in the regions near Ukrainian borders, the part attributed to the military needs could be even higher than the difference with the previous year. The estimated values for September-December 2022 have been extrapolated to the first months of 2023.

Fuel consumption for the first year of the war using a supply-based approach is estimated at **2.4 million tonnes.**

Fuel use based on manpower involved

The second approach to estimate war-related fuel consumption is based on the previously reported values of fuel consumption per soldier per day during military conflicts. Such values, however, depend on the composition of forces involved and reliance on different types of military power (in particular on the intensity of aviation use), and, thus, are also associated with high uncertainties.

Deloitte's study published in 2009 noted a constant increase in fuel consumption during military conflicts due to increasing mechanization of technologies used in wartime, expeditionary nature of conflict requiring mobility over long distances, rugged terrain, and irregular warfare nature of operations. The average fuel consumption as of 2007 was estimated at 22 gallons per soldier per day (equivalent to 83.3 litres per soldier per day) and was expected to grow further[14]. Other reports put estimated daily fuel consumption at 16[15] and 27.3[16] gallons per soldier per day (equivalent to 61 and 103 litres per soldier per day) for the conflicts in Iraq and Afghanistan.

At the start of the invasion, the number of Russian soldiers involved in the attack was estimated at 190,000[17] and at the beginning of 2023 the number of soldiers involved in the occupation of Ukrainian territory was reported as 326,000-350,000, since additional personnel was involved after the mobilization announced in September 2022[18].

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14. Deloitte, Energy Security. America's Best Defense, https://legacy-assets.eenews.net/features/documents/2009/11/11/document_gw_02.pdf
15. The World's Biggest Fuel Consumer, https://www.forbes.com/2008/06/05/mileage-military-vehicles-tech-logistics08-cz_ph_0605fuel.html
16. U.S. military in Iraq feels gouge of fuel costs, https://www.nbcnews.com/id/wbna23922063
17. Армія Лукашенка. Як організована армія Білорусі та які існують сценарії нападу на Україну з півночі, https://www.pravda.com.ua/articles/2022/12/29/7382763/
18. Please, refer to В Україні воюють 326 тисяч російських військових, – ГУР, and Сергій Наєв, командувач Об'єднаних сил ЗСУ, генерал-лейтенант Кількість ворога, задіяного на території України і довкола неї, – трохи більше 350 тисяч осіб https://www.ukrinform.ua/rubric-ato/3673121-sergij-naev-komanduvac-obednanih-sil-zsu-generallejtenant.html

There is a significant uncertainty with respect to the number of troops and its changes over the duration of the war. For the purpose of assessment, the conservative value of 190,000 soldiers and the value of 83.3 litres of fuel per soldier per day have been applied. As of the end of February 2023, estimated amount of fuel consumption using this approach is **4.8 million tonnes.**

Total fuel consumption by Russian forces

The estimates derived using the two above approaches could be used as a lower and upper limit of fuel consumption by Russia's invading forces. The average estimate is **3.6 million tonnes of fuel.**

Data	Based on fuel supply estimates	Based on manpower estimates	Average
Fuel consumption, Mt	2.4	4.8	3.6

Table 2. Fuel consumption estimates

Most of the fuel is consumed by ground-based equipment, including the fighting "tooth" of the military and the supporting logistics "tail" of the armed forces (see the Annex for the indicative bottom-up assessment of fossil fuel consumption during the war).

Ukraine's fuel consumption

As for Ukraine, there is also no data available on fuel consumption for military purposes, but it is very likely to be significantly lower compared to Russia's fuel consumption and significantly higher compared to previous years. Significantly lower fuel consumption by Ukraine is explained by the benefits of interior lines of defence for Ukraine and reliance on lighter equipment and vehicles, as well as longer supply-chain distances for the attacking country. This would also be in line with the difference in the numbers of visually confirmed main equipment losses during the war, where Russian losses are 3.1 times higher than Ukrainian ones[19].

In the national GHG emissions reporting established under the UNFCCC, military-related emissions, including emissions from military fuel use, are included in category 1.A.5 OTHER (Not elsewhere specified) of the common reporting framework[20]. This is the most reliable data source for the military use of liquid fuel available to estimate the scale of military-related emissions in Ukraine before the start of Russia's invasion.

19. According to OSINT sources, as of the end of April 2023, Russia has lost 10,067 units of equipment and Ukraine has lost 3,213 units of equipment. See Attack On Europe: Documenting Russian Equipment Losses During The 2022 Russian Invasion Of Ukraine, https://www.oryxspioenkop.com/2022/02/attack-on-europe-documenting-equipment.html and Attack On Europe: Documenting Ukrainian Equipment Losses During The 2022 Russian Invasion Of Ukraine, https://www.oryxspioenkop.com/2022/02/attack-on-europe-documenting-ukrainian.html
20. Ukraine. 2022 National Inventory Report (NIR), https://unfccc.int/documents/476868

NIR category	Emissions, 1000 tCO_2e	Fuel use, TJ	Fuel use, 1000 t
1.A.5.b – Other (mobile combustion)	448.03	6,159.43	140

Table 3. Ukraine's National Inventory Report (NIR) data for 2020

Since the beginning of the war in February 2022, consumption of fuel for military purposes in Ukraine has increased significantly. A conservative assumption is that consumption has increased at least threefold corresponding to annual consumption of 0.42 million tonnes of fuel. Combined with the consumption of fuel by various civilian vehicles supporting military activities (e.g. transportation of vehicles and other supplies to the frontlines by thousands of volunteers), fuel consumption for logistics and other needs would likely be significantly higher.

For the current assessment, Ukraine's fuel consumption for the military purpose is assumed to be in the range of 0.8 to 1.6 million tonnes with the average value of **1.2 million tonnes**. For comparison, in 2022 Ukraine imported 7.3 million tonnes of oil products[21] (assumed fuel consumption represents 11-22% of oil products import). Ukrainian fuel consumption could be likely verified after the end of the war.

Emissions from fossil fuel consumption

Total estimated GHG emissions associated with fuel combustion are 18.8 million tCO_2e.

DATA	RUSSIAN FORCES	UKRAINIAN FORCES	TOTAL
Assumed fuel consumption, Mt	3.6	1.2	4.8
Direct GHG emissions from fuel combustion (estimated using default emission factor for diesel fuel), Mt CO_2e	11.4	3.8	15.2
Upstream GHG emissions associated with fuel combustion[22], $MtCO_2e$	2.7	0.9	3.6
Total GHG emissions from fuel combustion, Mt CO_2e	**14.1**	**4.7**	**18.8**

Table 4. Total fuel consumption and GHG emissions

21. Україна у січні скоротила імпорт нафтопродуктів та вугілля, https://ua-energy.org/uk/posts/ukraina-u-sichni-skorotyla-import-naftoproduktiv-ta-vuhillia
22. Calculated based on the emission factor of 745.68 kg CO_2e per tonne of mineral diesel as reported by the UK Department for Environment Food & Rural Affairs – well-to-tank (i.e., upstream) emission factors for fuel in the "Conversion factors 2022: full set (for advanced users)" spreadsheet (on the "WTT- fuels" worksheet), available at https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022

GHG emissions from the use of ammunition

Artillery guns in both 152 mm (used by Russia and Ukraine) and 155 mm calibres (used by Ukraine) are able to deliver a projectile of approximately 40 kg to ranges of 17-40 km and are used during the war on a massive scale. While at the beginning of the war both sides used artillery shells of 152 mm calibre, later Ukraine switched mostly to 155 mm calibre artillery provided by Western partners. At the end of the first year of the war, the distribution of artillery shells used was reported to be 10 to 1 in favour of 155 calibre[23], while on average for 2022, some estimates reported relatively equal shares of both artillery ammunition types[24].

The most significant amount of GHG emissions is caused by the manufacturing of ammunition and relevant raw materials, while additional emissions occur during the use phase due to combustion of the propellant during firing of ammunition and detonation of the warhead at the point of impact.

Artillery ammunition used during the war are likely to be remanufactured to replenish the stocks and there are already many announcements about the intensification of production and new production lines. Therefore, emissions associated with manufacturing of ammunition are taken into account for the assessment of climate impact of the war.

The use of artillery and other types of ammunition depends on the intensity of warfare at different parts of the front and varies significantly since the start of Russian invasion.

During the first assessment, reviewed estimates of the number of shells shelled varied considerably in the range of 5,000-60,000 shells per day. It also varied over time depending on the intensity of shelling at different sections of the frontline. In May and June 2022, Russia's artillery fire intensity was especially significant. Later on, the emergence of HIMARS systems on the battlefield allowed breaking the artillery supply chains and destroying many warehouses and thus push the remaining depots 80 km behind the frontlines[25]. There was a large number of ammunition destroyed due to strikes at ammunition warehouses and storage sites, which caused detonation and explosion of ammunition (more than Russian 50 warehouses were destroyed).

The assumed artillery use level for the initial interim assessment was 0.9 million of artillery shells per month (30,000 shells per day) or 5.4 million per six months of war for Russia and,

23. Комбриг 45-ої бригади Олег Файдюк: Нам однозначно треба більше гармат, https://www.pravda.com.ua/articles/2023/02/7/7388192/
24. Ukraine finally launches domestic ammunition production. How will this impact the war? https://euromaidanpress.com/2023/01/10/ukraine-finally-launches-domestic-ammunition-production-how-will-this-impact-the-war/
25. https://twitter.com/TrentTelenko/status/1605644712458670080

additionally, 0.2 million shells per month for Ukraine (7,500 shells per day) or 1.35 million per six months of the war. The estimates could be considered conservative under the conditions of limited information available and high uncertainty levels, as well as reported artillery use intensity estimates reported by various analysts[26].

Since then, there were growing reports of evolving artillery deficit for both Russian occupying forces[27] and Ukrainian army. Though Russia might have huge stocks of artillery shells accumulated during Soviet times, their age and unsatisfactory storage conditions led to propellant deterioration and made the older stocks unusable[28].

At the beginning of 2023, US and Ukrainian officials indicated that Russia's artillery fire was down dramatically and in some places, by as much as 75% from the high levels observed in 2022. The decline was not linear and happened over time, and there still were periods and sections of the frontlines with a very intensive artillery fire. Nevertheless, drastic reduction in intensity, along with the use of old and degraded artillery shells and efforts to obtain ammunition from other countries like North Korea and Iran, was a sign of Russia's diminished stocks of weaponry[29].

Reports from February 2023 stated that Ukraine asked for an increased artillery shells supply in face of expected escalation and the average use level was about 5,000 shells per day[30]. At the same time, Russia was estimated to use four times more artillery shells while

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26. According to the Royal United Services Institute for Defence and Security Studies report, Russia was firing approximately 20,000 152-mm artillery shells per day compared to Ukraine's 6,000, with an even greater proportional disparity in multiple rocket launchers and missiles fired. Source: Ukraine at War Paving the Road from Survival to Victory, https://static.rusi.org/special-report-202207-ukraine-final-web_0.pdf. According to other analysts, the firing rate was 1-1.5 million rounds per month (30,000-50,000 per day) from May 2022 onwards, https://twitter.com/Volodymyr_D_/status/1560350883929620481. Representatives of the MoD of Ukraine reported the use of 40,000-60,000 rounds per day by Russia during the period of intense fighting, https://telegraf.com.ua/ukr/ukraina/2022-09-06/5715744-godovoe-proizvodstvo-snaryadov-raskhoduetsya-za-mesyats-okkupanty-istoshchayut-svoi-arsenaly-pomozhet-li-kndr. There were estimates that during the six months of war Russia alone used 7 million artillery rounds, excluding losses due to the destruction of warehouses, https://theins.ru/politika/254514
27. See, for instance: Russia Struggles to Maintain Munition Stocks (Part One), https://jamestown.org/program/russia-struggles-to-maintain-munition-stocks-part-one/
28. Комбриг 45-ої бригади Олег Файдюк: Нам однозначно треба більше гармат, https://www.pravda.com.ua/articles/2023/02/7/7388192/
29. According to the US officials, the rate has dropped from 20,000 shells per day to around 5,000 per day on average, while Ukraine estimated that the rate has dropped from 60,000 to 20,000 per day. Ukraine also had to ration artillery use throughout the war and was on average firing around 3,000-7,000 artillery rounds per day. See: Russian artillery fire down nearly 75%, US officials say, in latest sign of struggles for Moscow, https://edition.cnn.com/2023/01/10/politics/russian-artillery-fire-down-75-percent-ukraine/index.html. See also https://twitter.com/konrad_muzyka/status/1635923958036922368
30. Ukraine pleads for ammunition 'immediately' as Russia steps up attack, https://www.ft.com/content/817b7e61-9f09-494c-8f96-934810033b62

trying to gain territory in the east of the country and deploy tens of thousands of newly trained conscripts in the war [31],[32].

Assumptions on the artillery use rates applied in calculations are presented in the table below.

FIRST INTERIM ASSESSMENT (6 months period from 24 February till August 2022)			
Data	**Shells per day**	**Shells per month**	**Shells per 6 months**
Assumed use of shells by Russia	30,000	900,000	5,400,000
Assumed use of shells by Ukraine	7,500	225,000	1,350,000
Total	37,500	1,125,000	6,750,000
SECOND INTERIM ASSESSMENT (6 months period from September 2022 till February 2023)			
Assumed use of shells by Russia	20,000	600,000	3,600,000
Assumed use of shells by Ukraine	5,000	150,000	900,000
Total	25,000	750,000	4,500,000
TOTAL NUMBER OF SHELLS DURING THE FIRST YEAR OF WAR			
Assumed use of shells by Russia			9,000,000
Assumed use of shells by Ukraine			2,250,000
Total			11,250,000

Table 5. Estimated artillery ammunition use

31. Nato is in ammunition race against Russia in Ukraine, says Stoltenberg, https://www.ft.com/content/3d3c9102-b8ef-4b1c-a8dc-6c844de71981
32. As of April 2023, Ukraine was reportedly using 7,700 artillery rounds per day, while Russia was firing three times more. See: Facing critical ammunition shortage, Ukrainian troops ration shells, https://www.washingtonpost.com/world/2023/04/08/ukraine-ammunition-shortage-shells-ration/

Total artillery shells use would be over 2 million shells for Ukraine and 9 million shells for Russia or over 11 million shells in total for the 12 months of war. Assuming 80 kg weight of the artillery shell with container, the total weight would be 900,000 tonnes.

Since no reliable information on the historic and current balances of ammunition is available, it is hard to verify the estimations made. However, the assumptions are considered feasible and conservative taking into account reported use intensity and available information on the artillery stocks and supply.

In particular, over half of the assumed volume for Ukraine could be tracked via information about the assistance provided by various partners[33]. Ukraine had also some stocks of 152 mm artillery shells. Ammunition stocks had been depleted by regular explosions at Ukrainian arsenals as a result of Russian sabotage with around 210,000 tonnes estimated to be destroyed during six explosions from 2014 to 2018. Besides, about 70,000 tonnes were used during the five years of the war in Donbas[34]. Still, some reserves were maintained and actively used during the initial period of the war. In addition, Ukraine launched domestic 152 mm artillery ammunition production at the end of 2022 and, though production capacity has not been disclosed, it is assumed to be in thousands shells per month[35].

According to some estimates reported in December, before the war, Russia had about 17 million units of ammunition, of which 10 million have been reportedly used. Russia's artillery recovery capacity was about 1.7 million units per year before the war, and during the mobilization the capacity of the arms industry has also been increased and potentially

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33. According to the FACT SHEET: One Year of Supporting Ukraine (https://media.defense.gov/2023/Feb/20/2003164184/-1/-1/0/UKRAINE-FACT-SHEET-PDA-32.PDF), the US alone provided 160 155 mm Howitzers and over 1,000,000 155 mm artillery shells, as well as over 6,000 precision-guided 155 mm artillery shells, 45,000 152 mm artillery shells, and 20,000 122 mm artillery shells. Artillery shells were also supplied by other countries, including 50,000 152 mm shells provided by the UK and sourced from Pakistan https://euro-sd.com/2023/01/articles/29154/demand-and-supply-the-complexities-of-artillery-and-ammunition-supply-in-the-war-in-ukraine/; 27,000 155 mm rounds from Canada https://www.canada.ca/en/department-national-defence/campaigns/canadian-military-support-to-ukraine.html; 18,500 rounds from Germany https://www.oryxspioenkop.com/2022/09/fact-sheet-on-german-military-aid-to.html, over 4,000 rounds from Czech Republic, https://www.czdefence.com/article/czech-republic-donates-artillery-ammunition-worth-czk-366-million-to-ukraine; and thousands rounds from Estonia https://www.eurointegration.com.ua/eng/news/2023/01/23/7154651/; and other countries https://www.kyivpost.com/post/11042
34. In Five Years, Russian Agents Blew Up 210,000 Tons Of Ukrainian Ammo — And Nearly Silenced Kyiv's Artillery, https://www.rusi.org/news-and-comment/in-the-news/five-years-russian-agents-blew-210000-tons-ukrainian-ammo-and-nearly-silenced-kyivs-artillery
35. Ukraine finally launches domestic ammunition production. How will this impact the war? https://euromaidanpress.com/2023/01/10/ukraine-finally-launches-domestic-ammunition-production-how-will-this-impact-the-war/

doubled[36]. Some other analysis indicates that even likely overestimated production capacity is lower and was growing from 0.2 million shells in 2015 to 0.7 million shells in 2021[37]. Besides, Russia also relied on the stocks from Belarus with 67,000 tonnes reportedly supplied from March through September 2022[38].

The emissions from the use of artillery ammunition include the following:

- 1,530,000 tCO_2e due to manufacturing of ammunition (steel casing and explosives);
- 30,825 tCO_2e due to emissions at the point of firing and at the point of impact;
- 2,138 tCO_2e due to emissions from detonation at the point of impact.

Total emissions from the use of ammunition would be approximately **1.6 million tCO_2e**.

Since the estimates cover only artillery shells, it is assumed that at least additional 30% of estimated emissions could be associated with the use of other explosives and ammunition, such as small calibre shells, medium and heavy mortars projectiles, land mines, hand grenades and grenades used by drones, ammunition for tank guns, artillery rockets and air missiles, etc. (including various ammunition exploded during the destruction of equipment).

Overall emissions associated with the use of ammunition and explosives would be at least **2 million tCO_2e**.

GHG emissions from construction of fortifications

After the liberation of a significant part of the Ukrainian territory in autumn 2022, Russia has started preparation for a further Ukrainian counteroffensive. Defence lines were formed both in Russia along the border with Ukraine and on the occupied territories of Ukraine behind the frontlines.

Numerous fortifications were constructed along the frontlines, which stretched over approximately 1,000 km on the east and south of the country[39]. The longest distance of fortified lines is represented by trenches of different depth and width[40].

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36. Grosberg: Venemaal jätkub ründevõimet veel kauaks, https://www.err.ee/1608815563/grosberg-venemaal-jatkub-rundevoimet-veel-kauaks
37. Russia Struggles to Maintain Munition Stocks (Part Two), https://jamestown.org/program/russia-struggles-to-maintain-munition-stocks-part-two/
38. Belarus has supplied Russia with 65,000 tons of ammunition, https://finance.yahoo.com/news/belarus-supplied-russia-65-000-222500509.htm
39. See the following article for the visualization of fortification lines location and length: Follow the 600-mile front line between Ukrainian and Russian forces, https://www.washingtonpost.com/world/interactive/2023/russia-ukraine-front-line-map/
40. See the following article for the description and visualization of the trenches and other elements of the fortification lines: Digging in. How Russia has heavily fortified swathes of Ukraine – a development that could complicate a spring counteroffensive, https://www.reuters.com/graphics/UKRAINE-CRISIS/COUNTEROFFENSIVE/mopakddwbpa/index.html

Trenches are excavated as fighting positions and a means to ensure protected connection between dugouts, shelters, and strongholds. They can include some type of flooring made of timber planks or trench boards, revetment constructed with timber frames, poles, and planks, as well as sections with overhead covers constructed with logs or saplings and earth cover. Trenches are made with the use of specialized military equipment, civil construction equipment, or hand tools. Apart of trenches, obstacles with the "dragon's teeth", pillboxes to serve as shooting positions, and other fortification structures from concrete and steel are also widespread. They were spotted on video, photo, and satellite images both near the frontlines and in other locations on the occupied Ukrainian territories and on the territory of Russia.

In many locations, fortifications are built in several layers of protective lines and additional fortification lines are constructed around cities, airports, logistic hubs, and other important sites[41]. Also, trenches are typically not linear but follow octagonal or zigzag traces. Taking all this into account, the length of trench lines is significantly bigger than the length of the frontline, and based on the analysis of satellite images, it has been estimated at 2,837 km (based on the preliminary assessment as of 10 April 2023; see Fig 2 and the Annex for details on the approach).

Fig. 2. Location of fortifications on the occupied territory of Ukraine and in Russia.

Potential GHG emissions sources related to the construction of field fortifications include emissions associated with the production and delivery of materials (e.g. wood, cement, concrete, etc.), destruction of carbon pools in the soil, fuel consumption during the operation of earth-moving equipment involved in trench digging, as well as future works for dismantling of fortifications and restoration of the landscape.

41. See fortifications map prepared by Brady Africk (an open-source intelligence researcher and an analyst at the American Enterprise Institute), https://read.bradyafrick.com/p/russian-field-fortifications-in-ukraine

There is a special military trenching machine (BTM-3) used by motorized and mechanized infantry units for the construction of trenches. The machine is able to dig trenches up to 1.5 m in depth (1.1 m wide at top and 0.5-0.6 m wide at bottom) with earth working capacity of 270-560 m/h (higher if the depth is lower). BTM-3 carries enough fuel for continuous digging for 10-12 hours and has fuel consumption of 75 kg per hour[42]. The speed of digging and fuel consumption depend on soil characteristics. Assuming the average capacity of 400 m per hour, digging of 1000 km of trenches would require 2,500 hours and 187.5 tonnes of diesel fuel. Additional energy would be required for digging emplacements for shelters and machinery. Still, even though fuel consumption of a single trenching machine is significant, the overall consumption is not material compared to all fossil fuel use during the war and could be estimated as below 1,000 tonnes. Similar level of fuel consumption could be expected for dismantling and restoration works.

Construction of field fortifications requires amount of concrete, wood, and other construction materials[43].

Concrete, which is a carbon intensive material, is used for the manufacturing of “dragon’s teeth”, various other anti-tank obstacles, shelters and bunkers, protected firing positions, weapon emplacements, and other reinforced concrete structures. Carbon footprint of concrete is directly proportional to the share of cement in it, as cement production process is very energy and carbon intensive with main emissions resulting from fossil fuel consumption and calcination process during clinker production.

“Dragon’s teeth” obstacles represent a prominent example of concrete use for fortification lines on the occupied territories of Ukraine. They are typically installed in two or three rows and there are also cases of parallel lines with two rows of concrete pyramids in each line[44].

Based on the characteristics of concrete obstacles and spacing visible on satellite images, videos, and photos, it could be assumed that one line of dragon’s teeth would require approximately 250-270 elements for the arrangement of 1 km of the protection line (about 4 m per element, assuming the distance of approximately 2 m between the elements). Assuming that typically at least two rows are installed, approximately 50,000 elements would be required for the construction of 100 km of protective lines (75,000 elements in case of three rows).

There are no reliable estimates of the total length of the established “dragon’s teeth” lines

42. BTM-3 Trenching machine, http://www.military-today.com/engineering/btm_3.htm; see also https://bmz.ru/high-speed-trench-digging-machine-btm-3
43. See, for instance, a line of more than 75 trucks with construction materials for fortification lines near Svatove town, https://twitter.com/DefMon3/status/1596507887572234241
44. See analysis of satellite images: Defenses Carved Into the Earth, https://www.nytimes.com/interactive/2022/12/14/world/europe/russian-trench-fortifications-in-ukraine.html, First on CNN: Russian mercenary group constructs anti-tank fortification, satellite images show, https://edition.cnn.com/2022/10/22/europe/russia-anti-tank-fortification-intl/index.html

and the number of concrete pyramids used for such purposes. For the purpose of carbon footprint estimation, it is assumed that at least 100,000 units were manufactured, which is sufficient for the defence line with the total length of about 200 km (with two rows of dragon's teeth). The assumption seems reasonable and conservative taking into account reported initial plans, confirmed sites of installation, and production volumes. Thus, at least 120,000 t of concrete have been used for the construction of dragon's teeth structures.

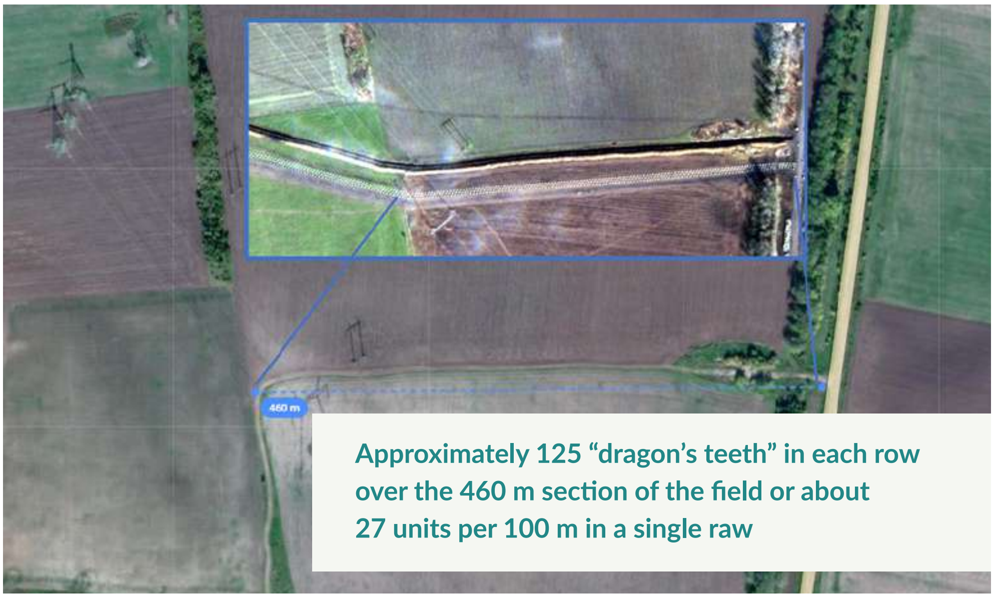

Fig. 3. Illustrative example of a dragon's teeth line in Zaporizhzhia region

High-resolution image ©Planet Labs 2023 | Powered by Planet, February 21 2023 | 47.31386, 35.2461. Graphic by Brady Africk (@bradyafr)

Still, this is only one type of concrete fortifications used at the battlefield. There were also numerous reports about the transportation and installation of precast concrete bunkers or pillboxes, in particular on the south of Ukraine[45]. For instance, the weight of a small firing position from concrete or machine-gun emplacement could be in the range of 1 to 2 tonnes. The weight of larger prefabricated or assembled from sections concrete pillboxes could be in the range of 10 to 30 tonnes. Large strongholds could require even higher volumes of concrete. For the purpose of assessment, it is assumed that at least 60,000 tonnes of concrete have been used for other fortification structures. The assumption requires further verification but is assumed conservative taking into account the massive length of the fortification lines (e.g. this would correspond to the use of about 20 tonnes of concrete per km of trenches, which is an equivalent of one concrete pillbox per km).

Ukraine also constructs fortifications on the liberated territories and other territories along the border with Russia and Belarus. Fighting positions and shelters from reinforced concrete were installed in Kyiv[46], Zhytomyr[47], and Rivne[48] regions. A concrete wall has

45. See, for instance: https://twitter.com/TrentTelenko/status/1588626918651621377
46. Reinforced concrete fortifications being built in the Kyiv region, https://mil.in.ua/en/news/reinforced-concrete-fortifications-being-built-in-the-kyiv-region/ and https://mil.in.ua/uk/news/na-kyyivshhyni-prodovzhuyut-rozbudovuvaty-fortyfikatsijni-sporudy/
47. Держкордон на Житомирщині укріплюють "ДОТами" та габіонами, https://mil.in.ua/uk/news/derzhkordon-na-zhytomyrshhyni-ukriplyuyut-dotamy-ta-gabionamy/
48. На кордоні з Білоруссю в Рівненській області зводять фортифікаційні споруди, https://mil.in.ua/uk/news/na-kordoni-z-bilorussyu-v-rivnenskij-oblasti-zvodyat-fortyfikatsijni-sporudy/

been also been constructed at some sections of the border between Ukraine and Belarus[49]. Field fortifications on the north of Ukraine include not only concrete fortifications but also shelters from special steel modules that are installed underground[50]. Concrete is also used for fortifications along the frontlines on the east and south of Ukraine (shelters, firing positions, strongholds, etc.). Besides, concrete shelters are installed in cities to protect civilians from shelling[51]. Smaller shelters and fortification structures could have a weight of about 20 tonnes while larger shelters weight around 70 tonnes.

There is no information available on the number of such structures installed, however, taking into account the announcements in the news and the length of the border, it is safe to assume that more than a hundred shelters have been installed in cities and many hundreds of concrete structures were used for fortifications. For the purpose of initial assessment, the assumption was made that at least 60,000 tonnes of concrete have been used for fortification structures and shelters.

Concrete used for dragon's teeth manufacturing, t	120,000
Concrete used for other fortification structures by Russian forces, t	60,000
Concrete used for fortification structures and shelters by Ukraine, t	60,000
Total amount of concrete used for fortifications, t	240,000
Total amount of concrete used for fortifications, m^3	100,000
Emission factor for concrete[52], t per m^3	0.5
GHGs emissions from concrete manufacturing, tCO_2e	**50,000**

Table 6. Assumptions used for the calculation of carbon footprint

In addition to concrete, carbon footprint of fortifications includes embodied carbon of other materials, such as steel shelters and various steel elements used for fortifications.

To estimate the carbon footprint of fortifications and shelters in a more precise way, a detailed inventory of the types of fortifications employed and materials used for their construction would be required (e.g. data on the quantities of materials used by militaries for the construction of fortifications or detailed analysis of a sample of fortifications lines with the description of the number and characteristics of shelters, strongholds, and other parameters of fortifications with further extrapolation for the overall length of fortification lines).

49. Україна будує стіну на кордоні з білоруссю. ФОТО, https://vechirniy.kyiv.ua/news/74184/ and https://mil.in.ua/uk/news/biloruski-prykordonnyky-pokazaly-stinu-yaku-buduye-ukrayina-na-kordoni/
50. Інженери готують позиції за допомогою підземних модулів, https://mil.in.ua/uk/news/inzhenery-gotuyut-pozytsiyi-za-dopomogoyu-pidzemnyh-moduliv/
51. See, for instance, a report about the installation of 10 concrete shelters in Ternopil city, https://te.20minut.ua/Podii/skilki-koshtiv-vitratili-na-betonni-ukrittya-bilya-zupinok-yak-u-inshi-11743891.html
52. Based on technical specification for B40 concrete class (i.e. 465 kg of cement, 1,750 kg of coarse and fine aggregates, and 180 kg of water per m3 of concrete) used for fortifications and emission factors provided by Concrete Embodied Carbon Footprint Calculator using data from the ICE database, https://circularecology.com/concrete-embodied-carbon-footprint-calculator.html

The initial analysis demonstrates that potential carbon footprint of fortifications could be up to **0.1 million tCO_2e**.

Embodied carbon in military equipment

Manufacturing of every piece of equipment and machines used during the war is associated with GHG emissions from consumption of energy and various raw materials.

The large-scale war caused by Russia's invasion of Ukraine resulted in an increased supply of military equipment and the need to increase investments in the manufacturing of new equipment. There are already reports demonstrating that military equipment manufacturing is increasing, and industrial plants are shifting to production of military-related products[53]. Thus, emissions associated with manufacturing of equipment are included in the estimation of climate damage.

The amount of embodied carbon is very specific to a particular equipment type and there is almost no data on life-cycle emissions associated with manufacturing of military equipment, such as main battle tanks or other armoured vehicles. Producers of equipment are starting to report the carbon footprint but limit information to mainly Scope 1 and Scope 2 emissions and do not report on the key categories of Scope 3 emissions, such as emissions associated with the production of raw materials and other products used during manufacturing. Therefore, indicative values have been used for the initial assessment of emissions associated with the destroyed and damaged military equipment (see the Annex for details).

Manufacturing of all machinery requires structural steels, alloyed steels, cast materials, light alloys, synthetic materials, and other resources. Armour of the main battle tanks and other armoured vehicles are made of steel and composite materials and its weight could be in the range of 30-50% from the weight of the tank, for instance. The amount of energy, materials, and GHG emissions associated with manufacturing process is proportional to the weight of machinery.

Data for civilian machinery and equipment (e.g. tractors, farm implements, trucks, etc.) could serve as a proxy and demonstrate the scale of emissions associated with military equipment manufacturing. Similar approach has been applied in a study assessing climate impact of Norwegian defence sector, where a proxy from the closest civilian type of equipment has been used to estimate the emission factors for the production of military equipment since corresponding values for military equipment are unavailable (even though

53. See, for instance: Russia Struggles to Maintain Munition Stocks (Part One), https://jamestown.org/program/russia-struggles-to-maintain-munition-stocks-part-one/

development, production, and cost differ)[54].

A study focusing on the lifecycle analysis of agricultural machinery estimated the amount of energy required per unit weight of farm machinery at 86.8 MJ/kg and the resulting emission factor at approximately 6 kg of CO_2e per kg of machinery weight[55]. This value has been applied as an indicative carbon footprint of military equipment for the purpose of initial assessment.

Manufacturing of military equipment is an energy- and resource-intensive process utilising specialist production facilities, complex international supply-chains, and (often rare) minerals, which themselves are energy intensive to extract and refine. Companies with higher proportions of military sales tend to have significantly higher emissions per employee compared to companies with higher share of civilian products. This indicates the more capital-intensive nature of military work, and also indicates that using the same GHG intensity for military and civilian work is a conservative approach that is likely to lead to an underestimation of the carbon footprint of military equipment[56]. Carbon intensity of military equipment manufacturing is likely higher than manufacturing of civil equipment and machinery.

As of the end of April 2023, the list of lost equipment based on open-source intelligence data included more than 10,000 visually confirmed losses for Russia and more than 3,200 losses for Ukraine. More than two thirds of the entries (68-70%) represent destroyed and damaged equipment, while the remaining units were captured or abandoned[57].

The lists of visually confirmed losses include various types of equipment, but only the following main categories were taken into account during the estimation of climate damage:

- Tanks
- Armoured Fighting Vehicles (AFVs)
- Infantry Fighting Vehicles (IFVs)
- Armoured Personnel Carriers (APCs)
- Infantry Mobility Vehicles (IMVs)
- Self-Propelled Artillery
- Multiple Rocket Launchers

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54. Magnus Sparrevik, Simon Utstøl, Assessing life cycle greenhouse gas emissions in the Norwegian defence sector for climate change mitigation, Journal of Cleaner Production, Volume 248, 2020, https://doi.org/10.1016/j.jclepro.2019.119196, https://www.sciencedirect.com/science/article/pii/S0959652619340661. See additional details in the Annex.
55. Carbon Dioxide Emissions Associated with the Manufacturing of Tractors and Farm Machinery in Canada, https://www.researchgate.net/publication/222979796_Carbon_Dioxide_Emissions_Associated_with_the_Manufacturing_of_Tractors_and_Farm_Machinery_in_Canada
56. The environmental impacts of the UK military sector, https://www.sgr.org.uk/publications/environmental-impacts-uk-military-sector
57. See Attack On Europe: Documenting Russian Equipment Losses During the 2022 Russian Invasion of Ukraine, https://www.oryxspioenkop.com/2022/02/attack-on-europe-documenting-equipment.html and Attack on Europe: Documenting Ukrainian Equipment Losses During the 2022 Russian Invasion of Ukraine, https://www.oryxspioenkop.com/2022/02/attack-on-europe-documenting-ukrainian.html

- Trucks, Vehicles and Jeeps
- Aircrafts
- Helicopters
- Naval ships

Only destroyed and damaged equipment was considered during the estimation of climate damage. For damaged equipment, only one third of the estimated embodied carbon has been taken into account in calculations. The eleven categories of equipment included in the assessment represent 89% of the visually confirmed destroyed and damaged equipment for Russia and 83% for Ukraine. For more detailed information on the indicative assumptions and results of GHG emissions calculation, see the Annex.

GHG emissions associated with manufacturing of the military equipment destroyed and damaged during the war was estimated at **0.9 million tCO_2e**, including 0.7 million tCO_2e for Russian losses and 0.2 million tCO_2e for Ukrainian losses.

Total warfare emissions

SOURCE OF EMISSIONS	$MtCO_2e$
Pre-invasion force accumulation[58]	0.1
Emissions from fuel consumption by Russian troops	14.11
Emissions from fuel consumption by Ukrainian troops	4.7
Emissions from the use of ammunition	2
Emissions from the construction of fortifications	0.1
Emissions associated with military equipment	0.9
TOTAL	**21.9**

Table 7. Total of GHG emissions from warfare

58. According to the assessment by KT-Energy LLC; please see for more detail the presentation titled "GHG emissions of Russian military preparations across borders of Ukraine", which is available at https://kt-energy.com.ua/en/projects/ghg-emissions-of-russian-militarypreparations-across-borders-of-ukraine/

3. FIRES

Fires result in significant GHG emissions from the combustion of carbon-containing materials (e.g. biomass in case of landscape fires or various construction materials in case of urban fires). Fires occur regularly even during peace time due to natural factors (e.g. lightening, meteorite impact, ignition of flammable materials during heatwaves and fire weather) or, more often, due to human impact (e.g. negligence while using fires or smoking in forests and other natural areas, arsons, open burning of agricultural residues on fields, technical failures of equipment, etc.). Most of the fires are registered in forest areas, agricultural fields, and other natural areas. During the war period, the number of fires and the area of affected lands have increased significantly, and most of them could be attributed to the impacts of Russia's invasion of Ukraine. The large number of refugees leaving the country, along with various restrictions, considerably reduced the number of fires that could be caused by negligence during the rest in natural areas. At the same time, large areas of land were affected by fires caused by shelling, bombing, explosions, mining of the territory, and other war-related impacts.

The impacts of the war have also significantly hindered the ability to monitor and respond to the fires due to the destruction of road infrastructure and bridges, power outages, closing the sky for civil aviation, risks for fire-fighting personal near the frontlines, lack of an efficient fire-fighting response system on the occupied territories, and other factors limiting fire-fighting options. This results in fires spreading to larger areas and greater levels of natural disturbance or destructions in urban areas.

Fires in natural ecosystems cause loss of biomass stocks and GHG emissions. The amount of emissions depends on the area affected by fires, average above-ground and below-ground biomass on this area, as well as fraction of biomass lost as a result of fires. Fires in forests affect not only living biomass but also litter and dead wood present in the forests.

For the purpose of assessment, it is assumed that all biomass losses result in emissions in the year of fires (Tier 1 approach in the IPCC guidelines), though some of the carbon emissions could occur immediately during the fires, while other biomass can be added to the dead organic matter pools and decomposed over decades causing GHG emissions or combusted later for heating or other purposes (harvested wood products).

Furthermore, forest fires reduce the sequestration ability, converting forests from a natural sink to a source of GHG emissions and further undermining climate mitigation efforts.

For urban areas, emission volumes depend on the amount of combustible material on the affected areas and carbon content of materials (e.g. wood, plastic, etc.).

The area affected by fires has been estimated using remote monitoring tools based on satellites data. The use of ground-based observations to collect a more reliable information on the level of fires impact was not possible during the war period.

Data on fires (number of fires, fire start and end time, coordinates of the boundaries of each fire, land categories for each fire) were obtained from open fire prevention information systems: the US-based Fire Information for Resource Management System[59] (FIRMS) and the European Forest Fire Information System[60] (EFFIS). The EFFIS system has begun to publish digital data on fires on the territory of Ukraine since 2020.

The assessment of the impact of the war was performed by comparing the areas of fires for two periods:

- Pre-war period: 24 February 2021 to 23 February 2022;
- First year of the war: a 365 days period from 24 February 2022 to 23 February 2023.

The assessment was limited to fires with an area larger than one hectare. Comparison with a longer historical period was not possible due to data limitations (lack of data from EFFIS before 2020) and the impact of very large single events during 2020.

To assess the impact of the war on fires, the territory of Ukraine has been divided into three zones (Fig. 4 and Fig.5):

- Zone 1 – covers 66.5% of the territory of Ukraine, where ground military operations were not conducted – blue areas on the maps;
- Zone 2 – zone of active hostilities (ground hostilities were conducted for more than 24 hours, frontlines from OSINT source[61]) covering 19.5% of the territory of Ukraine (12-mile zone on both sides of the changing front lines was applied) – yellow areas on the maps;
- Zone 3 – occupied territories (14.0% of the territory of Ukraine), in which ground military operations were conducted for no more than 24 hours or did not take place at all – red areas on the maps.

The maps below demonstrate a drastic increase in the number and area of fires during the first year of the war compared to the pre-war period.

59. https://firms.modaps.eosdis.nasa.gov
60. https://effis.jrc.ec.europa.eu
61. https://liveuamap.com/uk

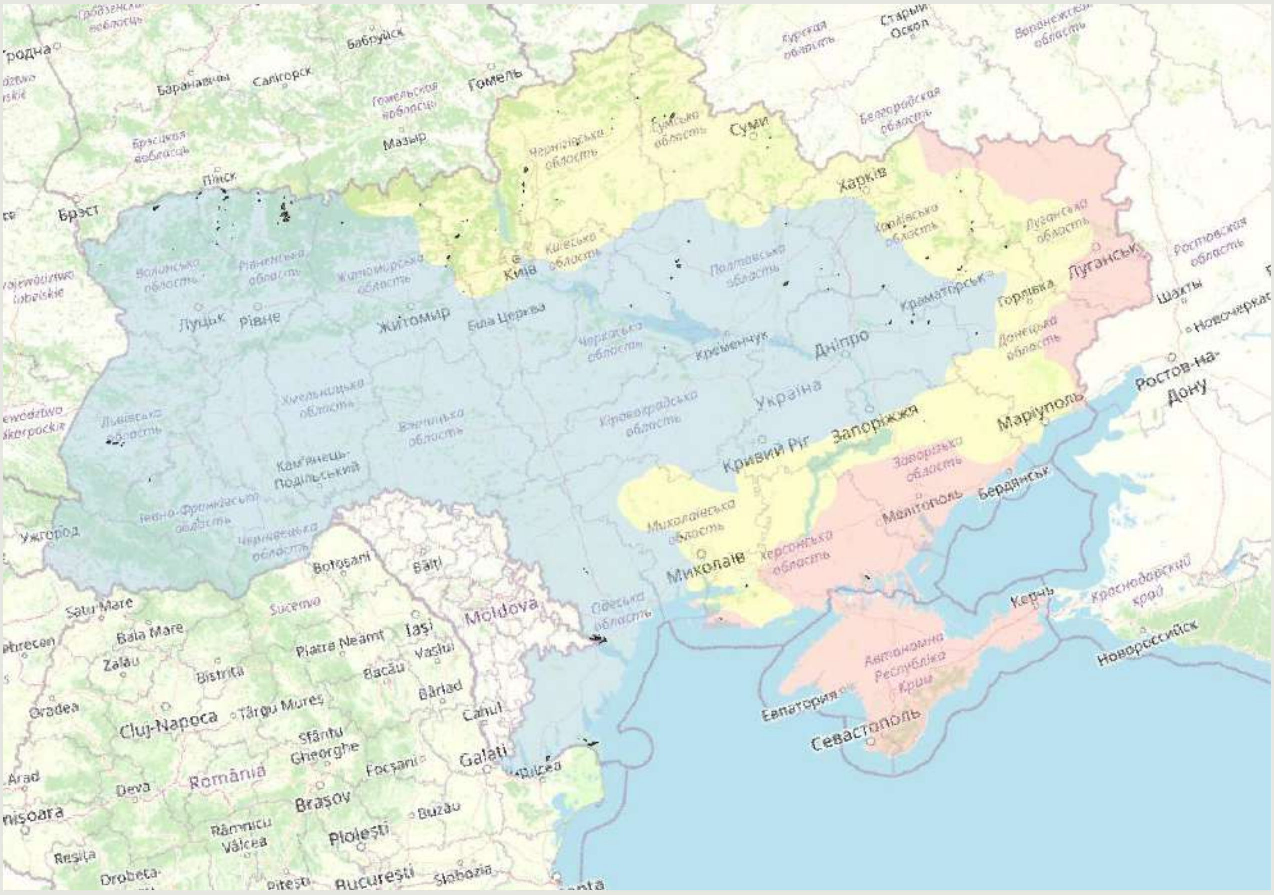

Fig. 4. Location of fires during the pre-war period (according to EFFIS)

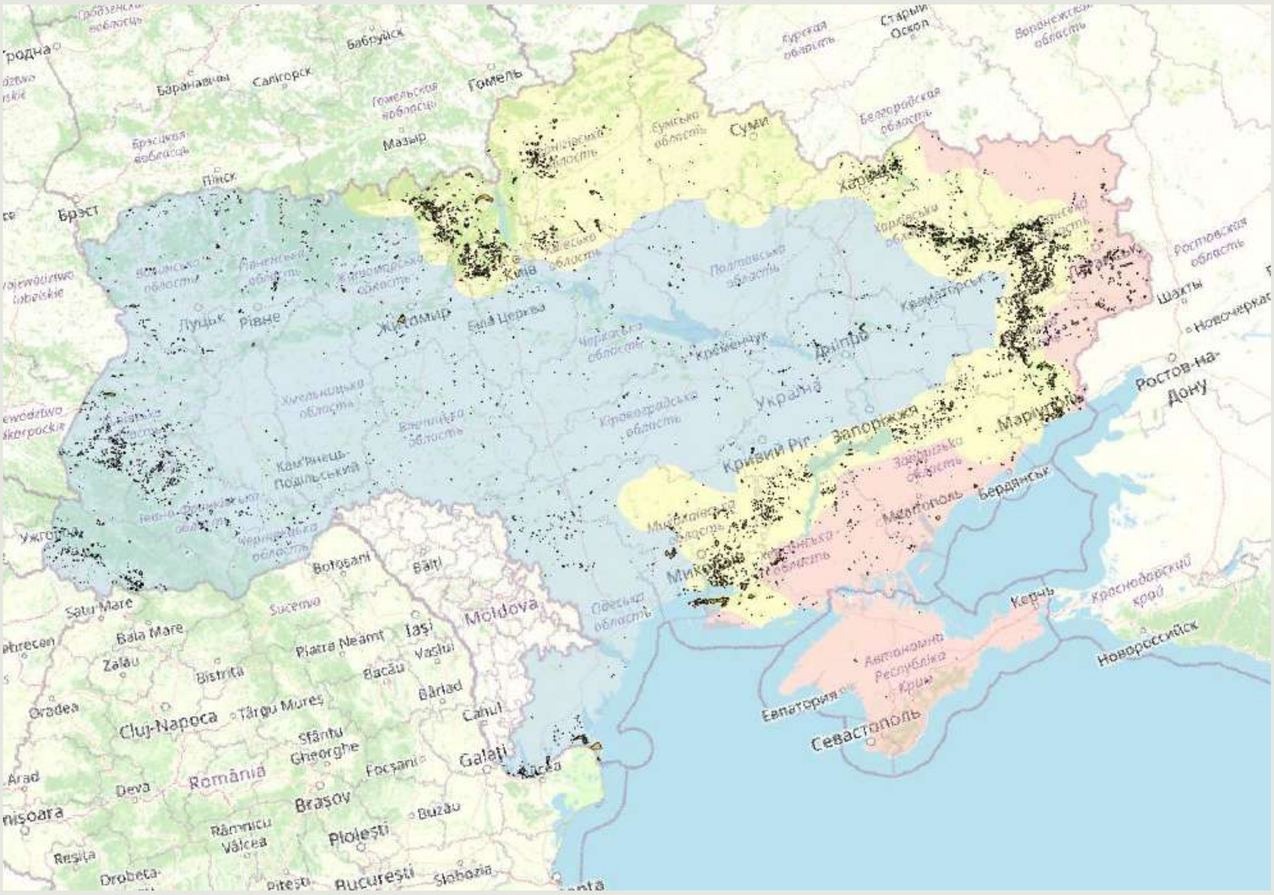

Fig. 5. Location of fires during the first year of the war (according to EFFIS)

Data on the number and areas of fires in different zones and different land use categories are presented in Table 8 below.

Zones	Number of fires	Total area of fires, ha	Area of forest fires, ha	Area of fires on agricultural fields, ha	Area of other andscape fires, ha	Area of fires in built-up areas, ha	Area of fires on other territories*, ha
PRE-WAR PERIOD							
Zone 1	120	24,865	7,084	5,851	11,784	43	102
Zone 2	53	10,489	763	4,778	4,794	49	102
Zone 3	4	262	0	126	109	0	27
Total	**177**	**35,616**	**7,847**	**10,755**	**16,687**	**92**	**235**
FIRST YEAR OF THE WAR							
Zone 1	2,100	129,629	7,905	94,656	25,775	474	819
Zone 2	3,749	316,536	48,571	234,002	29,581	2,733	1,649
Zone 3	439	48,926	2,405	43,057	3,222	146	96
Total	**6,288**	**495,091**	**58,882**	**371,715**	**58,578**	**3,353**	**2,563**

Table 8. Fires in Ukraine during the pre-war period and the first year of the war (larger than one hectare only)

* Fires on other territories are not taken into account during the analysis due to high uncertainty

The analysis of the data reveals a significant increase in both the number and area of fires caused by military actions. The total number of fires increased 36-fold and the total area increased 14-fold since the start of the war. The most significant increase occurred in the zone of active combat (Zone 2) and on the occupied territories of Ukraine (Zone 3). In absolute terms, the most significant increase occurred in Zone 2, which is directly related to active military actions and combat operations. In terms of land use categories, the most significant increase in the affected areas occurred on agricultural fields and built-up areas. However, in absolute terms the largest areas affected, along with the agricultural fields, were in forest areas and other natural landscapes.

For more detailed description of the methodological approach and emission factors used, see the Annex and the results of GHG emissions calculation for the pre-war period and the first year of the war presented in Table 9 below.

Zones	Total	Forest fires	Fires on agricultural fields	Landscape fires	Fires in built-up areas
PRE-WAR PERIOD					
Zone 1	1,676,008	1,493,469	66,016	82,491	34,032
Zone 2	287,330	160,880	53,901	33,559	38,990
Zone 3	2,184	0	1,422	762	0
Total	**1,965,522**	**1,654,349**	**121,339**	**116,811**	**73,022**
FIRST YEAR OF THE WAR					
Zone 1	3,290,403	1,666,714	1,067,909	180,424	375,356
Zone 2	15,252,184	10,240,247	2,640,011	207,066	2,164,860
Zone 3	1,130,666	507,076	485,769	22,557	115,264
Total	**19,673,253**	**12,414,037**	**4,193,689**	**410,047**	**2,655,479**
Increase in emissions	**17,707,730**	**10,759,688**	**4,072,349**	**293,236**	**2,582,457**

Table 9. GHG emissions from fires during the pre-war period and 12 months of the war, tCO_2e

Based on the analysis above, **17.7 million tCO_2e** of additional GHG emissions from fires were caused by military activities in Ukraine. Though three quarters of land affected by fires were represented by agricultural land, the majority of GHG emissions are associated with forest fires.

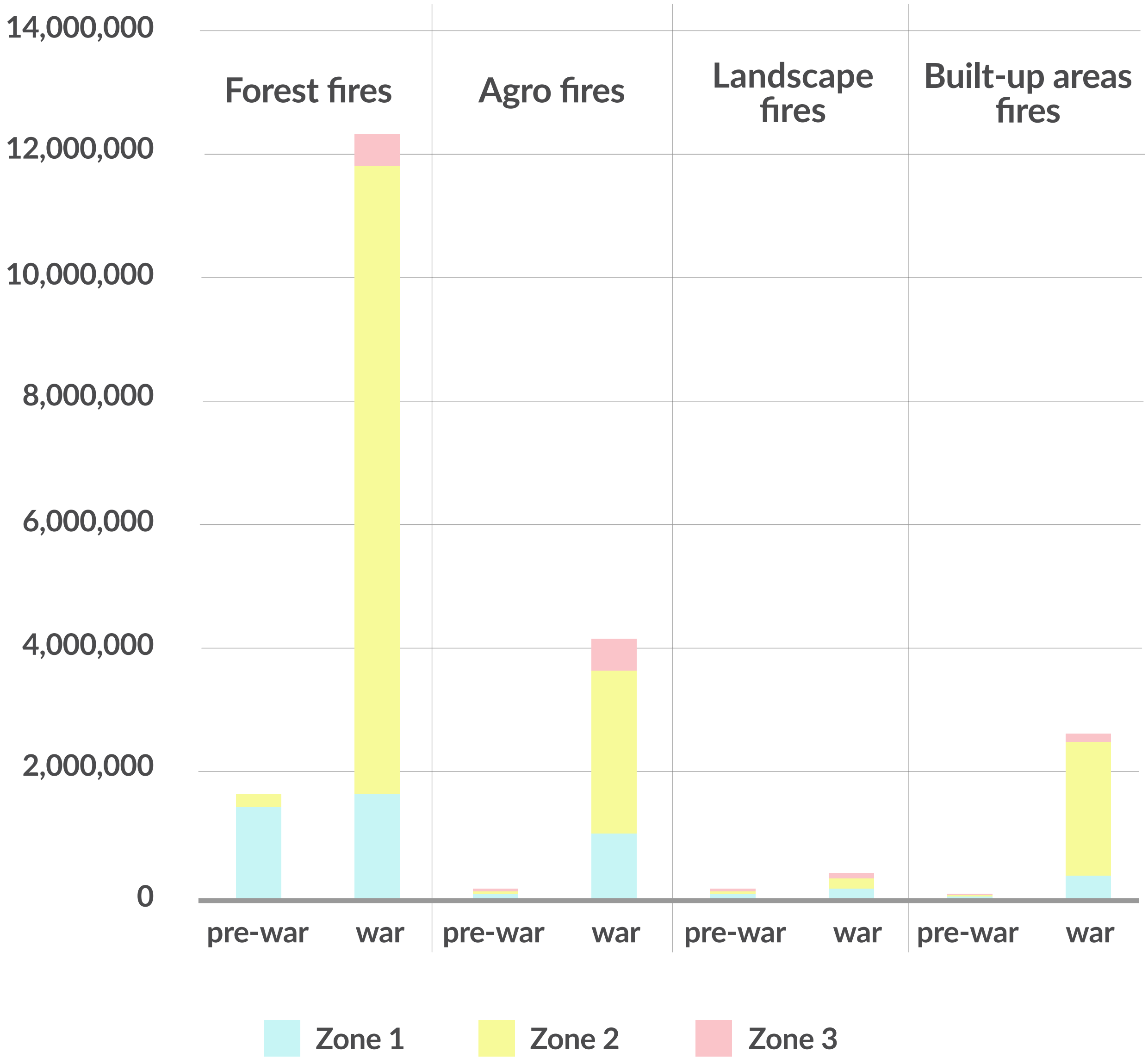

Fig. 6. GHG emissions by different land use categories, tCO_2e

The most significant increase in GHG emissions occurred in the active combat zone (Zone 2), which covers about 20% of Ukraine's territory. An increase in GHG emissions in other zones is also attributed to the impact of the war. In Zone 1, this is related to rocket and drone attacks on Ukrainian cities and limitations to respond to the fires in natural landscapes and urban territories caused by the war. Additional spatial-temporal analysis of the causes of fires revealed that most of the fires in this zone occurred in the regions and during the periods of air raid alerts (see the Annex for details). In Zone 3, which covers occupied territories, the attribution to the war is explained by the lack of efficient fire-response actions and additional impacts due to military operations.

4. REFUGEES AND IDPS

Immediately after the invasion on 24 February 2022, many Ukrainians decided to leave their homes. People fled westwards, staying in Ukraine as Internally Displaced Persons (IDPs), or went abroad to other European countries or even further, as Refugees. The number of Refugees and IDP that left their home at some point totals to 13.5 million, which is some 30% of the total population.

8,172,189	**Individual refugees from Ukraine recorded across Europe (18 April)**
5,044,039[62]	**Refugees from Ukraine registered for temporary protection or similar national protection schemes in Europe (18 April)**
5,352,000	**Estimated number of internally displaced people (IDPs) in Ukraine (23 January) Internal Displacement Report**

Table 10. Key figures on refugees and IDPs

Several months into the war, many refugees and IDPs have decided to return to their homes for various reasons. The liberation of occupied territories north of Kyiv, east of Kharkiv, and around Kherson made people feel safer. Other people simply did not want to be separated from their friends and families (18-60 year old men are not allowed to leave the country) for a longer time. Some refugees or IDPs simply did not have the means to stay somewhere else.

Although there is no exact data on how many refugees are abroad and how many have returned since then, a percentage can be derived from the difference between the total recorded refugees and the total refugees currently covered by the national protection scheme. The percentage is approximately 60%, assuming that 40% of the refugees have returned to Ukraine. For IDPs, the picture is less clear as those movements do not involve border crossings or foreign registrations. For simplicity, transport emissions of returning IDPs have not been taken into account.

62. https://data.unhcr.org/en/situations/ukraine, accessed 21 April 2023

Refugees that decided to stay abroad often visit their families from time to time. We assumed that, on average, each refugee staying in Europe made one visit to Ukraine in the first 12 months of the war.

The movement of people from and to Ukraine caused emissions of greenhouse gasses. In order to assess GHG emissions from refugees flying abroad and internally displaced persons (IDPs), we have considered three factors:

A) The number of people travelled; their departures and destinations

B) Transport modes

C) GHG emissions per person kilometre for each of those transport modes.

Please see the Annex for more detail regarding the calculation methodology.

Internally Displaced Persons	0.09
International Refugees	0.74
Transports returning empty	0.74
Refugees returning to Ukraine	0.20
Refugees in Europe visiting Ukraine	0.69
TOTAL	**2.46**

Table 11. Overview of transport emissions from Refugees and IDPs, $MtCO_2e$

5. EUROPEAN ENERGY SECTOR

The Russian Federation used its dominant position as supplier to the European gas market to pressure Europe in giving up its support to Ukraine. Russia significantly reduced the supply of natural gas already in 2021, but almost completely cut it off in 2022, triggering an unprecedented energy crisis in Europe. Gas supplies to the European Union more than halved — translating into a drop of 78 billion cubic meter (bcm) compared to 2021. The supply shock caused spot prices to average at a record high of EUR 120/MWh in 2022 – almost eight times their five-year average during 2016-2020, spiking to EUR 340/MWh at the end of August[63].

The price shock set several effects in motion including a significant drive to reduce gas consumption, replacement of Russian gas with Liquified Natural Gas (LNG), an increase of electricity prices and the reactivation of mothballed coal-fired power plants. Increasing energy prices amplified the cost-of-living crisis that emerged after the COVID pandemic.

In this section we discuss how the gas-supply shock impacted GHG emissions in the European energy sector in 2022 compared to 2021. We look into the consumption of natural gas by residential consumers and industry and emissions for the production of electricity. Other effects, not related to the war, impacted emissions in the energy sector as well and need to be separated from the war impact. Examples of non-war effects are lower generation of hydro power due to a historic draught, outage of French nuclear power plants and very mild winter weather.

Natural Gas

Total natural gas consumption in the European Union fell significantly with 55 bcm (or 13%) in 2022 compared to 2021[64]. In the residential sector, where consumption fell with 28 bcm, 18 bcm reduction was caused by mild weather condition which are obviously not related to the war. The remaining 10 bcm reduction was a mixture of energy-efficiency measures and behavioural changes, like lower room temperatures or shorter showers. Energy-efficiency measures are part of EU policy and the looming cost-of-living crisis would have led to reductions also in a no-war scenario, but given the significant fall in demand and impact of the war on energy prices, half of the reductions are attributed to the war. In the industry sector higher gas prices caused production curtailments (12.5 bcm) and energy-efficiency measures (5 bcm), which is fully attributed to the war.

63. Natural gas supply-demand balance of the European Union in 2023, https://iea.blob.core.windows.net/assets/227fc286-a3a7-41ef-9843-1352a1b0c979/Naturalgassupply-demandbalanceoftheEuropeanUnionin2023.pdf
64. Europe's energy crisis: What factors drove the record fall in natural gas demand in 2022? https://www.iea.org/commentaries/europe-s-energy-crisis-what-factors-drove-the-record-fall-in-natural-gas-demand-in-2022

Some industries were able to switch fuel with 7.5 bcm gas consumption being replaced with mainly oil. As oil is more carbon intensive, such fuel-switching led to higher GHG emissions. Taking into account both the reduction of gas consumption and increased oil emissions, an approximate reduction of 40 million tCO2e can be attributed to the war.

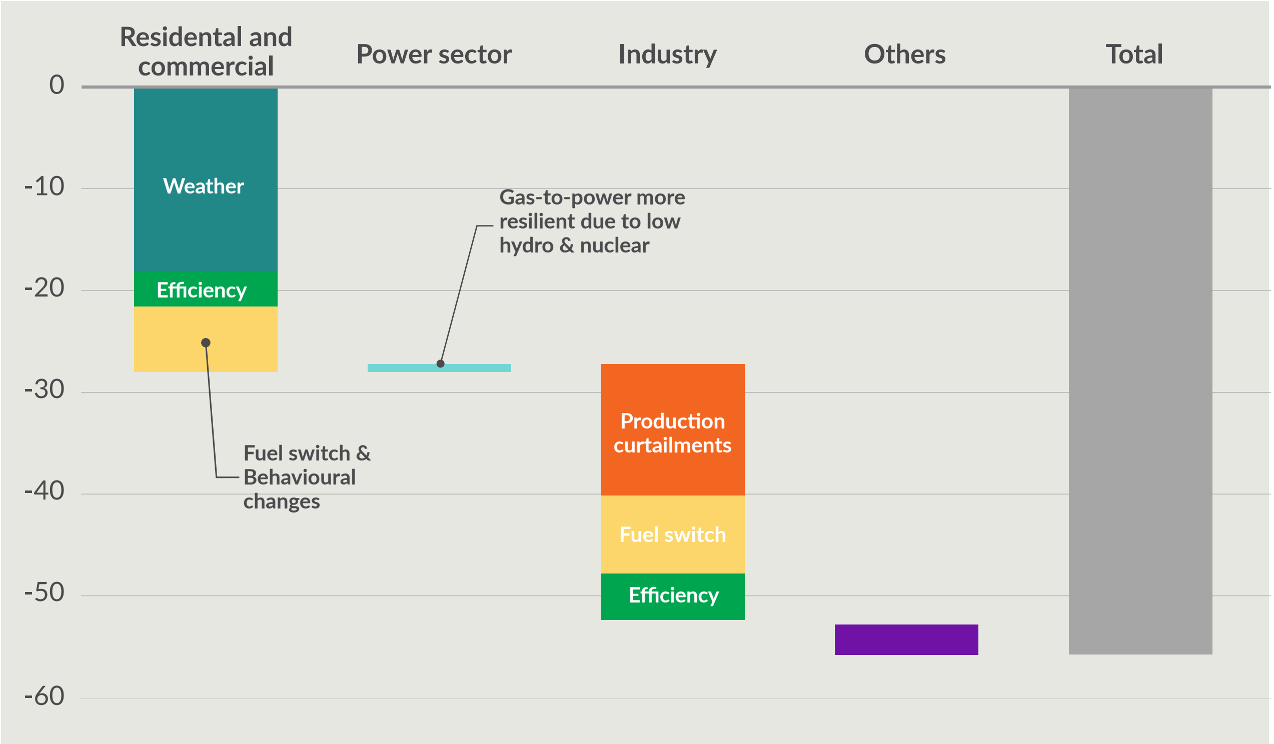

Fig. 7. Estimated year-on-year change (2021-2022,bcm) in natural gas demand in the European Union[65].

Source: International Energy Agency (IEA)

Electricity sector

Emissions in the EU power sector rose by 26 million tCO_2e (3.9%) in 2022 compared to 2021 despite the fall in demand. The power sector was faced with several crises at once: apart from the spiking gas prices due to Russia curtailing gas deliveries, many nuclear plants in France where out of order due to unscheduled maintenance while Germany was phasing-out the last nuclear power plants. A historic draught in Europe led to an all-time low hydro generation.

Fearing blackouts in winter, EU countries reactivated mothballed coal plants to have them ready for emergencies. The EU set a voluntary electricity demand reduction target for member states over winter.

The surge in coal-based generation ultimately did not materialize due to the surge in renewable energy production combined with reduced demand. No increase in coal generation took place, which could be mainly attributed to nuclear and hydro shortages.

65. https://iea.blob.core.windows.net/assets/227fc286-a3a7-41ef-9843-1352a1b0c979/Naturalgassupply-demandbalanceoftheEuropeanUnionin2023.pdf

However, the Russian Federation already started curtailing gas supplies in 2021 and, as a result, coal generation became cheaper than gas-based electricity generation. In 2022, no return to gas was observed as gas prices increased further. These additional emissions continued throughout 2022 and can be attributed to the war. (With the knowledge we have today, curtailing gas supply before the start of the full-scale invasion was a deliberate action by Russia to make the gas weapon more effective. However, it failed in the end).

2022 saw an acceleration of renewable energy generation (72 TWh), in particular in solar generation. There are many drivers that contributed to this surge, like local policies, higher electricity prices, and consumers' strife for becoming independent from the third-party power suppliers. The war has accelerated this surge. Given the lead times for permitting and installing the solar panels on roofs, we consider the war impact in 2022 to be moderate.

A drop in electricity demand was observed (79 TWh or 2.6%), although it was less significant compared to the drop in natural gas consumption. Similar to the causes of reduced demand in natural gas consumption, other effects, like mild weather and a looming cost-of-living crisis, affected electricity demand as well. Filtering out these non-war effects, we estimate that carbon emissions in the power sector increased by 15 million tCO_2e due to the war.

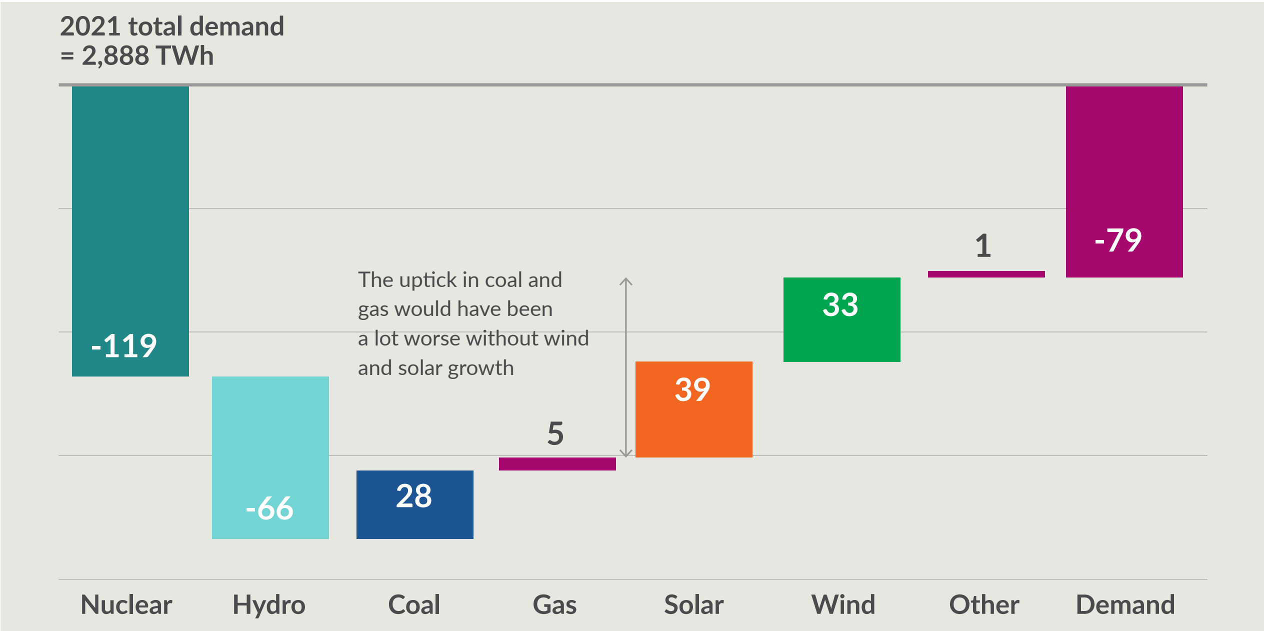

Fig. 8. Year-on-year change in EU-27 electricity generation* for 2022 (TWh).

Source: European electricity review, Ember
"Other" includes bioenergy, other renewables, other fossil fuels and net imports

*https://ember-climate.org/insights/research/european-electricity-review-2023/#supporting-

Pipeline gas versus LNG

The gas crisis forced European countries to look for alternative suppliers. Gas producers connected to the European pipeline network (e.g. Norway, Algeria) did not have the possibility to substitute all Russian gas and hence, the only option was to increase the import of LNG. In 2022, additional 55 bcm were imported into Europe, which is an increase of 70% compared to 2021.

An increase in demand led to more LNG being produced, but suppliers could not cover all the demand. Contrary to pipeline gas, the LNG market is a global market as LNG tankers, similar to oil tankers, can reach any destination in the world. The diversion of LNG streams towards Europe impacted emissions elsewhere in the world. Some customers were forced to switch to coal, thus increasing emissions. It was even reported that in some Asian countries, power supply was simply cut[66].

LNG has higher upstream emissions compared to pipeline gas: the gas has to be liquefied, tankers are needed to transport LNG, and LNG transportation is over much longer distances. Some estimations claim that these upstream emissions are up to 10 times higher compared to pipeline gas[67]. A UK analysis comes to lower differences, but still the difference is significant[68].

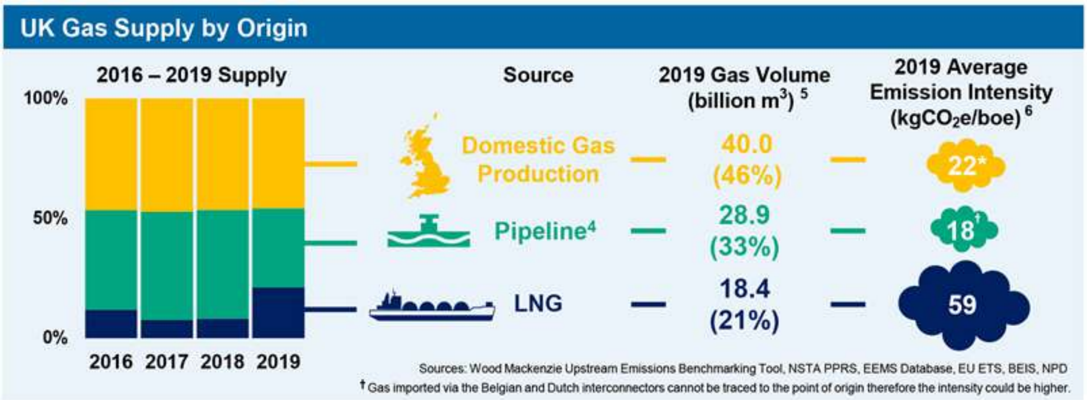

Fig. 9. Upstream emissions of LNG versus pipeline gas.
Source: North Sea Transition Authority

Increased LNG demand led to higher upstream emissions, estimated to be around 20 million tCO_2e.

Conclusions

Natural gas consumption in buildings and power sectors, as well as industry, reduced significantly and so did emissions. Some of these reductions were offset by increased consumption of more carbon intensive oil with increased upstream emissions of LNG causing the largest impact. Combined with an increase in power emissions, that can be attributed to the war, the decrease in emissions related to natural gas consumption is cancelled out by increased emissions elsewhere in the energy sector. An increase/decrease of 3 million tCO_2e could be observed in the European energy sector, which is negligible given the total emissions in the European energy sector.

66. Analysis: Gas shortage exposes fragile South Asian economies to more pain, https://www.reuters.com/markets/asia/gas-shortage-exposes-fragile-south-asian-economies-more-pain-2023-02-20/
67. Climate change: Hidden emissions in liquid gas imports threaten targets, https://www.bbc.com/news/science-environment-63457377
68. Natural gas carbon footprint analysis, https://www.nstauthority.co.uk/the-move-to-net-zero/net-zero-benchmarking-and-analysis/natural-gas-carbon-footprint-analysis/

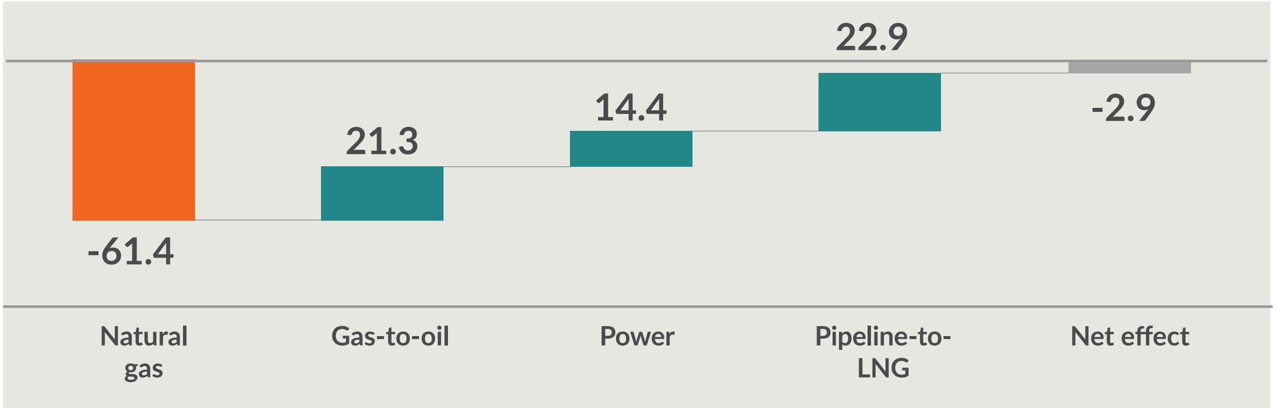

Fig. 10. Year-on-year change (2021-2022) of emissions in the EU energy sector attributed to the war ($MtCO_2e$)

The war will have a long-term effect on the European energy market. First of all, Russia's behaviour has shown that, contrary to earlier beliefs, it is fossil fuels that are an unreliable source of energy, not renewables. The energy shock has given an enormous boost to the renewable energy sector and made it evident that refusal from fossil fuels is the right choice. Despite a temporary, though moderate, increase in coal fired electricity generation and an increase in LNG imports, this war has accelerated the energy transition, a transition Europe is implementing to reach net zero emissions by 2050.

6. CIVIL AVIATION

Russia's war in Ukraine has had a significant impact on aviation. The closure of Ukraine's airspace to commercial traffic and the various airspace bans issued by Western countries and Russia have cut important east-west airways between Europe and Asia for many Western carriers, making nearly 18 million km^2 inaccessible for overflights. Carriers were forced to take detours on routes to East and Southeast Asia and resulting in longer flight times, as well as added fuel costs and higher greenhouse gas emissions.

Although technically only European and North American carriers are explicitly banned from Russian airspace, Asian airlines, including JAL, ANA, Korean Air, Cathay Pacific, Singapore Airlines, and Asiana are all avoiding Russian airspace. Similarly, Australian airlines are avoiding Russian airspace as a precautionary move.

The closure of airspace affected airlines in different ways, depending on the location of their hubs and specific routes. An April 2022 update by Eurocontrol shows significant increases of flight times to Asia from Nordic hubs[69].

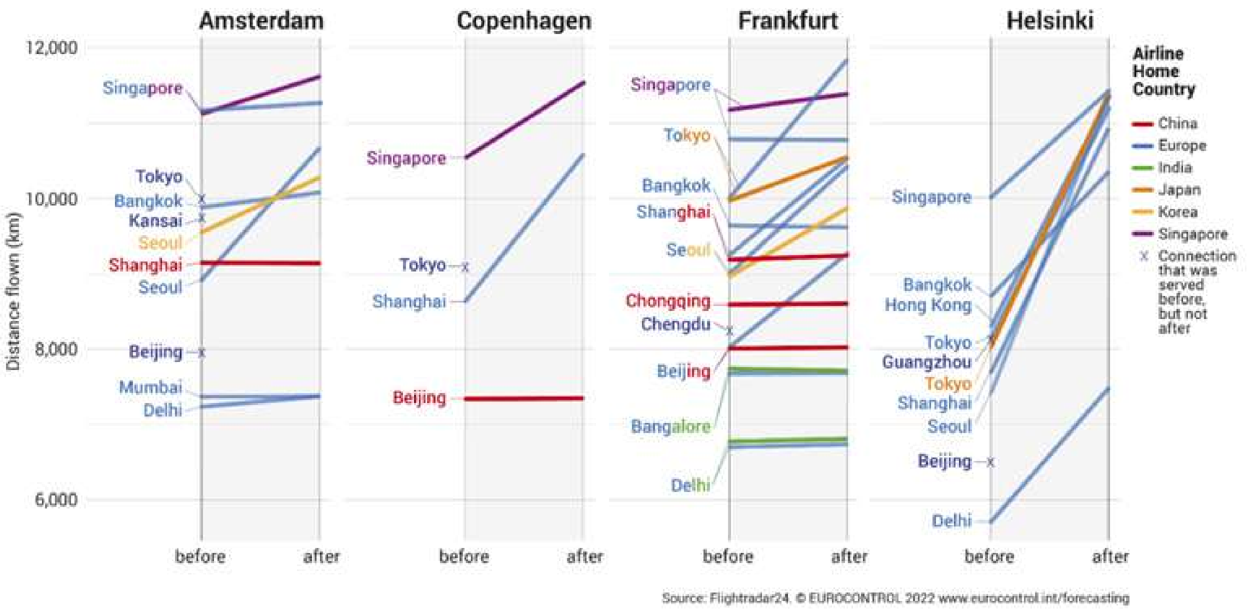

Fig. 11. Asian City Pairs: Changes in distance flown pre/post-Ukraine invasion

Out of the examples analysed by Eurocontrol, Helsinki was the most affected departure hub with additional distances between 1,400 km (Singapore) and nearly 4,000 km (Seoul), adding correspondingly 1.25 hours and 3.5 hours to the original one-way segment. For a Helsinki ↔ Seoul round-trip, as much as 7 hours needed to be added. Flying out of Copenhagen now requires an additional distance of around 1,500 km to Singapore and Shanghai. For Lufthansa, Beijing is now about 1,200 km further.

69. Eurocontrol data snapshop, 12 April 2022, https://www.eurocontrol.int/sites/default/files/2022-04/eurocontrol-data-snapshot-29.pdf

European carriers are routing south, through Georgia and Armenia, and non-European carriers still using Russian airspace are keeping further north, passing through Estonia and Latvia rather than Lithuania[70]. Qantas' flagship flights from Sydney and Melbourne to London currently run via Darwin, with Darwin to London now averaging a marathon of 17.5 hours, and sometimes even longer[71].

Fig. 12. Flying route from London to Tokyo.

Avoiding Russian airspace is having a much bigger impact on Japanese Airlines. Before the war, two of Japan's largest carriers, JAL and ANA, operated about 60 flights per week through Russian airspace between Tokyo and London, Paris, Frankfurt, and Helsinki[72]. JAL's flights between Tokyo and London, for example, travelled almost entirely through Russia and were regularly covered in under 11 hours. Avoiding Russian airspace, the journey

70. Eurocontrol data snapshot, 23 March 2022, https://www.eurocontrol.int/publication/eurocontrol-data-snapshot-28-how-re-routing-around-ukraine-disrupting-traffic-flows
71. Airlines chart new paths to avoid Russian airspace, https://www.pointhacks.com.au/news/airlines-avoid-russian-airspace/
72. Japanese Airlines Cancel, Reroute Flights Scheduled to Fly Over Russia, March 3, 2022, https://www.travelpulse.com/News/Airlines-Airports/Japanese-Airlines-Cancel-Reroute-Flights-Scheduled-to-Fly-Over-Russia

has been extended by at least 1,800 miles and four flight hours, taking the flight in the opposite northeastern direction, over Alaska, Canada, Greenland, and Iceland. The flight time has correspondingly increased to almost 15 hours when bound for the UK.

On the other hand of the spectrum, South East Asian carriers have been affected less due to the more advantageous location of their hubs. Singapore Airline's flights to London, for example, only extended the flight time by 15 minutes[73].

The impact has been also felt with regard to intra-European flights. Flight time to and from Romania has grown significantly, as well as Scandinavian and Baltic flights that are now avoiding Ukraine.

With many flights now taking longer than before and consuming more fuel on the back of increased oil prices, multiple factors affected the pre-war routes. Significant disruptions to flight schedules meant that some airlines were physically unable to run flights at the volumes they could previously. For example, Finnair's routes to Asia had been based on faster turnarounds, allowing one plane to operate out and back from Helsinki within 24 hours. This meant Finnair could offer daily flights on many routes without needing as large a fleet as some other airlines. Yet, with Asia-Helsinki services stretching to 14 hours each way, combined with service time on the ground, it became impossible to serve every destination at the frequency Finnair did before. The pass-through of the costs has also affected passenger demand for long-haul flights to and from Asia.

Some Western airlines have abandoned routes to East Asia as a result of these challenges. Virgin Atlantic put an official end to its London to Hong Kong route in March 2023 after almost 30 years of service, citing the logistical impact of the detour. London to Hong Kong flight times would have needed to be extended by approximately 60 minutes and Hong Kong to London by 1 hour and 50 minutes if the flight were to remain operational[74]. Finnair has stopped flights from Helsinki to Beijing, and SAS has stopped flights from Copenhagen to Tokyo. In many cases, if not cancelled, the frequency of the connection has been reduced.

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73. Ibid
74. Russia's war on Ukraine redrew the map of the sky – but not for Chinese airlines, CNN, 25 April, 2023, https://edition.cnn.com/travel/article/china-europe-airlines-russia-ukraine-airspace/index.html

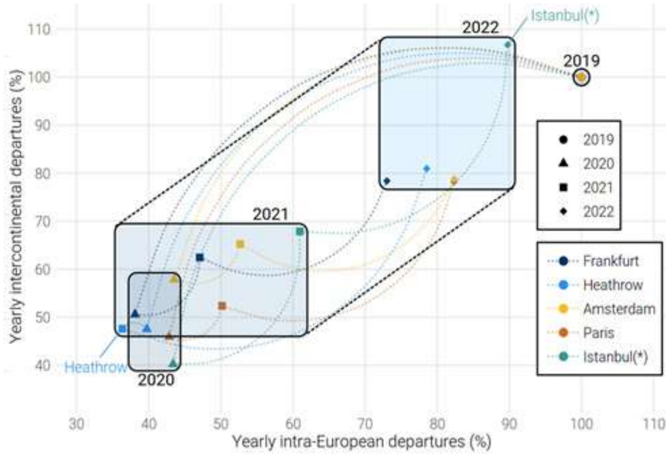

Fig. 13. Path to recovery for the top 5 airports (in 2019)
Source: Eurocontrol

Some of the European data also shows potential redirection of passenger flows. For example, the number of yearly intercontinental departures from Istanbul grew disproportionately in 2022 compared to other European hubs[75].

The impact of these developments on GHG emissions is harder to interpret. Before 24 February 2022, the air traffic in Europe steadily increased and continued to grow in 2022, reaching 83% of pre-pandemic levels by the end of 2022. The overall number of flights in the Eurocontrol member states has not shown a perceptible difference between before and after the start of the war. The flights between Germany and China have actually increased by 10%[76]. Part of this increase is likely to be taken by Chinese airlines that are not affected by the airspace closure.

In terms of actual emissions, redistribution of air traffic was similarly reflected in CO2 emissions assigned to each state as per ICAO rules when compared to 2019 data[77]. The data demonstrates an increase in flights from/to Serbia and Armenia, the two countries that, along with Turkey, have absorbed the passenger flows from/to Russia in the Eurocontrol area.

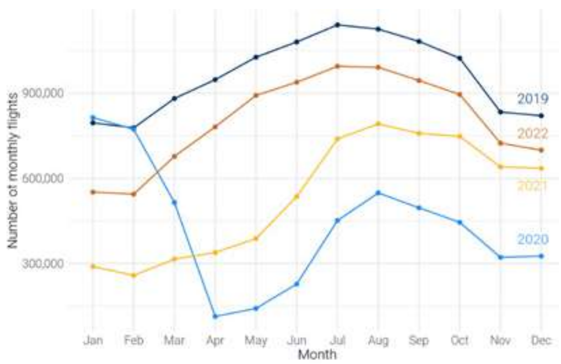

Fig. 14. Network traffic as monitored in the Eurocontrol member states.
Source: Eurocontrol

75. Eurocontrol data snapshot, 18 January 2023, https://www.eurocontrol.int/publication/eurocontrol-data-snapshot-28-how-re-routing-around-ukraine-disrupting-traffic-flows
76. Eurocontrol data snapshot, 23 March 2022, https://www.eurocontrol.int/publication/eurocontrol-data-snapshot-28-how-re-routing-around-ukraine-disrupting-traffic-flows
77. Euroconrol, accessed May 2023, https://ansperformance.eu/efficiency/emissions/

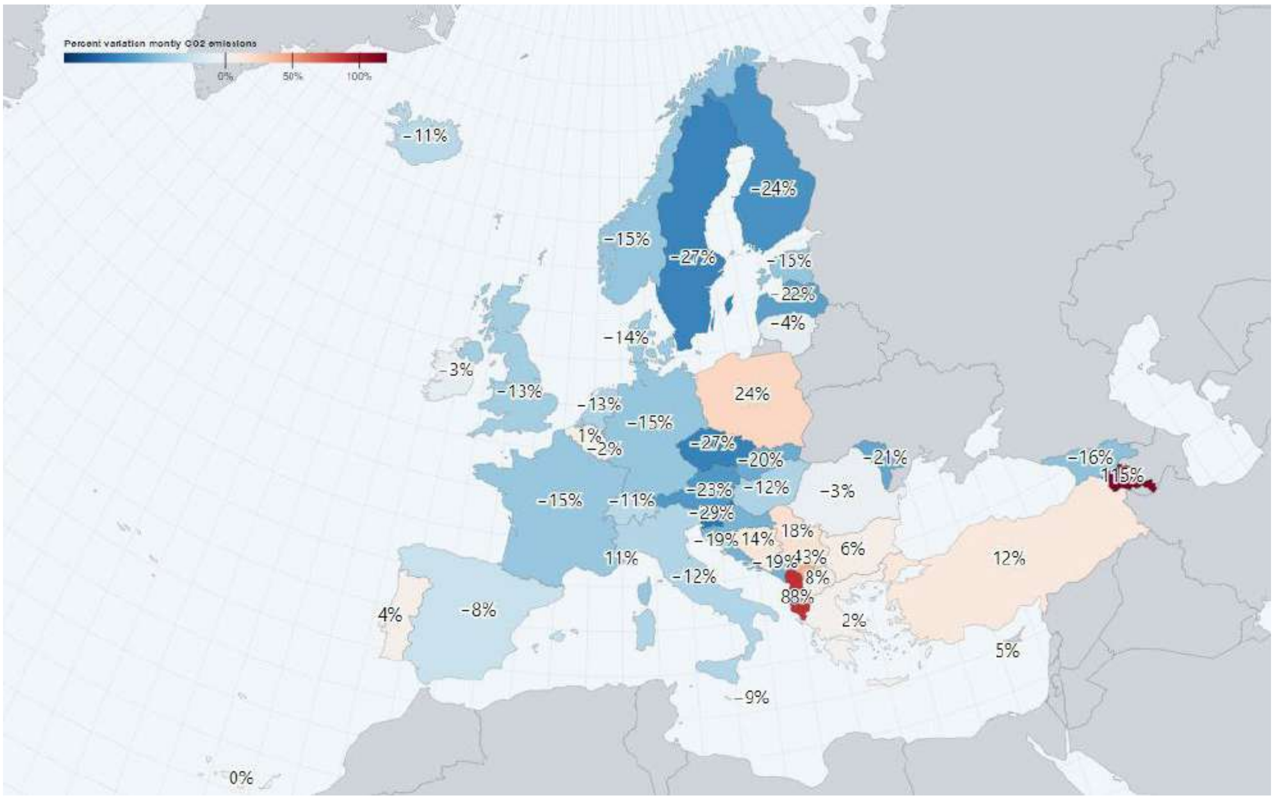

Fig. 15. Percent variations in monthly CO_2 emissions, April 2019 to April 2023.
Source: Eurocontrol

Total emission volumes in the Eurocontrol area, however, have only been marginally affected by the changes caused by Russia's war. The overall emissions show a growth of 62 million tCO_2e (56.9%) between 2021 and 2022. The majority of this increase is driven by air traffic recovery from pandemic levels, which grew by 51.0% between 2021 and 2022.

The actual impact of additional fuel consumption resulting from re-routing of specific flights is harder to see using the aggregate data set, as the impact of re-routings is masked by cancellation of routes and drops in passenger flows to and from Russia, Belarus, and Ukraine, cancellation of some of the Asian routes, and a decrease in the service frequency on some of the affected routes. Furthermore, the growth of carbon intensity of European traffic would need to be decoupled from carbon intensity growth in the years preceding the war, when CO_2 emissions were observed to be increasing faster than air traffic due to larger aircraft use and servicing farther distances, with emissions increase being significant enough to even offset improvements in aircraft and flight efficiency.

Nonetheless, if air traffic intensity were assumed to be constant between 2021 and 2022, the incremental increase that could be potentially attributed to re-routings, among other factors, could reach just over **12 million tCO_2**, based on the Eurocontrol data.

7. CIVILIAN INFRASTRUCTURE

Destroyed or damaged civilian infrastructure is an important component of the climate damage caused by Russia's war in Ukraine. Some of the repair works are already happening with the war still ongoing, like in liberated areas north of Kyiv or east of Kharkiv. The majority of the rebuilding or reconstructing efforts, mainly in the eastern and southern part of the country, will happen only after the end of the hostilities.

Ukrainian authorities started collecting and assessing, in a systematic way, information about the damaged or destroyed facilities soon after the start of the full-scale invasion. The Kyiv School of Economics (KSE) is aggregating this information coming from different Ukrainian ministries and other sources. Where information is not available or restricted due to security reasons, public-sources and estimations are used by KSE to provide a comprehensive picture.

The first full assessment was made over the period 24 February - 30 August 2022, which was the basis of our first carbon assessment. In March 2023, the second full assessment was published covering the first 12 months of the war (24 February 2022 - 23 February 2023)[78]. The overall damage assessment has been carried out in accordance with the methodology of the World Bank and monetary damages represent the replacement value. This report is the basis of our estimations.

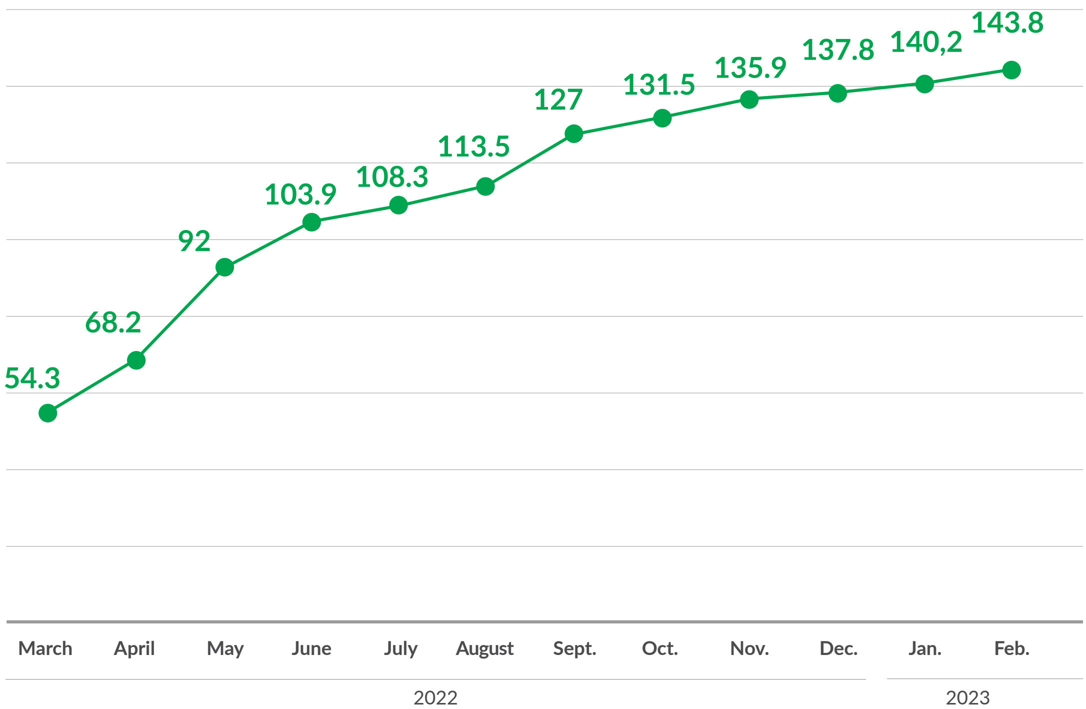

Fig. 16. Dynamics of the aggregate assessment of direct damages to Ukraine's economy, $ bn.
Source: Kyiv School of Economics

78. Report on Damages to Infrastructure Caused by Russia's War against Ukraine One Year after the Start of the Full-Scale Invasion, March 2023, https://kse.ua/wp-content/uploads/2023/03/ENG_FINAL_Damages-Report_.pdf

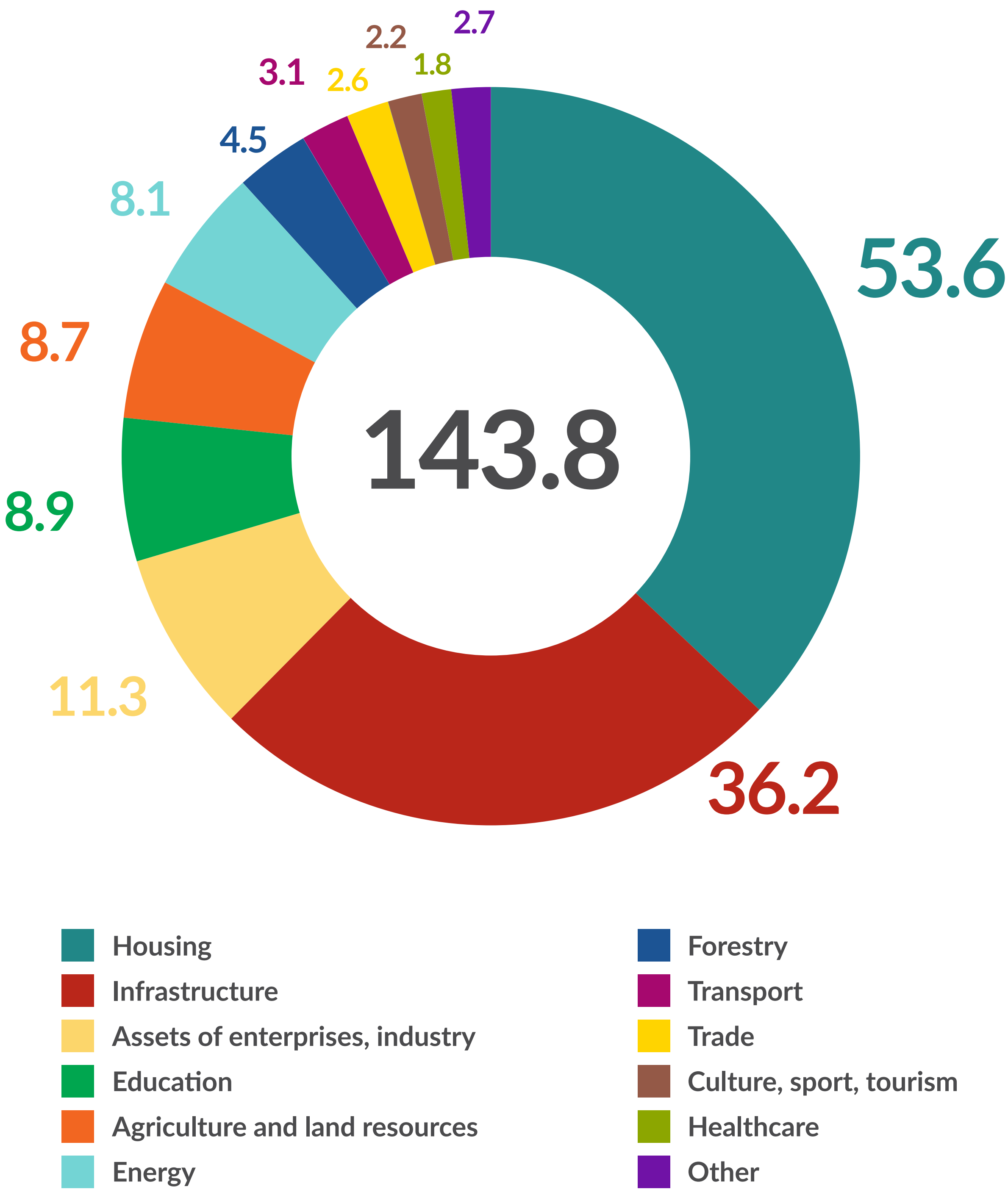

Fig. 17. Direct damages by type of property, $ bn.

The largest damage in monetary terms faced the residential sector (housing) followed by infrastructure. Most damage was done during the first six months of the war, while in the second half of the 12 month period, the growing rate of damages decreased, as shown in the graph below. This is mainly caused by the fact that front lines have hardly moved and many objects had already been destroyed in the first months of the war. Large increases were, however, observed in the energy sector and forestry.

Fig. 18. Growth of direct damages, $ bn. Source: Kyiv School of Economics

As an example, below one can see a list of the residential sector units (housing stock) that existed in Ukraine before the war (first column) but were then either damaged (second column) or destroyed (third column). Similar lists are provided for each type of property.

	STOCK (units)	DAMAGED (units)	DESTROYED (units)
Apartment buildings	178,921	6,016	11,535
Private houses	8,984,976	66,618	63,391
Dormitories	7,114	79	223

Table 12. Overview of residential housing available before the war and units damaged or destroyed

The reconstruction works will demand amount of construction materials, like cement, steel, or asphalt. Transportation of these materials to construction sites and construction activities will require fossil fuel. In general, reconstructing Ukraine will cause significant amount of GHG emissions.

For the purpose of this assessment, we have grouped different types of properties into three categories:

- The first category comprises residential sector, health care, social sector, education and science, culture, religion, sports, tourism, and retail. These objects mainly include buildings.
- The second category comprises infrastructure, vehicles, and agricultural machinery. These objects are a mixture of civil engineering objects, e.g. bridges and roads, plus transport vehicles of different types.
- The third category comprises energy sector, industry and business services, digital infrastructure, and utilities. These objects mainly include machinery and equipment combined with buildings housing the machinery.

To assess GHG emissions from the reconstruction of civilian infrastructure, the embodied carbon approach is used. Under this approach, all emissions, both direct and indirect, are estimated over the whole life cycle of an object, but excluding operational emissions. Operational emissions are typically caused by energy used to heat a building, petrol to fuel a car, or coal to fire a thermal power plant.

For the category of buildings, the embodied carbon is based on the average buildings' areas, data which were provided by the Kyiv School of Economics. For each type of building, a specific embodied carbon factor (tCO_2e/m^2) was assigned based on current averages of recently designed buildings in Central and Eastern Europe. For more details, see the Annex.

For the category of transport and infrastructure, embodied carbon factors were considered for different types of objects, like tCO_2e/km of damaged road or tCO_2e of damaged car.

For the category of industry and utilities, no embodied carbon factors exist and/or the information is aggregated at such a high level that different types of equipment cannot be distinguished. For this category, spend-based emission factors are used based on the Environmentally Extended Input Output (EEIO) analysis. These factors reflect the amount of carbon emitted when purchasing a certain good or service for a certain value (tCO_2e/USD). As KSE considers damages as a replacement value, this approach is applicable with this data. Ideally, these spent-based factors should be determined at the country level, but, unfortunately, these factors are not available for Ukraine. As a proxy, spend-based emission factors for the United Kingdom were used[79]. As a verification step, the spend-based approach was also applied in the category of Buildings and total emissions were compared with those emissions resulting from the embodied carbon approach.

For the purposes of assessment of emissions from reconstruction, assumptions had to be made on how the reconstruction will look like. One of the assumptions is that the housing stock destroyed or damaged will be fully reconstructed as was before the war. Obviously, the reconstruction of Ukraine will take into account the changed circumstances and the actual needs of the country. For example, not all of the destroyed apartments will probably be renovated in the residential sector given the shrinking of Ukraine's population. On the other hand, as Soviet-built apartments are rather small compared to modern standards, new apartments will probably be larger in size.

The assumption was made that fully destroyed facilities will be completely rebuilt, and hence 100% of the embodied or spend-based emission factor is therefore applied. For

79. UK Department for Environment, Food & Rural Affairs, Conversion factors by SIC code 2019, updating Table 13, https://www.gov.uk/government/statistics/uks-carbon-footprint

damaged property, a 33% factor was applied to the embodied carbon factor unless a prorate adjustment could be derived from replacement value for destroyed and damaged property.

Compared to the first assessment that covered the first seven months, several observations can be made. First of all, the overall rate of damages and destruction has slowed over the months as mentioned previously, while damages in the energy sector have significantly increased. The average size of apartment buildings (in m^2) was adjusted downwards by 21%. Moreover, in the embodied carbon approach, some adjustments were made to the emission factors used for buildings. The previously omitted construction stage A5 (installation into building) was added. At the same time, stages B4 & B5 (replacement & refurbishment) were excluded of the embodied carbon factor: as replacement and refurbishment would also have happened in buildings in a no-war scenario, including B4 & B5 could lead to double counting of emissions. See the Annex for more information.

The results over the first twelve months of the war are provided in the table and graph below. Due to the above mentioned adjustments, the share of carbon emissions for buildings reduced from 70% to less than 50%. Transport & Infrastructure and Industry & Utilities emissions significantly increased, in particular in absolute terms, mainly due to the energy infrastructure damages in the autumn and winter. Specific data becoming available allows estimating emissions from damaged bridges, overpasses, and railway infrastructure.

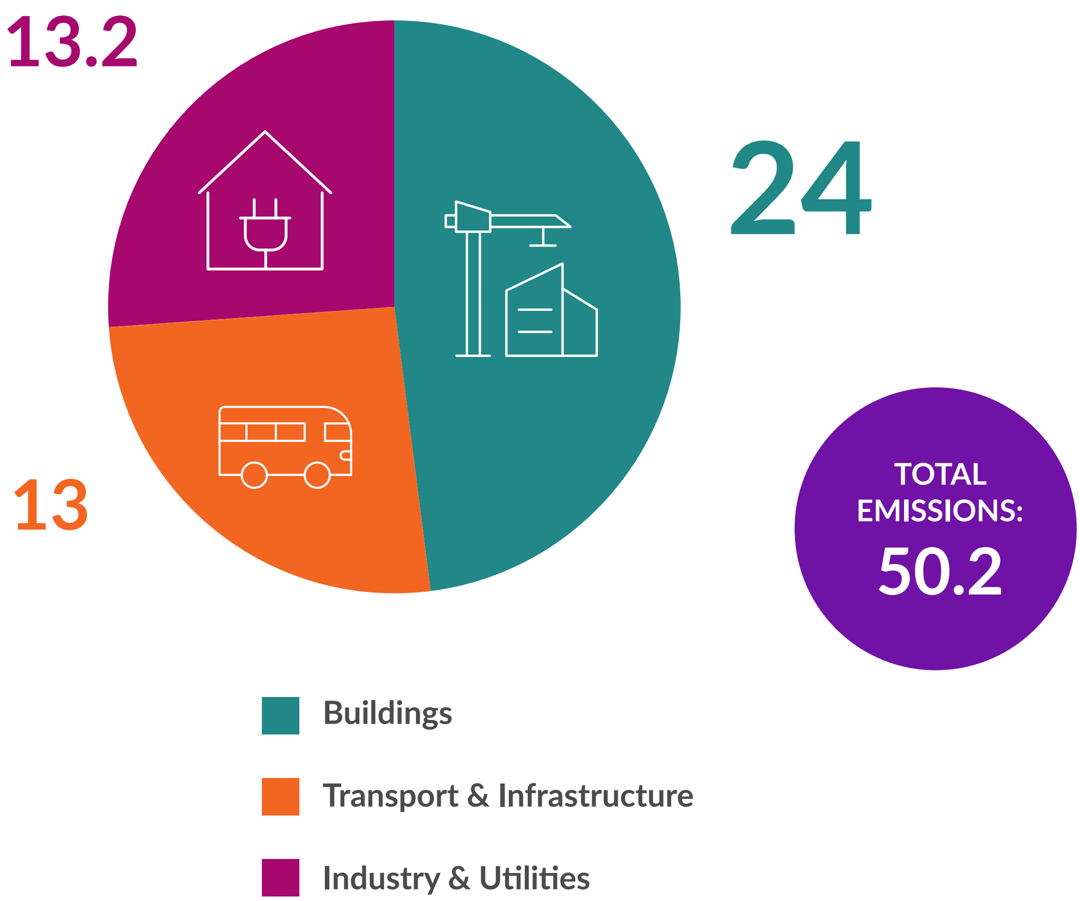

Fig. 19. Distribution of emissions from civilian infrastructure reconstruction by sectors, $MtCO_2e$

CATEGORY	EMISSIONS ($MtCO_2e$)	PERCENTAGE (%)
Buildings	24	48
Transport & Infrastructure	13	26
Industry & Utilities	13.2	26
TOTAL	50.2	100

Table 13. Overview of emissions from civilian infrastructure reconstruction

7. COUNTRY-WIDE IMPACT ON EMISSIONS IN UKRAINE

Russia's invasion resulted in a significant economic decline. In 2022, the GDP of Ukraine dropped by almost 30% with the most considerable reductions in manufacturing, steel, mining, power, agriculture, and transportation sectors[80]. As a result, GHG emissions have also reduced significantly although no official data is available. We expect, however, that emissions have reduced to a lesser extent than GDP. Emissions from the road transport are likely to have reduced at a lower rate due to switching logistics from the sea transport to automobiles, increased transportation of military-related cargo, and movement of refugees and internally displaced persons. Natural gas consumption for heating has also reduced at a lower rate compared to economic decline as district heating often cannot be regulated at the individual apartment level and heating needs for households do not depend on economic activity. Emissions from agriculture reduced due to the lower use of mineral fertilizers; however, business-as-usual trend for emissions associated with enteric fermentation and manure management is likely to have followed. Similarly, emissions from waste management were affected at lower rates compared to economic decline. Based on preliminary estimates, we believe that overall GHG emissions within the territorial boundaries of Ukraine could have reduced by about 60-80 million tCO_2e during 2022, of which 28 million tCO_2e in the energy sector alone.

Such economic impact on emissions will have longer-term consequences as, even assuming gradual economic recovery starting from 2023, GHG emissions will be lower compared to the pre-war business as usual scenario for at least several years. Emissions from agriculture, for instance, could rebound very quickly with the restored mineral fertilizers use and yields. Other sectors will require longer time for recovery or will even remain at lower levels in the future due to complete destruction of some industrial facilities. Still, reconstruction activities and new investments will result in rebound emissions after the end of the war.

Reductions in GHG emissions in Ukraine, however, do not mean overall emission reductions at the global level, as a significant share of emissions just moved to other countries. Some 8.6 million Ukrainians were forced to leave the country and settled as refugees in other countries. They consume electricity, natural gas, and other energy resources in various countries, mainly in Europe. Only for electricity and natural gas consumption, the amount of transferred emissions was estimated at 5 million tCO_2e (see the case study below). Refugees also use transport, live in apartments, purchase food, clothes, and other goods and services, which are all associated with a certain carbon footprint.

80. State Statistical Service of Ukraine, https://www.ukrstat.gov.ua

Carbon dioxide emissions associated with the EU consumption were 6.8 t per capita in 2019, of which 5.7 tonnes were emissions within European geographical boundaries. As refugees in general live in modest circumstances and would not be investing in properties or new cars, for example, we take a footprint of 50% of that of an average European citizen. Assuming that after 6 months 40% of refugees have already returned to Ukraine (see Chapter 4), while the remaining 60% stayed the full 12 months, the refugees would mean a shift of 20 million tCO_2e to Europe .

Similar effect is applicable to industrial emissions. Manufacturing of carbon intensive export oriented goods, such as iron and steel products, was likely picked up by other countries around the globe. Steel production in 2022 declined by 70% compared to 2021, which resulted in emission reductions of 34.5 million tCO_2e within Ukraine but increase elsewhere within the highly globalized steel market.

Products consumed in Ukraine that were previously manufactured at local enterprises are now often manufactured in other countries and imported to Ukraine. There are examples of various Ukrainian products manufactured under the same brands but using foreign production capacities. Besides, large volumes of humanitarian aid provided to Ukraine also substitute products previously manufactured in Ukraine. The volume of associated emissions amounts to several millions of tCO_2, if not higher.

Taking these "leakage" effects into account could cancel out a significant, if not the full, share of emission reductions in Ukraine.

The war also undermines possibilities to invest in climate adaptation and mitigation projects and initiatives. Investments required for transition to the low carbon economy in line with the approved Nationally Determined Contribution (NDC) were estimated at 102 billion euro for the period until 2030[82]. At the same time, the direct damage caused to Ukraine's infrastructure during the war has already reached $63 billion as of the end of March 2023, while the overall Ukraine's economic losses due to the war, taking into account indirect losses (GDP decline, investment cessation, outflow of labour, additional

81. CO2 emissions associated with the EU consumption were 6.8 t per capita in 2019. This includes 1.6 t per capita of direct emissions by private households (e.g. for heating and private transport) and 5.2 t per capita emitted indirectly along the production chains of final products that were either consumed or invested in within the EU-27. The latter mostly — 4.1 t per capita — stemmed from domestic production activities actually located within the EU-27. For more details see: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_statistics_-_carbon_footprints#Carbon_dioxide_emissions_associated_with_EU_consumption

82. Уряд схвалив цілі кліматичної політики України до 2030 року, https://www.kmu.gov.ua/news/uryad-shvaliv-cili-klimatichnoyi-politiki-ukrayini-do-2030-roku

defence and social support costs, etc.) range from $543 billion to $600 billion[83]. Dozens of billions of investments that could be spent on reducing GHG emissions by millions of tCO_2e would now be required for the post-war reconstruction and recovery to restore the pre-war levels of economic activity.

Case study: Emissions from energy consumption

The impact on energy consumption resulting from the war can be estimated through the change in consumption of fossil energy sources. Demand for energy has dropped significantly due to a decrease in economic activity, migration, and loss of control over territories.

In the electricity sector, consumption has dropped by more than a 1/3 due to the war. This was contributed by a combination of factors: reduction of economic activity, destruction of business sites, reduced demand due to supply disruptions, and reduced demand due to migration. The blackout events triggered by relentless rocket attacks starting from October 2022 have led to further drop in electricity consumption and forced some consumers to switch to off-grid generators.

The changes in power supply sources were dictated by loss of control over power plants in war zones and rocket attacks, which temporarily disabled the availability of some power stations. Combined with the drop in demand and changes in hourly load profile, the production mix of power plants generating power changed in 2022. According to our estimates, the share of thermal generation in power production has decreased from 30.3% in 2021 to 27.2% in 2022. If compared to electricity balance forecast for 2022, the decrease is even more pronounced: from expected 33.3% to 27.2%, or 6.1%. This led to a change in emissions from electricity sector.

To assess the effect of the war on emissions in the electricity sector, we estimate changes in the upstream generation of electricity, where coal and gas are burnt by thermal power plants. We compare the estimated electricity production by thermal power plants[84] to the baseline assumption for 2022 represented by the forecast electricity balance for 2022 approved by the Ministry of Energy[85]. We compare only the last 10 months of 2022 with the baseline to factor out potential discrepancies between the forecast and the actual data for January-February 2022[86], which are not attributable to war. For representation

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83. The direct damage caused to Ukraine's infrastructure during the war has already reached almost $63 billion. Global economic losses are about $543–600 billion, https://kse.ua/about-the-school/news/zbitki-naneseni-infrastrukturi-ukrayini-v-hodi-viyni-skladayut-mayzhe-63-mlrd/
84. https://gmk.center/ua/news/metalurgi-ukraini-u-2022-roci-skorotili-spozhivannya-elektroenergii-na-52-r-r/
85. https://vse.energy/balance-ee-2022
86. https://map.ua-energy.org/uk/resources/8998f2ed-379f-4fa9-9076-88782b32ee4f/

purposes, we exclude the power consumption of iron & steel industry, which is estimated separately.

We also account for energy consumption by households that moved from Ukraine to other countries, assuming they consume the same amount of power abroad as in Ukraine. We used the UN Refugee Agency (UNHCR) data on the number of Ukrainian refugees residing in countries across Europe[87] to allocate the "migrated" electricity consumption to each country. We then estimate the additional electricity that must be produced in each power system to cover the additional demand, including adjustment for grid losses[88]. We apply CO_2 emission factors for each of the countries[89] to get the total emissions resulting from Ukrainian migrants consuming electricity outside of Ukraine.

In total, the drop in electricity demand due to the war resulted in a reduction of 16.9 million tCO_2 compared to the baseline expectations (excluding consumption of iron & steel industry).

In the gas sector, consumption has also dropped by 23% compared to 2021 based on our estimates. The decrease is contributed to by decreased economic activities, destruction of iron & steel mills, and reduction in residential consumption, as well as reduced district heating demand.

To assess the effect of the war on emissions in the gas sector, we estimate the change in the downstream demand for natural gas by final consumers, where gas is burnt. We use historic data on gas exiting the transmission system to final consumers and distribution networks published previously by the Ukrainian Gas Transmission System Operator[90]. We then estimate the change in demand in 2022 based on publicly available data on the drop in demand. The change in emissions from natural gas burning due to war activities represents the difference between the baseline gas demand (which we assume to be at the 2021 level) and our estimated demand for 2022. We adjust for gas consumption of thermal power plants already accounted for in the electricity sector and consumption by iron & steel industry.

We also account for energy consumption by households that moved from Ukraine to other countries, assuming they consume the same amount of natural gas abroad as in Ukraine. We estimate that the natural gas of the same quality and emission factor is burnt by Ukrainian migrants in other countries.

In total, the drop in natural gas demand due to the war resulted in a reduction of 6.2 million tCO_2 compared to the baseline expectations (excluding consumption of iron & steel industry).

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87. https://data.unhcr.org/en/situations/ukraine
88. https://www.ceer.eu/documents/104400/-/-/fd4178b4-ed00-6d06-5f4b-8b87d630b060
89. https://www.carbonfootprint.com/docs/2023_02_emissions_factors_sources_for_2022_electricity_v10.pdf
90. https://tsoua.com/prozorist/test-platformy/

In oil products, our report covers the estimated emissions from electricity demand met by small generators during blackouts and oil products burnt due to rocket attacks on depots and petrol stations.

The demand for petrol and diesel from small generators is estimated based on the analysis of independent Consultancy Group A-95[91], cross checked by our own estimations based on the number of imported generators in 2022 and a set of assumption on the intensity of utilization of these generators. Our cross-check calculation used open-source data from various media publications to estimate the total available electrical capacity of diesel and petrol generators for October-December 2022. Generators were used during blackout events, which were distributed unevenly across the country and could last from 1-2 hours to 4-8 hours in some regions. Petrol generators are usually of smaller capacities of up to 10 kW and are used in residential applications or by small businesses for a limited number of working hours. Diesel generators are usually of higher capacity and are used by medium businesses (business centers, hotels, industrial processes, etc.) as well as hospitals, utilities, and other public infrastructure. They are usually more efficient, produce fewer emissions, and are utilized for longer hours.

Despite the perception that the power supply replaced by off-grid generators should be significant, in fact its contribution in total emissions is not. Nevertheless, emissions per MWh of electrical power produced from small diesel and petrol generators were 2.6 times higher compared to emissions of the power generation mix in 2022 in Ukraine. We estimate that the power generated by small generators was around 2.4% of generation in October, 3.5% in November, and around 5.5% in December 2022, or around 1% compared to the whole 2022 production.

Data on the burnt oil depots and petrol stations is sourced from Ecozagroza[92], the official platform of the Ministry of Environmental Protection and Natural Resources of Ukraine.

In total, additional demand for oil products, together with the loss of oil products stock due to the Russian invasion, resulted in an increase of 1.1 million tCO_2.

Total changes in energy consumption induced by the Russian invasion resulted in a net decrease of 21.9 million tCO_2e.

91. https://enkorr.ua/uk/news/aktivne_vikoristannya_generatorv_ne_prizvede_do_destablzac_palivnogo_rinku_a-95/253194
92. https://ecozagroza.gov.ua/

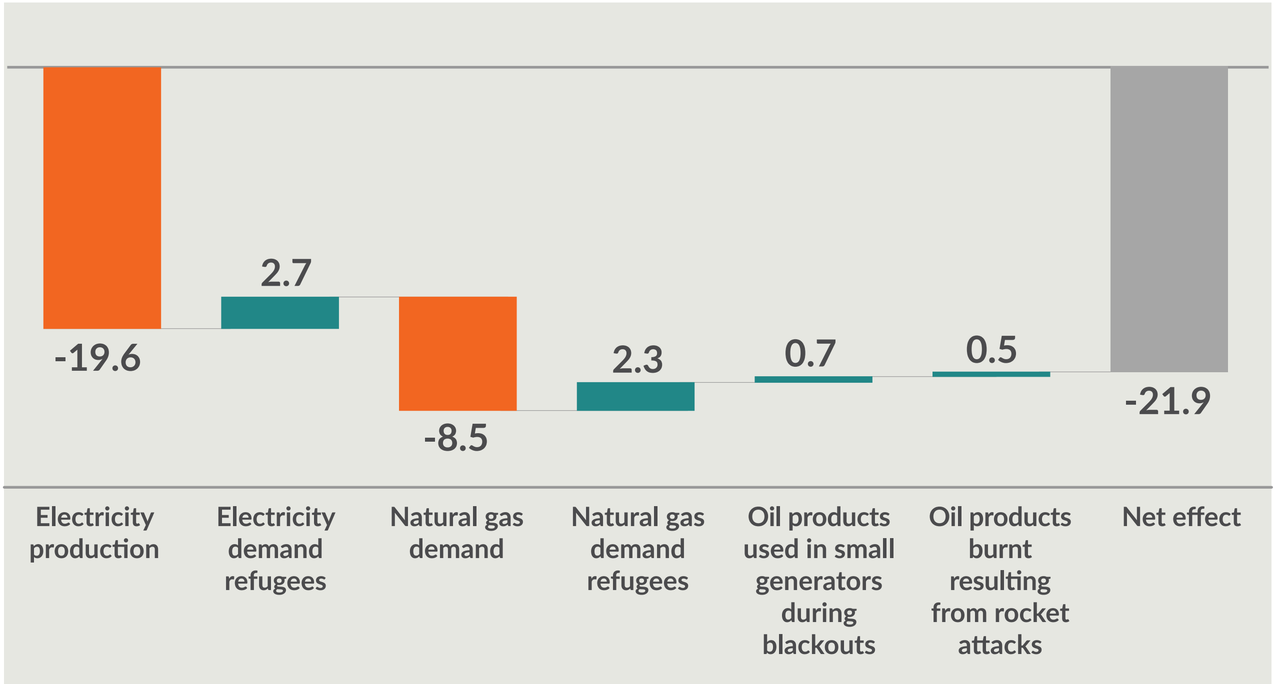

Fig. 20. Emission in Ukrainian energy sector, $MtCO_2e$

9. CONCLUSIONS AND NEXT STEPS

The full-scale invasion of Ukraine by the Russian Federation is well into its second year. Many residential blocks and various industries have been damaged or completely destroyed and Russia continues to strike civilian facilities. Starting last October, energy and water infrastructure were especially targeted, trying to make life for Ukrainian unbearable in winter (they failed though).

The impact of this war is significant foremost in Ukraine, but the effects can be felt outside Ukraine as well, starting from millions of Ukrainians seeking refuge in Europe to Russia trying to use gas as a weapon to weaken Europe. The resulting energy crisis amplified the looming cost-of-living crisis in Europe and even caused power blackouts in some Asian countries.

As the world economy is still driven by fossil fuels, disturbances have a direct impact on GHG emissions. In our first assessment, we looked into the most direct impacts on GHG emissions being the emissions from warfare, emissions from wildfires and movement of refugees and IDPs, and post-war reconstruction emissions. Due to winter conditions (less fires) and limited movement of the front line (lower rate of destruction), the rate of carbon emissions was lower than in the early phases of the war. Some adjustments to the previously provided data led to some corrections, but warfare emissions continued unabated.

Two new impact sectors were addressed in this second assessment, of which both are geographically not located in Ukraine. The impact of the war on the European energy sector (gas and power) was assessed, where it was observed that some impacts increased emissions, while other impacts decreased emissions, cancelling each other out (i.e. a negligible impact on emissions). The closure of Ukrainian and Russian airspace led to longer flying routes between European and Asian cities.

The war is devastating for the Ukrainian economy with industry close to the front line in tatters, 30% of the population on the move, a large share of the working force fighting against the Russian forces, and power outages bringing the economy to a standstill in winter. Obviously, shrinking economy leads to shrinking emissions. But, as is argued in the relevant section, a large share of these emissions has simply moved abroad, either directly through Ukrainians living abroad, production of exports (steel) taken over by other producers, or increased import of products (humanitarian aid and food) into Ukraine.

In the table below, an overview of GHG emissions of the four updated sectors and two new sectors is provided. Similarly to our first report, the one-time emissions from the sabotage of the Nord Stream 1 & 2 pipelines[93] are included as well.

SECTOR	EMISSIONS 12 months ($MtCO_2e$)	PERCENTAGE (%)
Warfare	21.9	19
Fires	17.7	15
Refugees	2.7	2
Civil aviation	12	10
Civilian infrastructure	50.2	42
Nord Stream 1 & 2	14.6	12
European energy sector	nihil	0
TOTAL	119	100

Table 14. Overview of total GHG emissions after 12 months of the war

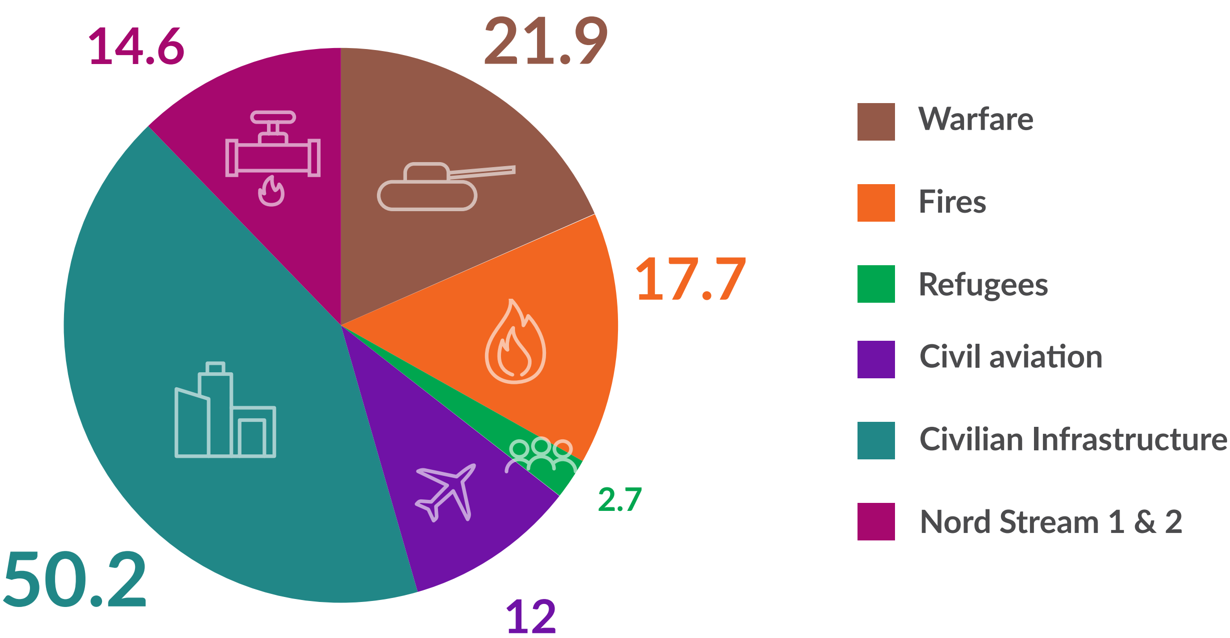

Fig. 21. Distribution of GHG emissions after 12 months of the war, $MtCO_2e$

93. The possible climate effect of the gas leaks from the Nord Stream 1 and Nord Stream 2 pipelines, Danish Energy Agency, https://ens.dk/en/press/possible-climate-effect-gas-leaks-nord-stream-1-and-nord-stream-2-pipelines

As seen from the above, the reconstruction of civilian infrastructure accounts for the largest share of emissions with almost half of the total emissions. Almost 20% is emitted by warfare, with fires, in forests, agricultural fields, and built-up areas, adding up to 15%. Interestingly, the leakage from the Nord Stream 1 & 2 pipelines released large amounts of natural gas (consisting of methane, a potent greenhouse gas), leading to significant GHG emissions, which are almost as large as the emissions from fires.

After twelve months of the full-fledged war, total emissions already add up to the total GHG emissions that a country like Belgium emits annually.

The Russian invasion of Ukraine will have a long-lasting impact on climate change and GHG emissions. The transition to renewable energy in Europe is accelerating and a rethinking of the role of natural gas as a bridge fuel is underway. The war in Ukraine will result in policy changes in many countries throughout Europe and the world.

Ukraine is keen to engage in this green transition during the post-war reconstruction period. They understand that such transition is a requirement to join the European Union. But apart from the environmental benefits, Ukrainians have realized that a fossil-free energy system increases national security and this security argument will be a strong driver for Ukrainian policy making[94].

The transition can only occur when the territorial integrity of Ukraine is restored and Ukraine is embedded in a European security architecture. Long-term stability is required to invest in the green transition. A cessation of hostilities and freezing the war into a frozen conflict might provide a short-term relief for carbon emissions. But in the long-term this will be detrimental to the climate as Ukraine will be forced to focus on increasing militarisation of the economy and society instead of pursuing a green transition.

Next steps: Closing the gaps

Both the scope and completeness of the assessment have been extended compared to the initial report but not all climate impacts are covered. Examples of additional sources of GHG emissions caused by Russia's war in Ukraine include:

- destruction of carbon reservoirs other than the impact of large fires, in particular unsustainable use and destruction of biomass resources (e.g. forests, shelter lines along the fields, etc.) for heating and construction of fortifications and other needs, damage of trees and other vegetation from explosions and other impacts (e.g. both due to the direct mechanical damage and creation of conditions for subsequent spread of pests);

94. Accelerating the green transition is a matter of national security for Ukraine, says German Galushchenko, Governmental Portal of Ukraine, accessed 20 May 2023, https://www.kmu.gov.ua/en/news/herman-halushchenko-pryskorennia-zelenoho-perekhodu-pytannia-natsionalnoi-bezpeky-ukrainy

- combustion of a wide variety of goods from shelling of industrial facilities and logistic centres (e.g. food products, chemical products, various construction materials, fiberglass composite products, etc.), as well as emissions associated with attacks on agro-industrial facilities[95], including destruction of nitrogen mineral fertilizer products;
- other emission sources related to the destruction of infrastructure, such as SF6 leakage from the damaged and destroyed electric transformers, HFC and PFC emissions from fire extinguishing equipment, etc.
- carbon footprint of humanitarian aid supply and distribution operations;

Next steps: Military emissions outside Ukraine

So far, our assessment of warfare emissions has focused on the emissions directly related to the actions of Russia as an aggressor and Ukraine defending its territorial integrity. Impacts of GHG emissions extend beyond the geographical boundaries of Ukraine as we have shown with the rerouting of civil aviation. An increased activity in military aviation has been observed outside Ukraine. For example, NATO has increased surveillance flights along its eastern border[96]. Also, some heavy military equipment, supplied to Ukraine to fend of the Russian aggression, has been transported by air over the Atlantic Ocean[97].

A longer-term impact of Russia's invasion is the rearmament of Europe: Russia's aggression has shown that peace on the European continent cannot be taken for granted. Even after this war will be over, Europe will be confronted with a deteriorated security environment and will have to protect its democracy and values from an unfriendly neighbour in the east. The first signs of increased military spending have already been documented[98] and will lead to substantial increases in the number of platforms in use, as well as training, exercising, and patrolling, which consequently will cause higher fuel demand and GHG emissions.

The assessment also highlights the importance of military emissions accounting using common internationally recognized frameworks. As mentioned in the NATO's Climate Change & Security Impact Assessment[99], climate change is already a 'threat multiplier'

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95. Research: Bombing of agro-industry in Ukraine poses serious environmental health risks, https://paxforpeace.nl/news/overview/research-bombing-of-agro-industry-in-ukraine-poses-serious-environmental-health-risks
96. NATO deploys AWACS surveillance jets to Romania, NATO, https://ac.nato.int/archive/2022/nato-awacs-to-ROU
97. RAF transport aircraft flies Canadian Military Assistance supplies to Europe for Ukraine, RAF, https://www.raf.mod.uk/news/articles/raf-transport-aircraft-flies-canadian-military-assistance-supplies-to-europe-for-ukraine/
98. World military expenditure reaches new record high as European spending surges, SIPRI, https://www.sipri.org/media/press-release/2023/world-military-expenditure-reaches-new-record-high-european-spending-surges
99. NATO releases its Climate Change and Security Impact Assessment, https://www.nato.int/cps/en/natohq/news_197241.htm

and its impact will worsen, opening new areas of strategic competition and causing new conflicts over access to resources. Though there is some room for increasing energy-efficiency and deployment of renewable energy sources by militaries, military effectiveness will remain its primary role. Monitoring of GHG emissions from militaries is thus important to be able to manage such a potentially significant impact on climate change and track the achievement of emission reduction targets, while Europe aims for a net-zero carbon world by 2050.

Next steps: Green recovery and climate finance

The assessment has demonstrated a large scale of GHG emissions that would result from post-war reconstruction activities. At the same time, this scale of impact reveals the potential to minimize climate damage in case of application of sustainable and low-carbon technologies and materials for reconstruction works.

Embodied carbon is the most significant source of emissions related to the buildings sector, which is often overlooked in estimating the carbon footprint and potential GHG emission reductions.

Embodied carbon includes, in particular, GHG emissions released during extraction, manufacturing, transportation, and assembly of materials used for construction and, thus, the impact depends on the choice of such materials and technologies. The impact associated with embodied carbon occurs at the time of construction and renovation and cannot be reduced afterwards, which underlines the importance of design choices at the early stages.

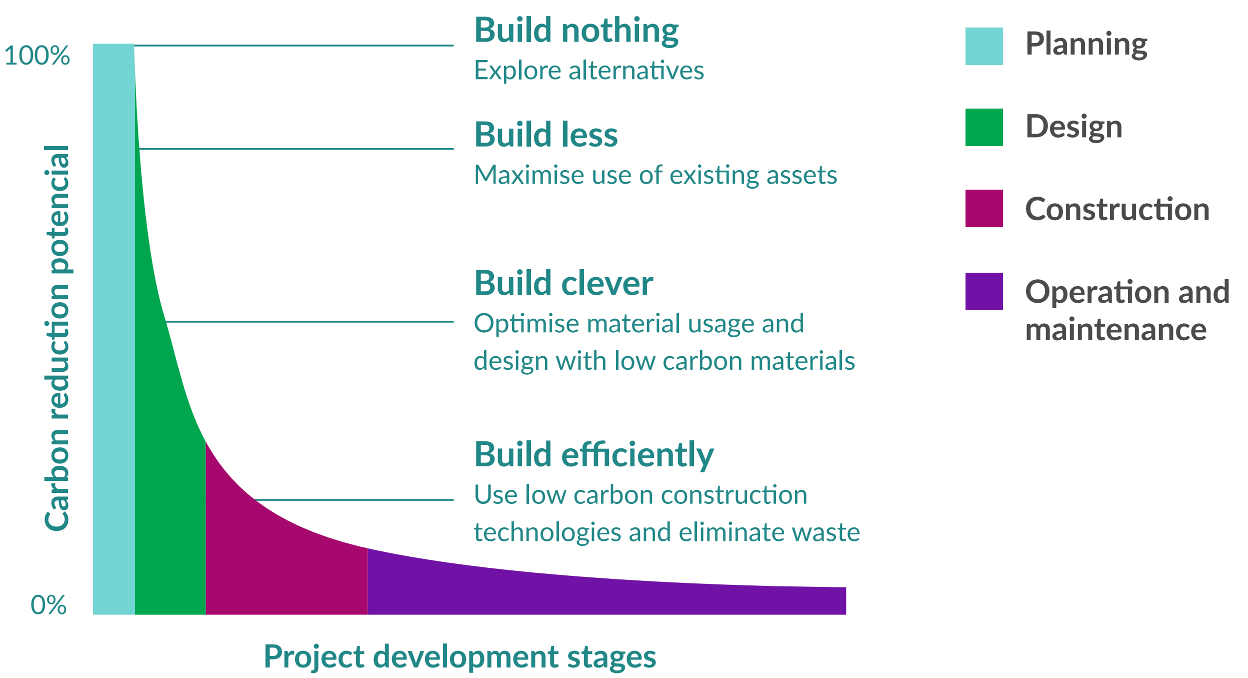

Fig. 22. Opportunities to reduce embodied carbon from the stage of design process.
Source: HM Treasure: Infrastructure Carbon Review, 2013

Comparison of emission factors for apartment buildings within typical construction practices in the region (i.e. 575 kg CO2/m^2 for Central and Eastern Europe) with modern technologies and standards demonstrate a significant emission reduction potential. Five European countries (Denmark, Finland, France, the Netherlands, and Sweden) have recently introduced regulations on the whole life carbon emissions, addressing both operational and embodied emissions. In France, for instance, the standard foresees a reduction of embodied carbon emissions to 490 kg CO_2-eq/m^2 starting from 2031[100]. Taking into account the 15% difference and the scale of reconstruction activities, potential emission reductions with low-carbon technologies compared to the use of typical construction materials with high embodied carbon content could be estimated at millions of tCO_2e. The use of local materials and development of local supply chains would also contribute to economic recovery and job creation.

Market instruments, like those defined in Article 6 of the Paris Agreement, could provide a framework for channelling additional international support for reconstruction activities in the form of climate finance. Designing of such programs would require confirmation of interest from potential partners and buyers, broad stakeholder consultation activities, and building appropriate MRV systems. There are methodologies already in place for the buildings sector under existing standards and programs, which could serve as a basis and inspiration for designing future programs and estimation of carbon emission reductions. City scale or regional scale programmes of activities should be designed in consultation with stakeholders, including IFIs and development partners. Such programs could also cover the establishment of local supply chains for construction materials production, which would further reduce the climate impact and support economic recovery. Supporting policy measures that could be required should be also explored and introduced into national legislation.

Next steps: Climate damage litigation

Ukraine, together with its international partners, wants to hold the Russian Federation accountable for its act of aggression, including damages caused to the environment[101]. There are known examples of environmental damage claimed as a part of post-conflict reparations, i.e. the compensation paid by Iraq after the invasion of Kuwait under the UN Compensation Commission[102]. This proves the importance of comprehensive documentation of environmental damage and collection of evidence. In the anticipation

100. Embodied carbon: What it is and how to tackle it, https://www.gresb.com/nl-en/embodied-carbon-what-it-is-and-how-to-tackle-it/
101. Environmental accountability, justice and reconstruction in the Russian war on Ukraine, SIPRI, https://www.sipri.org/commentary/topical-backgrounder/2023/environmental-accountability-justice-and-reconstruction-russian-war-ukraine
102. United Nations Compensation Commission, https://uncc.ch/state-kuwait

of future litigation efforts, Ukraine is registering all damages done to the country including damages to the Ukrainian environment[103].

Additional GHG emissions cause damage to the climate. Litigation of climate damage, in particular that resulting from a military conflict, remains uncharted territory. Since the early 2000s, legal frameworks for combating climate change have increasingly been available through legislation, and an increasing body of court cases have developed an international body of law, connecting climate action to legal challenges related to constitutional law, administrative law, private law, consumer protection law, or human rights[104]. In the next update, we will look into, among other things, the relevant mechanisms within the framework of peace treaties and the practice of the International Court of Justice, the UN Compensation Commission, as well national jurisdictions. As climate damage affects not only Ukraine, but also the climate of the whole planet, we will explore which parties, other than Ukraine, could be eligible to submit a claim related to Russia's act of aggression.

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103. See the dashboard of the Ministry of Environmental Protection and Natural Resource of Ukraine, www.ecozagroza.gov.ua
104. Climate change litigation, Wikipedia, https://en.wikipedia.org/wiki/Climate_change_litigation#:~:text=Climate%20litigation%20typically%20engages%20in,other%20organizations%20for%20negligence%2C%20nuisance%2C

ANNEX:
Methodological components

Key definitions

Adapted from the Framework for Military Greenhouse Gas Emissions Reporting proposed by CEOBS

Military GHG emissions – all sources of direct and indirect GHG emissions associated with the operation of the military and warfare.

Direct Scope 1 GHG emissions – GHG emissions associated with the operation of military facilities, equipment use, use and disposal of munition, and fugitive emissions.

Indirect Scope 2 GHG emissions – emissions from the use of purchased energy.

Operational emissions include Scope 1 and Scope 2 emission sources and can be divided by stationary and mobile emission sources.

Other indirect Scope 3 GHG emissions (supply chain emissions) – emissions from extensive and complex upstream and downstream supply chains, including emissions associated with the use of capital goods, purchased goods and services, building and construction, and other sources.

Life cycle GHG emissions – total operational and supply chain emissions.

Other indirect GHG emissions linked to the military (Scope 3 plus) – emissions associated with military and warfare, including emissions from the combustion of bunker fuels not reported within Scope 1 or Scope 2, in theatre building and construction, emissions from landscape fires, emissions from fires and damage to the infrastructure (e.g. methane leakage), debris management and disposal, soil degradation, land use changes, environmental remediation and restoration needs, medical care, displacement of people and humanitarian support, as well as post-conflict reconstruction (sometimes also referred to as “carbon boot-print” of the military).

WARFARE:
War stages and climate impact

0 PHASE

Second half of 2021 – 24 February 2022

PREPARATION STAGE

Relocation of military equipment and troops from permanent bases to the staging bases near the borders of Ukraine. Training and accumulation of forces.

CLIMATE IMPACT

1 PHASE

24 February – mid-April 2022

LARGE-SCALE INVASION

Air-strikes, missile attacks and ground invasion from multiple axis. Long-distance movement of hundreds of tanks, other armoured vehicles, trucks, as well as use of aircrafts and helicopters. Destruction of fuel storage facilities. Occupation of Ukrainian territories on the north, east, and south. Resistance of the Ukrainian armed forces, territorial defence units, other divisions, and volunteers. Counter-offensive and liberation of the territories on the north of Ukraine (Kyiv, Chernihiv, and Sumy regions) and relative stabilization of the frontlines in other regions.

CLIMATE IMPACT

2 PHASE

mid-April – June 2022

FOCUS ON THE EASTERN FRONT

Redeployment of Russian units to the eastern front and concentration of efforts to occupy Donetsk and Luhansk regions of Ukraine. Massive bombardment and destruction of Mariupol city. Occupation of additional territories on the east of Ukraine. Continuation of missile attacks on Ukrainian cities. Liberation of additional territories in Kharkiv region and Zmiinyi (Snake) Island in the Black Sea by Ukraine.

CLIMATE IMPACT

3 PHASE

July – September 2022

FRONT STABILIZATION AND START OF UKRAINIAN COUNTER-OFFENSIVE

Relative front stabilization on the east of Ukraine. Destruction of warehouses and logistic nodes by the Ukrainian armed forces. Ukrainian counter-offensive in Kherson and Kharkiv regions with limited gains on the south and liberation of almost all territory of Kharkiv region. Nord stream pipeline sabotage. Significant impact on economy and logistics with the redirection of grain cargo and other types of cargo to the automobile transport due to the ongoing blockade of Ukrainian sea ports.

CLIMATE IMPACT

4 PHASE

October – November 2022

CONTINUATION OF UKRAINIAN COUNTER-OFFENSIVE

Mobilization of additional personnel and equipment by Russian armed forces. Large-scale attacks on the Ukrainian power grid infrastructure. Partial collapse of the Crimean bridge with severe impact on Russian logistics on the south of Ukraine. Liberation of Kherson city and part of Kherson region on the right bank of the Dnipro river. Destruction of power, heating, and other infrastructure by Russian army before retreating.

CLIMATE IMPACT

5 PHASE

December 2022 – January 2023

FRONT STABILIZATION

Relatively stable frontlines but significant fighting on the east of Ukraine. Gradual destruction of equipment and warehouses on the south of Ukraine by the Ukrainian armed forces. Continued attacks on the Ukrainian power grid infrastructure. Extensive use of diesel- and petrol-fuelled power generators due to the long and frequent periods of power outages. Shelling and missile attacks on Ukrainian cities.

CLIMATE IMPACT

6 PHASE

February 2023
– April 2023

RENEWED OFFENSIVE

Though the frontlines remained relatively stable, Russian forces renewed regular attacks on the east of Ukraine with limited territorial gains. The use of artillery became less intensive and concentrated in several locations with most intensive fighting. Uninterrupted power grid operation has been mainly restored in mid-February. Shelling and missile attacks on Ukrainian cities.

CLIMATE IMPACT

Legend

emissions due to fuel consumption during the operational movement of military machinery and supporting vehicles

emissions due to fuel consumption for the supply of ammunition, fuel, food, medicines, and other cargo

emissions due to manufacturing and use of artillery, missiles, ammunition, and explosives

emissions associated with the manufacturing of destroyed and damaged military equipment

emissions associated with reconstruction activities to restore civilian infrastructure (buildings, roads, bridges, airports, power plants, etc.)

emissions associated with forest and other landscape fires, as well as fires in built-up areas

emissions associated with the massive movement of refugees from the affected regions to the west of Ukraine and Europe.

emissions due to petrol and diesel combustion in power-generators.

Overview of studies estimating GHG emissions from the military

There is a number of scientific studies trying to estimate military-related emissions in various countries and at the global level.

For instance, a recent study on global military emissions[105] arrived at an astonishingly high estimate of the global military carbon footprint equal to 2,750 MtCO_2e or 5.5% of total global emissions. This figure includes operational emissions equal to 500 MtCO_2e or 1% of global total GHG emissions and supply-chain emissions covering the rest. The study used a number of assumptions based on the review of military emissions data reported for the USA, the UK and some EU nations. The underlying data included assumptions for:

- stationary operational emissions per head of personnel (e.g. for both Ukraine and Russia 12.0 tCO_2e per military head was used based on US estimates);
- number of active military personnel;
- ratio between mobile military activities (use of aircraft, marine vessels, land vehicles, and spacecraft) and stationary activities within operational emissions (ranging between 0.7 and 2.6 depending on the level of reliance on the air force and maritime service);
- supply-chain multiplier, which captures emissions from extensive and complex supply-chains, comprising a large proportion of the military carbon footprint (assumed to be 5.8).

The large number of assumptions, variations, and extrapolation to regional and global levels limit the accuracy of any global estimate. Still, the estimates can serve as an indication of global military emissions.

In Norway[106], for instance, the life cycle greenhouse gas emissions from the defence sector have been estimated at 0.8 million tCO_2e, corresponding to approximately 1.1% of the national emissions (consumption-based). Fuel use by military equipment and systems (vehicles, ships, and aircraft) is the largest single contributor to GHG emissions from the sector and has been estimated to be responsible for around 31% of emissions. However, upstream activities were defined as the main contributor to emissions (68%) in general with the most significant impact attributed to buildings and construction activities, including embodied carbon of construction materials (18% from the total); procurement of goods and materials required for operational purposes (12% from the total); as well as procurement of assets used for transportation and transportation services related to business travel, in particular air travel (8% and 7% of the total, respectively).

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105. Stuart Parkinson, Scientists for Global Responsibility (SGR) with Linsey Cottrell, Conflict and Environment Observatory (CEOBS). Estimating the Military's Global Greenhouse Gas Emissions, https://www.sgr.org.uk/publications/estimating-military-s-global-greenhouse-gas-emissions
106. Magnus Sparrevik, Simon Utstøl, Assessing life cycle greenhouse gas emissions in the Norwegian defence sector for climate change mitigation, Journal of Cleaner Production, Volume 248, 2020, https://www.sciencedirect.com/science/article/pii/S0959652619340661

In the UK military-industrial sector, military equipment manufactures and other suppliers of the Ministry of Defence (MOD), have been estimated to generate 6.5 million tCO_2e in the 2017-2018 financial year. If the consumption-based approach is applied (i.e. including all life-cycle emissions), the estimated GHG emissions increase to approximately 11 million tCO_2e[107]. The estimates for the armed forces include emissions from estate (military bases and civilian buildings) and equipment (marine vessels, aircraft, and land vehicles) and constitute about 3 million tCO_2e or almost half of the total production-based emissions of the military-industrial sector. Emissions from UK arms/ defence industry (including MOD-orientated work and exports) was estimated at the level of approximately 1.5 million tCO_2e. The remaining part of emissions was attributed to the supply chain within the UK (elements of the supply chain outside the UK have not been considered). Total production-based emissions represented about 1.4% of the total national emissions.

For the European Union, the carbon footprint of military expenditure in 2019 was estimated at approximately 24.8 million tCO_2e[108]. The estimate was based on the analysis of GHG emission figures for the combined sectors of the armed forces and military technology industry of the six case study countries (France, Germany, Italy, the Netherlands, Poland and Spain) and extrapolation of the results to the EU as a whole. The estimated value corresponds to about 0.7% of GHG emissions in the EU, however, the authors of the report underline that due to poor data availability, the estimate should be treated as conservative.

In the case of the US, conservative estimates of military emissions for the period FY 2001-2018 were 1,267 million tCO_2e. The emissions from overseas contingency operations (war-related emissions for the operations in major war zones, including Afghanistan, Pakistan, Iraq, and Syria) were estimated to be more than 440 million tCO_2e or approximately 35% of the total[109]. The average annual value over this 18 years period would be 70.4 million tCO_2e, including 24.4 million tCO_2e on average for the overseas contingency operations. The total value corresponds to approximately 1% of average GHG emissions in the US during this period[110] though the estimates do not take into account upstream emissions associated with the supply chain. Emissions covered by the estimation include operational energy consumption by military vehicles, equipment, and platforms (approximately 70% of energy consumption) and energy consumption (electricity, natural gas, and others) by military facilities (approximately 30% of energy consumption). Within operational energy consumption, around 70% of fuel consumed is typically jet fuel used by military aviation while another significant part of up to 20% is diesel fuel. Though fuel consumption is to some extent conditioned by the modalities of warfare, it is still primarily located domestically, and the US military would be the largest institutional consumer of oil in the world even without foreign oil-fuelled operations[111].

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107. The environmental impacts of the UK military sector, https://www.sgr.org.uk/publications/environmental-impacts-uk-military-sector
108. Under the radar. The carbon footprint of Europe's military sector. A scoping study, https://ceobs.org/wp-content/uploads/2021/02/Under-the-radar_the-carbon-footprint-of-the-EUs-military-sectors.pdf
109. Pentagon Fuel Use, Climate Change, and the Costs of War. Neta C. Crawford, Boston University, https://watson.brown.edu/costsofwar/files/cow/imce/papers/Pentagon%20Fuel%20Use%2C%20Climate%20Change%20and%20the%20Costs%20of%20War%20Revised%20November%202019%20Crawford.pdf
110. GHG data are available at the EPA web-site https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks and the average value during 2001-2018 is about 7 billion tCO_2e.
111. Hidden carbon costs of the "everywhere war": Logistics, geopolitical ecology, and the carbon boot-print of the US military, Oliver Belcher, Patrick Bigger, Ben Neimark, Cara Kennelly, https://doi.org/10.1111/tran.12319

Where did the fuel get burnt? A bottom-up assessment of fuel consumption

Estimation of fuel consumption based on a bottom-up approach is very complicated and likely not possible without the detailed studies of military logistic systems and military operations conducted during the war. Such estimates would require detailed information on the types and numbers of self-propelling military equipment in action, typical operation patterns of key military equipment types (e.g. distance travelled per day, percentage of time equipment involved in active operations, etc.), as well as specific fuel consumption of the equipment. Indicative figures for aviation and ground-based military equipment have been estimated for the purpose of this assessment to demonstrate the scale of consumption by different systems.

Fuel consumption by aviation

Aviation is often considered as a main single fuel consumer during military warfare. During Russia's invasion of Ukraine, aviation, however, was used to a limited extend and thus contributed, probably, to only a small fraction of GHG emissions from fuel consumption. According to a comprehensive analysis of aviation use during the war conducted by RUSI[112], Russia has deployed a fast-jet force of around 350 modern combat aircraft for operations in Ukraine. The intensity, goals, and operational patterns of aviation use varied during different periods of the war. At the start of the invasion, Su-34 "frontal bomber" and Su-30SM and Su-35S multi-role fighter aircraft flew around 140 sorties per day up to 300 km inside Ukrainian territory engaging Ukrainian aircrafts and ground targets along the routes of invasion. Later on, operation of Ukrainian air-defence made Russian medium- and high-altitude operations prohibitively dangerous on the Kyiv and Kharkiv axes, and the priority of aviation use was changed to the support of ground forces and heavy bombing of Ukrainian cities (e.g. Chernihiv, Sumy, Kharkiv, Mariupol, etc.). Air operations have been often conducted in the vicinity of the frontlines and without entering Ukrainian-controlled airspace due to persistent losses. Starting from September 2022, with the successes of Ukrainian counter-offensive in Kherson and Kharkiv regions, Russia's aviation has been forced to adopt an increasingly defensive posture. The Russian Aerospace Forces have divided the Ukrainian/Russian lines into eight zones and maintained a regular posture of a pair of Su-35S fighters or Mikoyan Mig-31BM interceptors in each one, which required at minimum of 96 sorties per day. Apart of aircrafts, Russia actively used helicopters for ground attacks (Ka-52 "Alligator", Mi-28 "Havok", and Mi-24/35 "Hind" gunships). Attack helicopters escorted Mi-8/17 transport helicopters carrying airborne troops during the initial days of invasion, as well as conducted low altitude sorties during the early months of the war up to 50 km into Ukrainian controlled territory. After heavy initial losses, Russian helicopters almost solely engaged in attacks with unguided rockets from behind the Russian frontlines during the Russian offensive in Donbas between April and

112. Royal United Services Institute for Defence and Security Studies. Justin Bronk with Nick Reynolds and Jack Watling, The Russian Air War and Ukrainian Requirements for Air Defence, https://static.rusi.org/SR-Russian-Air-War-Ukraine-web-final.pdf

July, and in defensive operations against Ukrainian counter-offensives in Kherson and Kharkiv since September.

Based on other sources, the number of sorties during the initial stages of the war was even higher and reached 200[113] – 300[114] sorties per day but reduced to dozens missions per day by the end of 2022. In July 2022, the Air Force Command of UA Armed Forces reported that the number of sorties of Russia's operational and tactical aviation has exceeded 6,400[115] (which results in about 50 sorties per day on average). However, Russian sources reported 34,000 sorties conducted between February and October 2022 with an average value of about 150 sorties per day[116].

For comparison, Ukrainian aviation conducted 5-10 sorties per day[117] at the beginning of the war while during the first year of the war fighter jets conducted over 5,300 sorties[118] (approximately 15 sorties per day on average).

Apart from fighter jets and helicopters, strategic bombers are actively used during the war for missiles launches. Missiles launched by strategic bombers include Kh-101, Kh-555 / 55SM, and Kh-22/32. As of early 2023, 824 of such missiles attacked Ukraine from the beginning of the war[119]. In 2023 (as of 28 April), additional 132 missiles were launched by strategic bombers during five waves of attacks[120], bringing the total number to 956 missiles. The number of launches per sortie depends on the type of strategic bomber involved, types of the missiles used, weapon load on board, and other factors (e.g. Tu-95MS can carry six or eight missiles depending on their type[121]). The number of launches, however, could be significantly lower than the maximum carrying capacity. For instance, during the attack on 9 March 7, Tu-22M3 and 10 Tu-95MS strategic bombers launched 34 missiles (i.e. two missiles per aircraft on average). Besides, there could be a significant number of sorties without launches, including those conducted for training purposes and those simulating launches for other goals. For the purpose of analysis, an assumption of a total of 1,000 sorties conducted by strategic bombers has been applied.

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113. Pentagon highlights the way the Ukrainians organized air defense during the war with Russia, https://mil.in.ua/en/news/pentagon-highlights-the-way-the-ukrainians-organized-air-defense-during-the-war-with-russia/
114. Defence Intelligence, https://twitter.com/DefenceHQ/status/1599656741381328896
115. Понад 70 % російських некерованих снарядів та керованих авіаракет не досягають цілей, https://armyinform.com.ua/2022/07/07/ponad-70-rosijskyh-nekerovanyh-snaryadiv-ta-kerovanyh-aviaraket-ne-dosyagayut-czilej/
116. Despite Modernization Drive, Russia's Air Force Struggles for Superiority in Ukraine, https://www.themoscowtimes.com/2022/10/25/despite-modernization-drive-russias-air-force-struggles-for-superiority-in-ukraine-a79158
117. Pentagon highlights the way the Ukrainians organized air defense during the war with Russia, https://mil.in.ua/en/news/pentagon-highlights-the-way-the-ukrainians-organized-air-defense-during-the-war-with-russia/
118. Air Force Command of UA Armed Forces, https://www.facebook.com/kpszsu/posts/pfbid0Yu8ga2bNGzkVmqDA5Co5YMxa2qViwncJH8FBB1jrNZEfwfXxNFRmSGiCfRezVUwGl
119. See the infographic shared by the Minister of Defence, https://twitter.com/oleksiireznikov/status/1611449870040109058
120. See https://twitter.com/MassDara/status/1634300311744438272 for the estimates as of 10 March 2023. On 28 April 23 missiles were launched.
121. What Is Special About the Tu-95MS Strategic Bomber, And Why This Aircraft Is Chosen For Strikes On Ukraine, https://en.defence-ua.com/analysis/what_is_special_about_the_tu_95ms_strategic_bomber_and_why_this_aircraft_is_chosen_for_strikes_on_ukraine-5261.html

PARAMETERS	FIGHTER JETS	STRATEGIC BOMBERS	HELICOPTERS
Sorties	100 sorties per day	1,000 sorties in total	50 sorties per day
Distance per sortie	1,000 km	2,000 km	200 km
Comments	Assumed radius of action is 500 km (distance from the main air bases to the Ukrainian border is 200-300 km; combat range is >1000 km)	Assumed based on the approximate distance from the bases to the typical launch areas (about 1,000 km)	Assumed based on the need to protect temporary bases from the long-range precision artillery strikes (at 100+ km)
Specific fuel consumption[122]	5.6l per km	10.1 l per km	3.2 kg per km
Estimated fuel consumption per sortie	4,442 kg (e.g. approximately 40% of internal fuel capacity of Su-34)	16,044 kg (e.g. approximately 20% of internal fuel capacity of 84 t for Tu-95MS)	647 kg (e.g. approximately 40% of internal fuel capacity of Ka-52)
Fuel consumption	163,916 tonnes	16,044 tonnes	11,928 tonnes

Table 15. Information on assumed aviation activity data and estimated fuel consumption*

* All assumptions are indicative to demonstrate potential fuel consumption volumes

Total fuel consumption for aviation based on the limited data available and indicative assumptions described above was estimated to be about 192,000 tonnes while associated GHG emissions would constitute about 604,000 tonnes. This corresponds to less than 10% of the total estimated fuel consumption for military operations during the war, which could be explained by a relatively limited use of aviation during the war.

122. Based on the data for similar US aircrafts (i.e. values for F-35 fighter bomber were used as a proxy for fighter jets and values for B-2 bomber were used as a proxy for strategic bombers; values were converted to l per km). See Neta C. Crawford, Pentagon Fuel Use, Climate Change, and the Costs of War, https://watson.brown.edu/costsofwar/files/cow/imce/papers/Pentagon%20Fuel%20Use%2C%20Climate%20Change%20and%20the%20Costs%20of%20War%20Revised%20November%202019%20Crawford.pdf; fuel consumption by helicopters has been assumed based on internal fuel load and operational range of Ka-52 helicopter (see https://weaponsystems.net/system/494-Kamov+Ka-52+Alligator)

Fuel consumption by ground-based equipment

The majority of fuel is consumed by ground forces; however, it is very difficult to determine the complete picture on where exactly most of the fuel is spent.

Even at the operation level, estimating fuel consumption is complex because of the large variety of vehicle types, consumption rates, terrain, and hours of use, and thus, a detailed analysis of the manoeuvre concept for the operation is needed[123]. For a large-scale war, this becomes even more complicated and complex due to the scale of the forces involved and a big number of various defensive and offensive operations conducted at different sections of the frontline during different periods of time.

Russia's forces involved in the war, at least at the initial stages, were organized in battalion tactical groups (BTG), which were formed as semi-permanent task forces in regiments and brigades to be capable of acting and fighting independently for a period of days. A BTG consists of a motorised rifle battalion or tank battalion with varying combat support attachments depending on the assigned tasks.

The most common BTG variant is based on a motorised rifle battalion with an attached tank company, self-propelled howitzer battalion, air defence platoon, engineer squad, and logistic support. BTGs were designed with the intention to be able to operate at a considerable distance from the bases and have considerable logistic assets, including motor transport (for bulk goods, fuel, and water), maintenance, vehicle recovery, etc. Most BTGs have between 700–800 personnel, but a few have around 900. Depending on the severity of combat, a BTG could likely sustain itself in combat conditions for 1–3 days before requiring additional logistic support. BTG No. 1 of the 200th Motorised Rifle Brigade included more than 60 armoured vehicles, more than 70 wheeled vehicles for transportation of people and cargo, around 30 logistic vehicles (e.g. ATMZ-5.5 and / or Ats-7,0 tankers, maintenance and repair vehicles, mobile kitchens, etc.), more than 20 different artillery vehicles (self-propelled howitzers, MLRS vehicles, command and fire control vehicles, and support vehicles), more than 10 engineer vehicles, around 10 communication vehicles, and other vehicles (medical, electronic warfare, etc.) – in total, more than 200 units of equipment, which requires fuel for moving and operation[124].

Typical BTG structures provide a lower number of equipment and vehicles operated by the BTG. The total number is in the range of 122-142 units of equipment, which include sometimes two, but usually three to five, tankers for the resupply of fuel[125].

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123. By Capt. Michael Johnson and Lt. Col. Brent Coryell, Logistics forecasting and estimates in the brigade combat team, https://alu.army.mil/alog/2016/NOVDEC16/PDF/176881.pdf. Reported values for temperate climate were converted to litres.
124. Getting to Know the Russian Battalion Tactical Group, https://rusi.org/explore-our-research/publications/commentary/getting-know-russian-battalion-tactical-group
125. See the typical structures of BTGs at https://www.globalsecurity.org/military/world/russia/army-btg.htm and https://www.thefivecoatconsultinggroup.com/the-coronavirus-crisis/ukraine-context-d60. As mentioned above, typical fuel tanker size is 5.5 or 7 m^3.

Fuel carried by a BTG is expected to be sufficient for one resupply round and support one day of combat operations. Russian logistic channels must supply fuel to over 100 BTGs in addition to a number of paramilitary groups[126].

Fuel is consumed in large quantities during combat marches conducted by BTGs and manoeuvring during offensive and defensive operations (e.g. envelopment, encirclement, breakthrough, frontal attack, and evasive movement)[127].

DATA	1 BTG	100 BTGS	150 BTGS
Fuel in fuel tankers, t[128]	24	2,400	3,600
Annual fuel consumption with daily refuelling, t	8,760	876,000	1,314,000
Annual fuel consumption with refuelling every second day, t	4,380	438,000	657,000

Table 16. Estimated fuel consumption by BTGs*

* All assumptions are indicative to demonstrate potential fuel consumption volumes

Depending on the assumptions on the number of BTGs involved in the invasion during different periods, their structure and equipment, as well as the length of refuelling cycles, annual fuel demand would be in the range of **0.4-1.3 million tonnes**.

Tanks and infantry fighting vehicles (IFVs) are most significant fuel consumers on the battlefield. Each BTG could have about 10 tanks and 40 IFVs[129] and with 150 BTGs involved in combat, that would result in at least 1,500 tanks and 6,000 IFVs present on the battlefield.
For comparison, according to Oryx's list as of April 2023, visually confirmed losses of equipment for Russia include 1,905 tanks and 3,151 armoured fighting vehicles and infantry fighting vehicles combined[130].

Fuel consumption of military equipment depends significantly on the specific conditions of manoeuvring and resulting average speed. Equipment characteristics often include range in kilometres that the equipment is able to pass using the fuel from its own full fuel tank when moving on a hard surface road. Manoeuvring on field roads significantly increases fuel consumption and reduces average speed and range. More complicated manoeuvring conditions reduce the speed even further and increase fuel consumption up to two or three times compared to the use of hard surface roads[131].

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126. Ukrainian Military Is Targeting Russian Fuel Supply Lines As Winter Approaches, https://www.forbes.com/sites/vikrammittal/2022/12/11/ukrainian-military-is-targeting-russian-fuel-supply-lines-as-winter-approaches/?sh=3e3b43353e2d
127. Márk Takács, Short Study: Describing the Major Features of the Russian Battalion Tactical Group, https://folyoirat.ludovika.hu/index.php/aarms/article/view/5045/4782
128. Assumed based on the average number of four fuel tankers of a BTG (28 m3 of fuel or approximately 24 tonnes). Corresponds to daily fuel consumption with daily refuelling cycle.
129. Nicolas J. Fiore, Defeating the Russian Battalion Tactical Group, https://www.benning.army.mil/Armor/eARMOR/content/issues/2017/Spring/ARMOR%20Spring%202017%20edition.pdf
130. Attack On Europe: Documenting Russian Equipment Losses During The 2022 Russian Invasion Of Ukraine, https://www.oryxspioenkop.com/2022/02/attack-on-europe-documenting-equipment.html
131. В.В. Брехин, В.С. Дорогин, С.В. Дорогин, Е.В. Калинина-Иванова, Приближенная оценка расхода топлива и запаса хода ВГМ. «Вестник бронетанковой техники». 1991. № 2.

It is worth mentioning that tanks and armoured vehicles use fuel not only during manoeuvring in combat but also while idling. According to some estimates, about 10 to 14% of fuel consumption is spent while vehicles are idling (to operate sensors, communication systems, and other enablers on the platforms), and periods of idling time could be significant during army ground combat operations. For instance, some vehicles need several minutes to warm up before movement and since unexpected enemy ambushes or artillery fires are often a threat, it is safer to keep the engine running than to shut it down when stationary[132]. Also, older tanks and armoured fighting vehicles (AFVs) do not have auxiliary power units to run for recharging their batteries and hence, the main engines have to run periodically to recharge the batteries.

CHARACTERISTICS	T-72B3 MAIN BATTLE TANK	BMP-2 INFANTRY FIGHTING VEHICLE
Mass, tonnes	46.5	14.3
Internal fuel tank size, l	1,200	462
Fuel consumption on hard surface roads, l/100 km	240	77
Range on hard surface roads, km	500	600
Fuel consumption on field roads, l/100 km	260-450	80-110
Range on field roads, km	270-460	420-575

Table 17. Fuel use efficiency for some typical military equipment[133]

Apart from vehicles and equipment included in BTGs, there are other fuel consumers, including vehicles involved in logistic operations beyond the frontlines (i.e. in addition to BTG logistic units).

Military literature sometimes uses the concept of the fighting “tooth” of the military and the supporting logistics “tail”. The size and requirements of the “tooth” of the fighting force directly affect the size and requirements of the resupplying “tail”. Support elements of the combat units require regular resupply along the “tail” to sustain military operations[134].

For the US army since 1945, the “tail” portion had steadily grown larger while the “tooth” portion had decreased as a percentage of the entire force (e.g. from 39% in the 1945 European Theatre of Operations to 28% in 2005 in Iraq). The logistics and support share

132. Endy M. Daehner, John Matsumura, Thomas J. Herbert, Jeremy R. Kurz, Keith Walters, Integrating Operational Energy Implications into System-Level Combat Effects Modeling. Assessing the Combat Effectiveness and Fuel Use of ABCT 2020 and Current ABCT, https://www.rand.org/pubs/research_reports/RR879.html
133. Based on the following sources: T-72B3 Fourth generation T-72 tank, https://weaponsystems.net/system/1410-T-72B3; BMP-2, https://weaponsystems.net/system/329-BMP-2
134. Samaras, Constantine; Nuttall, William J.; Bazilian, Morgan (2019), Energy and the military: Convergence of security, economic, and environmental decision-making, Carnegie Mellon University, Journal contribution, https://doi.org/10.1184/R1/10087334.v1

have grown to almost three quarters of the active ground forces[135],[136].

Though the tooth-to-tail ratio would be specific to each military and operation, an important conclusion is that the supporting logistic “tail” is typically larger than the fighting “tooth”. If 3 to 1 ratio is applied, then for each million tonnes of fuel burnt by the fighting “tooth”, additional three million tonnes would be required for the logistic “tail”. In this case, total fuel consumption would be 4 million tonnes, which is in line with the average estimate used in the assessment of climate damage from the first year of the war. Of course, these are very indicative figures, but they still demonstrate the scale of potential fuel demand.

135. James M. Berry, The ‘Tooth-to-Tail’ Ratio and Modern Army Logistics, https://dalecentersouthernmiss.wordpress.com/2021/11/03/the-tooth-to-tail-ratio-and-modern-army-logistics/
136. John J. McGrath, The Other End of the Spear: The Toothto-Tail Ratio (T3R) in Modern Military Operations, https://apps.dtic.mil/sti/pdfs/ADA472467.pdf

Emissions from the use of ammunition

Functional unit - artillery shell	Total 152/155 mm ammunition weight of various models of projectiles ranges from 42.6 to 46.9 kg and the explosive fill weight ranges from 5.85 to 11.30 kg (the weight of propellant is not included)*. Artillery ammunition consist of warhead, propellant charge, and fuze. Generic 155 mm ammunition, for which life cycle assessment of environmental impact has been reported, has the overall weight of 77 kg with container, including: • warhead – 44.5 kg, including 35.5 kg of steel casing and 8.5 kg of composition B explosive; • propellant charge – 9.67 kg, including 9.5 kg of triple base powder; • fuze – 1 kg; • steel container – 22 kg (reusable). There is no information on carbon footprint of other artillery ammunition types (152 mm and 122 mm shells used by Russia) and therefore the assessment is based on the data for generic 155 mm ammunition.
Emissions from energetic material manufacturing	Global warming impact of energetic materials used in explosives varies from 5.06 to 42.4 kg CO_2e per kg of material with most estimates in the range of 5.06 to 12.9 kg CO_2e per kg of material (i.e. 5.06 kg CO_2e for TNT, 6.53 kg CO_2e for nitrocellulose, 8.59 kg CO_2e for RDX)**. For composition B explosive, which is typically used in artillery projectiles and other ammunition (standard composition include 59.5% RDX and 39.4% TNT phlegmatized with 1% paraffin wax), the weighted average global warming impact would be 7.1 kg CO_2e per kg of material.
Emissions from artillery shell manufacturing	Thus, the carbon footprint of materials used for the manufacturing of 155 mm projectile would be 136 kg CO_2e and would consist of: • 60.35 kg CO_2e for the manufacturing of composition B explosive; • 75.62 for the manufacturing of steel casing***.
Emissions at point of firing	Carbon dioxide emissions at point of firing (associated with the generic 155 mm ammunition) is 2.74 kg CO_2e.
Emissions during detonation	Carbon dioxide emissions during detonation (associated with the generic 155 mm ammunition) is 0.19 kg CO_2e per 155 mm ammunition shell.

Table 17. Specific emission factors related to ammunition

* Explosive weapon effects – final report, GICHD, Geneva, February 2017, http://characterisationexplosiveweapons.org/studies/annex-b-152-155-artillery-version/

** Carlos Miguel Baptista Ferreira, Extended environmental Life-cycle assessment of munitions: Addressing chemical toxicity hazard on human health, https://estudogeral.sib.uc.pt/bitstream/10316/42309/4/Extended%20environmental%20life-cycle%20assessment%20of%20munitions%3A%20adressing%20chemical%20toxicity%20hazard%20on%20human%20health.pdf

*** Assuming emission factor of 2.13 kg CO_2e per kg from ICE Database (cradle to gate, A1-A3 modules), embodied carbon value for Steel seamless tube, World average. https://circularecology.com/embodied-carbon-footprint-database.html

Data on fortifications

As of early April 2023, based on the analysis of satellite images, the total length of fortification structures identified was 2,837 km.

These include 4,081 objects (4,075 polyline type objects with a total length of 2,837,391 m or 2,837 km and six polygon type objects with a total area of 2,501,991 m^2 or 2.5 km^2). All objects can be identified and well distinguished on the Sentinel-2 L2A satellite images with the minimum trench width of 150 cm.

Identification was carried out during the periods of clear weather and absence of clouds and precipitation as indicated in the table below.

ADMINISTRATIVE REGION	OBSERVATION PERIODS
Kharkiv	2023-03-14, 2023-01-23
Luhansk	2022-10-15, 2022-12-19, 2023-01-03, 2023-01-11, 2023-01-23, 2023-03-14
Donetsk	2022-11-29, 2022-12-19, 2023-01-03, 2023-01-08, 2023-01-11, 2023-01-23, 2023-01-26, 2023-03-14
Zaporizhzhia	2022-12-22, 2023-01-03, 2023-01-08, 2023-01-11, 2023-01-26, 2023-02-07, 2023-03-02, 2023-03-14, 2023-03-22
Kherson	2022-11-15, 2022-12-22, 2022-12-30, 2023-01-21, 2023-02-03, 2023-02-08, 2023-02-13, 2023-02-20, 2023-02-23, 2023-02-25, 2023-03-27
Autonomous Republic of Crimea	2023-01-01, 2023-01-11, 2023-01-16, 2023-01-21, 2023-02-20, 2023-02-25, 2023-03-05, 2023-03-22, 2023-03-27
Regions of Russia (Belgorod, Kursk, and Bryansk regions)	2023-01-11, 2023-01-23, 2023-01-24, 2023-01-26, 2023-03-14, 2023-03-15, 2023-03-18

Tools used:

- EO Browser https://apps.sentinel-hub.com/eo-browser/; manual https://www.sentinel-hub.com/explore/eobrowser/user-guide/
- Google My maps https://www.google.com/maps/d/u/0/; manual https://support.google.com/mymaps/?hl=en#topic=3188329
- QGIS https://qgis.org/ru/site/forusers/download.html; manual https://docs.qgis.org/3.28/ru/docs/user_manual/index.html

Example of analysis is provided for the following location:
Zaporizhzhia region, Ukraine, latitude: 47.21901, longitude: 35.50734

Date of the satellite image: 2022-12-22. URL to Sentinel HUB: https://apps.sentinel-hub.com/eo-browser/?zoom=14&lat=47.21901&lng=35.50734&themeId=DEFAULT-THEME&visualizationUrl=https%3A%2F%2Fservices.sentinel-hub.com%2Fogc%2Fwms%2Fbd86bcc0-f318-402b-a145-015f85b9427e&datasetId=S2L2A&fromTime=2022-12-22T00%3A00%3A00.000Z&toTime=2022-12-22T23%3A59%3A59.999Z&layerId=1_TRUE_COLOR&gain=1.7&demSource3D=%22MAPZEN%22

Step 1 - Fragment of the satellite image from Sentinel hub

Step 2 – Corresponding vector lines on Google map (image) after vectorisation

Step 3 – Corresponding vector lines on Google map (map) after vectorisation

Dragon's teeth lines

The overall length of the first dragon's teeth line on the east of Ukraine was expected to reach 200 km, from which about 12 km were reportedly installed back in October 2022[138]. However, since that period, installation of such obstacles was reported in many other locations, including Belgorod region in Russia, Kherson, Zaporizhzhia, and Luhansk regions and Crimea.

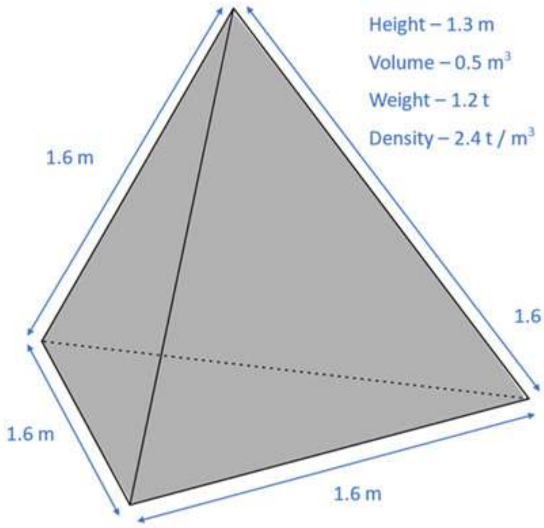

Fig. 23. Parameters of concrete tetrahedrons used as "dragon's teeth" obstacles[137]

In Crimea, for instance, fortification lines with dragon's teeth were installed near all main roads entering the peninsula, including the road connecting Crimea with Russia over the Kerch bridge. Three lines of dragon's teeth were installed at a narrow area between the Kerch peninsula and the main part of Crimea peninsula stretching over 20 km between the Azov Sea and the Black Sea[139]. Similar defensive lines were installed near Medvedivka village on the north-east of the peninsula along the E105 road, where the width of the land between Syvash waters is about 3 km. Miles of fortifications, which also included sections with "dragon's teeth", were built on the western part of Crimea near Vitino Village. Piles of "dragon's teeth" were also visible on the satellite images to the north of Armiansk town on the north of Crimea, where the width of the strip of land between Syvash and the Black Sea is about 9 km. Besides, additional defensive lines with concrete pyramids were installed along the North Crimea Canal, in particular near villages Maslove and

137. Based on the tetrahedron image available at https://commons.wikimedia.org/wiki/File:Tetrahedron_grey.svg
138. Satellite photos reveal fortification plans in Russia-occupied Ukraine: Analysts, https://abcnews.go.com/International/satellite-photos-reveal-fortification-plans-russia-occupied-ukraine/story?id=91734319
139. Протитанкові «зуби дракона» на сході Криму продовжують до Чорного моря (фото), https://ua.krymr.com/a/news-zuby-drakona-krym/32347585.html

Novoivanivka[140]. Fortifications are built in several echelons; as for the south of Armiansk, between Armiansk and Krasnoperekopsk town additional dragon's teeth line could be observed on satellite images[141]. Thus, in Crimea alone the length of fortification lines with dragon's teeth reaches dozens of kilometres.

In Zaporizhzhia region, dragon's teeth lines were observed to the north of Tokmak town, around Berdiansk airport to the north of Berdiansk town[142], to the north of Mykhailivka town[143], and in other locations. In Luhansk and Donetsk regions, dragon's teeth lines were observed to the north of Kreminna town in the direction of Svatove town, north to Svatove town, as well as near Hirske town, and to the north of Soledar city (spanning more than 5 km)[144].

Journalist investigation revealed that concrete pyramid-shaped structures used for the construction of dragon's teeth protection lines were manufactured at least at six plants within Belarus in massive volumes starting from November 2022. According to the investigation, enterprises located in Homel region received orders for the manufacturing of 20,000-30,000 units of concrete pyramids[145]. Manufacturing of such obstacles was also reportedly started in Crimea with the capacity of 5,000 units per month[146]. Similar production lines were launched in Russia using the capacities of concrete producers and other construction companies. At two plants alone, the production volume was reportedly reaching 6,000 and 15,000 units per month, and there were also other producers with manufacturing capacity of thousand units per month[147].

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140. A web of trenches shows Russia fears losing Crimea, https://www.washingtonpost.com/world/interactive/2023/ukraine-russia-crimea-battle-trenches/
141. Brady Africk, https://twitter.com/bradyafr/status/1645754948297138176/photo/1
142. See the visual confirmation provided by Brady Africk: https://twitter.com/bradyafr/status/1645105992508612608; Russian field fortifications in Ukraine. Satellite imagery shows trenches and barriers span the front line in Ukraine, https://read.bradyafrick.com/p/russian-field-fortifications-in-ukraine
143. See https://twitter.com/Tatarigami_UA/status/1645651237415575553
144. See the visual confirmation provided by Brady Africk: Russian field fortifications in Ukraine. Satellite imagery shows trenches and barriers span the front line in Ukraine, https://read.bradyafrick.com/p/russian-field-fortifications-in-ukraine; https://twitter.com/bradyafr/status/1654640871974002688/photo/1; https://twitter.com/bradyafr/status/1654859814328217600
145. Расследование: «Зубы дракона» выпускают минимум 6 беларусских предприятий, и ими укрепляют границу в Брянской области, РФ, https://motolko.help/ru-news/zuby-drakona-vypuskayut-minimum-na-6-i-belarusskih-predpriyatiyah-imi-ukreplyayut-graniczu-v-bryanskoj-oblasti-rf/
146. Production of anti-tank barriers launched in occupied Crimea, https://www.pravda.com.ua/eng/news/2022/11/29/7378476/
147. "Мы сейчас только с Мелитополем работаем. Все в том районе". Как Россия возводит укрепления на оккупированных территориях Украины, https://www.bbc.com/russian/features-64055785

Data on embodied carbon in military equipment

Indicative assumptions, data used, and results are presented in the tables below.

Russian equipment losses

Equipment	Indicative weight, t	Indicative embodied carbon, t	Amount of destroyed equipment	Amount of damaged equipment	Indicative mass of destroyed equipment, t	Indicative mass of damaged equipment, t	Emissions, tCO_2e
Tanks	40	240	1,165	101	46,600	4,040	284,448
Armoured fighting vehicles	8	48	523	17	4,184	136	25,267
Infantry fighting vehicles	14	84	1,505	72	21,070	1,008	127,630
Armoured personnel carriers	11	66	193	8	2,123	88	12,844
Infantry mobility vehicles	6	36	131	4	786	24	4,745
Self-propelled artillery	27	162	259	16	6,993	432	42,476
Multiple rocket launchers	14	84	130	5	1,820	70	11,004
Trucks, vehicles and jeeps	8	48	1,802	39	14,416	312	86,870
Aircrafts	12	72	72	8	864	96	5,299
Helicopters	11	66	73	10	803	110	4,950
Naval ships	-	-	8	4	14,137	3,119	88,562
TOTAL	-	-	5,861	284	113,796	9,435	694,096

Table 19. Information on Russian equipment losses and associated emissions

(Calculated based on data reported at https://www.oryxspioenkop.com/2022/02/attack-on-europe-documenting-equipment.html)

Ukrainian equipment losses

Equipment	Indicative weight, t	Indicative embodied carbon, t	Amount of destroyed equipment	Amount of damaged equipment	Indicative mass of destroyed equipment, t	Indicative mass of damaged equipment, t	Emissions, tCO_2e
Tanks	40	240	303	29	12,120	1,160	74,112
Armoured fighting vehicles	8	48	180	2	1,440	16	8,659
Infantry fighting vehicles	14	84	372	13	5,208	182	31,466
Armoured personnel carriers	11	66	136	13	1,496	143	9,148
Infantry mobility vehicles	6	36	156	19	936	114	5,753
Self-propelled artillery	27	162	84	33	2,268	891	14,677
Multiple rocket launchers	14	84	27	8	378	112	2,402
Trucks, vehicles and jeeps	8	48	376	15	3,008	120	18,192
Aircrafts	12	72	65	1	780	12	4,694
Helicopters	11	66	25	1	275	11	1,663
Naval ships	-	-	7	2	5,257	3,154	35,326
Total	-	-	1,731	136	33,166	5,915	206,093

Table 20. Information on Ukrainian equipment losses and associated emissions

(Calculated based on data reported at https://www.oryxspioenkop.com/2022/02/attack-on-europe-documenting-ukrainian.html)

The value of 6 kg of CO_2e per kg of machinery weight has been applied as an indicative carbon footprint of military equipment. For comparison, a study on climate impact of Norwegian defence sector used the following emission factors for manufacturing of military systems based on Ecoinvent database data[148]:

Ships and boats:

- 18,034 tCO_2e per unit of big boats (i.e. a transoceanic freight ship);
- 1,429 $tCO2_e$ per unit of medium boats (i.e. a barge tanker);
- 1,188 $tCO2_e$ per unit of small boats (i.e. a barge);

148. Personal communication with Prof. Magnus Sparrevik and Supplementary materials for Magnus Sparrevik, Simon Utstøl, Assessing life cycle greenhouse gas emissions in the Norwegian defence sector for climate change mitigation, Journal of Cleaner Production, Volume 248, 2020, https://doi.org/10.1016/j.jclepro.2019.119196, https://www.sciencedirect.com/science/article/pii/S0959652619340661

Aircrafts:

- 7,022 tCO_2e per unit of long haul aircraft;
- 2,195 tCO_2e per unit of medium haul aircraft;
- 8,9 tCO_2e per unit of helicopters;

Vehicles:

- 33.7 tCO_2e per unit of heavy vehicles (i.e. a building machine);
- 24.4 tCO_2e per unit of medium vehicles (i.e. a 16 metric ton lorry);
- 6.8 $kgCO_2e$ per kg of weight of light vehicles (i.e. a diesel passenger car; weight values of 1,200 and 2,000 kg were used).

These data demonstrate wide variations in emission factors as well as limitations related to comparison of civilian equipment and military equipment types. For instance, for vehicles, the emission factor varies from 8.2 to 33.7 tCO_2e per unit depending on the type of vehicles. For the purpose of climate damage assessment, the indicative value used for "Trucks, Vehicles and Jeeps" category is 48 tCO_2e per unit, which reflects the greater weight of military equipment. For Aircrafts and ships, the difference in values is more significant, which is related to the very different potential types and sizes of equipment in these categories. Analysis of a more detailed inventory of destroyed military equipment and additional research on embodied carbon of military equipment is required for a more precise estimation of the climate damage.

FIRES

Historical data on fires

Impact of the war has been estimated by comparing the areas of fires during the first year of the war with historical data on fires. Data from the European Forest Fire Information System (EFFIS) for the territory of Ukraine are available starting from 2020. However, 2020 was not a representative year with large fires in Ukraine and data for this year could not be used for comparison.

Ukrainian official statistics on landscape fires, including forest fires, has significant limitations and allows recording only a part of the fires that occurred. Based on long-term statistical data, there are three or four years with significantly higher numbers and areas of forest fires each decade, with weather conditions, in particular the amount of precipitation during April-September, being the key factor influencing fire risks[149]. Large-scale single events or an unusually high number of fires during a particular year significantly impact the average values for historical periods. During 1990-2021, there were 3,519 fires affecting about 6,800 ha on average per year. However, if years with unprecedented large areas of fires (>5,000 ha) are excluded, the average values will be reduced to 2,817 fires affecting about 2,300 ha of forests[150].

In 2020, the area of fires was extremely high, reaching about 75,000 ha according to official statistics, which is more than five times higher than the second largest area of fires recorded during 1990-2021.

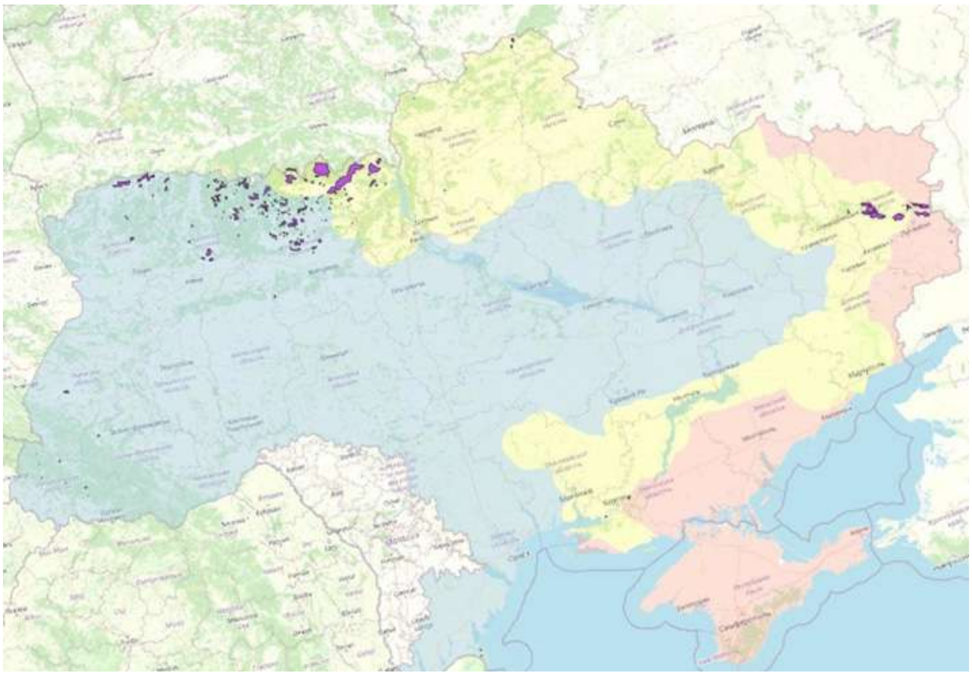

Fig. 24. Fires during the period of 24 February 2020 – 23 February 2021

149. S. V. Zibtsev, O. M. Soshenskyi, V. V. Humeniek, V. A. Koren (2019), Long term dynamic of forest fires in Ukraine, Ukrainian Journal of Forest and Wood Science, 10(3):27-40, https://nubip.edu.ua/sites/default/files/u184/13113-29360-1-sm1.pdf
150. Calculated based on the information provided by the Statistical Service of Ukraine, https://ukrstat.gov.ua/druk/publicat/Arhiv_u/07/Arch_dov_zb.htm

The EFFIS data for the period of 24 February 2020 – 23 February 2021 recorded 220 fires with the total area of 255,645 ha, including 147,597 ha of fires in forest areas (larger than one hectare). From the total number of recorded fires, 134 fires with the area of 119,557 ha started in a very short period in spring (31 days from 28 March – 29 April) and took place on the territory of four northern regions (Volyn, Rivne, Zhytomyr, with to Kyiv).

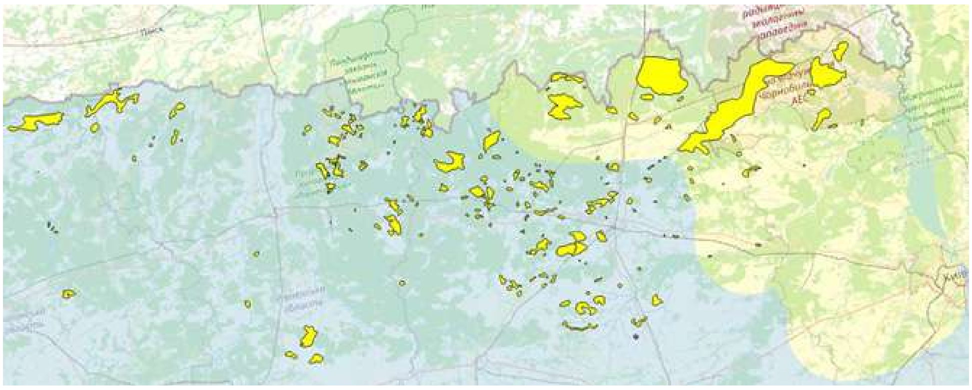

Fig. 25. Fires during the period of 28 March – 29 April 2020 in the northern regions of Ukraine

Thus, data from 2020 were not used for the analysis and assessment, which were hence based on comparison of the fire areas during the first year of the war and the pre-war period (365 days before the start of the war).

Areas affected by the war

The war resulted in a significantly increased number and area of fires, including forest fires. During 2022, there were 133 fires with the area exceeding 500 ha and some fires exceeding 1,000 ha, with the largest fire recorded affecting more than 6,000 ha. The largest number of fires was observed in March and July[151].

The whole territory of Ukraine has been affected by the war for some extent, however, the level and nature of impact differs in the following three zones (Fig. 26):

A) Zone 1 – (66.5% of the territory of Ukraine) where ground military operations were not conducted;

B) Zone 2 – (19.5% of the territory of Ukraine) zone of active hostilities (ground hostilities were conducted for more than 24 hours);

C) Zone 3 – (14.0% of the territory of Ukraine) occupied territories, in which ground military operations were conducted for not more than 24 hours or did not take place at all.

151. Advance Report on Forest Fires in Europe, Middle East and North Africa 2022, https://publications.jrc.ec.europa.eu/repository/handle/JRC133215. Also see the examples of large fires on Kinburn Split, https://bihus.info/peklo-u-rayu-yak-okupanty-znyshhuvaly-kinburnsku-kosu-vbyvayuchy-pryrodu-i-teroryzuyuchy-misczevyh/

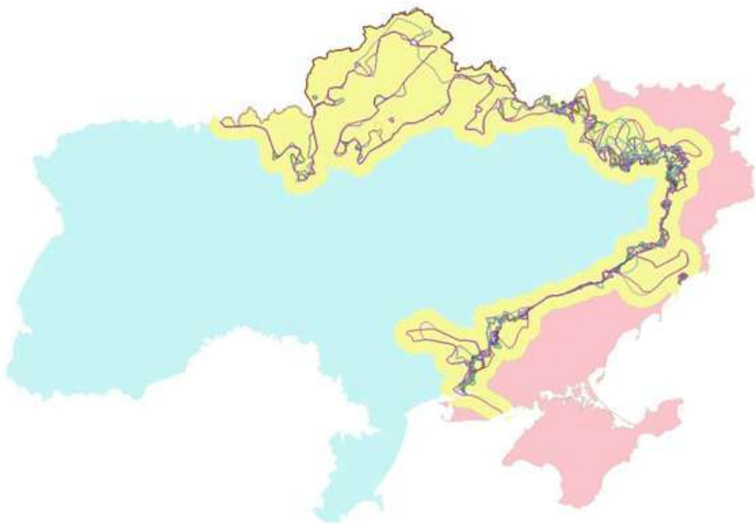

Fig. 26. Frontlines and territory distribution by zones: Zone 1 (blue), Zone 2 (yellow), and Zone 3 (red)

Territories in Zone 1 were under rocket and drone attacks, which often caused fires. The ability to monitor and provide an early response to fires, which determines the scale of affected land, was limited due to the safety risks related to air raid alerts and other factors (e.g. power outages, infrastructure damage, etc.).

Additional spatial-temporal analysis of the relationship between air raid alerts[152] in Ukrainian regions and locations of 2,100 fires recorded by the EFFIS service in this zone for 365 days of the war revealed that most of the fires occurred during the periods of and in locations with air raid alerts. During this period, the air raid alerts were announced 21,306 times, including 596 air raid alerts that started on one calendar day and ended on the next day. The air raid alerts were active on the territory of regions or individual settlements. The total area of fires recorded in Zone 1 was 131,193 ha but only 363 fires with the area of 20,561 ha (less than 16% from the total area of fires in this zone) were recorded during the periods without active air raid alerts. This figure is comparable with the area of fires in Zone 1 during the pre-war period (24,865 ha). Thus, it is assumed that an increase in the number and area of fires in Zone 1 is attributable to the war either due to the direct impact of missiles and drones or other factors limiting the ability to ensure early response to the fires.

Territories in Zone 2 were most severely affected by increased areas of forest fires due to the direct impact of combat operations. The frontlines changing during the course of the war as reported by OSINT[153] are indicated on figure 26. The 12-mile zones on both sides of the changing front lines were applied to map Zone 2.

In Zone 3, which covers occupied territories, the attribution to the war is explained by the lack of efficient fire-response actions or even cases, when occupying forces prohibited local population to respond to fires in natural ecosystems, as well as additional impacts due to the military operations. According to the provisions of the Convention on the laws and customs of war on land[154] (Hague, II) (29 July 1899), articles 23, 43, and 55, the occupying country is responsible for the fires on the occupied territory.

152. Statistics of air raid alerts in Ukraine, https://air-alarms.in.ua/en
153. https://liveuamap.com/uk
154. Laws of War: Laws and Customs of War on Land (Hague II); July 29, 1899, https://avalon.law.yale.edu/19th_century/hague02.asp

Emissions from fires

A general methodology to estimate the emissions of individual greenhouse gases for any type of fire is provided by the IPCC[155]:

$L_{fire} = A \cdot M_B \cdot C_f \cdot G_{ef} \cdot 10^{-3}$, where:

- L_{fire} – amount of greenhouse gas emissions from fire, t of each GHG (e.g., CH_4, N_2O);
- A – area burnt, ha;
- M_B – mass of fuel available for combustion, t per ha; this includes biomass, ground litter, and dead wood, but when Tier 1 methods are used, then litter and dead wood pools are assumed zero;
- C_f – combustion factor, dimensionless;
- G_{ef} – emission factor, g per kg of dry matter burnt.

The area affected by fires has been determined based on satellite observations as provided by open fire prevention information systems: the US-based Fire Information for Resource Management System (FIRMS) and the European Forest Fire Information System (EFFIS). The mass of fuel available for combustion during forest fires has been estimated using the data on average values of stocks of forest stands (stocks of stem wood) for the regions most affected by the war. The weighted average value of forest stands (233 m^3/ha) has been applied in calculations. However, the biomass of stem wood represents only a fraction of total biomass in the forest (approximately two thirds), while other biomass includes branches, leaves, stumps, and various forest vegetation[156]. Therefore, the value of biomass content in forest stands has been converted into overall above-ground and below-ground biomass content in forests in tonnes of dry matter per hectare using the approaches applied in the national GHG emissions inventory.

155. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories, Equation 2.27, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index .html
156. Lakyda P.I., Vasylyshyn R.D., Matushevych L.M., Zibtsev S.V., Wood biomass energetic of Ukrainian forests using in conditions of global climate change, https://nv.nltu.edu.ua/Archive/2009/19_14/18_Lak.pdf

Region	Forest stand, m³/ha	
	Coniferous	Deciduous
Donetsk	209	159
Kyiv	297	222
Luhansk	202	150
Kherson	161	85
Chernihiv	354	230
Zaporizhzhia	133	73
Kharkiv	305	248
Sumy	341	269
Average	250	180
Assumed value*	233	

Table 21. Average stock of forest stands (stocks of stem wood) in the forests located in the regions most affected by the war[157]

** Based on the data from EFFIS (see Advance Report on Forest Fires in Europe, Middle East and North Africa 2022, https://publications.jrc.ec.europa.eu/repository/handle/JRC133215), 75% of the forest land affected by fires in Ukraine in 2022 were represented by coniferous forests, 21% by broadleaf forests, and 4% by mixed forests*

For forest ground litter, the default value of 10 t of dry biomass has been applied in line with the national GHG emissions inventory[158].

For crown fires, the amount of fuel available for combustion includes both trees and ground litter. During the low-intensity surface fires, only litter and grass are assumed to be affected while trees remain mostly intact.

Fires usually start as surface fires but may transfer to canopy fuel causing crown fires if not extinguished timely. Since most of the forest fires were recorded in active combat zone, the ability to respond to them was limited. Lack of fire suppression allows low intensity and medium intensity fires evolve into high intensity fires spreading on large territories due to topography characteristics, wind, and fuel availability. Besides, coniferous forests (75% of forests affected by fires in Ukraine in 2022) are more vulnerable to fires and face a greater risk of crown fire development. Similar results were obtained based on the additional analysis of the areas of forest fires, for which hotspots were initially detected by FIRMS and then the fires were mapped using satellite imagery by EFFIS. Such fires were assumed to represent crown fires and constituted 77% of the total area of forest fires recorded. Fires not detected by FIRMS assumed to be surface fires, since tree canopy and lower level of mid-infrared radiation from such fires obscures fire detection by the FIRMS service.

157. Ukraine's Greenhouse Gas Inventory 1990-2021 485 Table A3.3.8. Average stock of forest stands in forests of the State Forest Resources Agency of Ukraine, m³/ha, https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2023

158. Ukraine's Greenhouse Gas Inventory 1990-2021, https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2023

Based on this, for the purpose of climate damage assessment, it was assumed that three quarters of the forest fires area was affected by crown fires, while the remaining territory was affected by surface fires. Additional research, including ground-based verification of the impact would be required for a more detailed assessment.

Combustion factor, which indicates the fraction of fuel that is actually combusted during the fire, depends on various characteristics, including weather, moisture content, type and structure of the forest, and type of the fire.

The severity of fire impact could be assessed based on spectral indices from remote sensing imagery, in particular, a difference between the pre-fire and post-fire normalized burn ratio index (delta NBR or dNBR), which was designed to identify burnt areas[159]. Due to the lack of such analysis for the affected areas, the default value of the fraction of biomass lost in fires equal to 0.7, as provided in the national GHG inventory[160], was applied to crown fires. The Tier 1 assumption is that all of the biomass assumed to be lost results in emissions in the year of disturbance (i.e. in the year of fire).

Emissions from fires also include other greenhouse gases, or precursors of greenhouse gases, that originate from incomplete combustion of the fuel. These include carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOC), and nitrogen (e.g., N_2O, NOx) species[161].

Default emission factors provided by the IPCC for all main GHGs were used in calculation of GHG emissions from fires[162]:

- CO_2 – 1569 g/kg of dry matter burnt;
- CH_4 – 4.7 g/kg of dry matter burnt;
- N_2O – 0.26 g/kg of dry matter burnt.

The final emission factors in tCO_2e per hectare of land affected by fires for different land categories are presented in table 22 below.

159. Normalized Burn Ratio (NBR), https://un-spider.org/advisory-support/recommended-practices/recommended-practice-burn-severity/in-detail/normalized-burn-ratio
160. Ukraine's Greenhouse Gas Inventory 1990-2021, https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2023
161. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index .html
162. Table 2.5 (all other forest types), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index .html

Land category and fire type	Emission factor, tCO_2e/ha	Source of information
Forests – crown fires	275	The National Center for GHG Emissions Inventory. Calculated based on the provisions of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Ukraine’s Greenhouse Gas Inventory, and assumptions described above.
Forests – surface fires	18	
Agricultural land	11	
Other nature/landscape	7	
Built-up areas	792	The methodology for calculating of unorganized emissions of polluting substances or mixtures of such substances into atmospheric air as a result of emergency situations and/or during martial law and determining the amount of damage caused[163]. The methodology provides emission factor of 2.64 tCO_2e per tonne of material and an example of a shopping mall with the combustible material content of 0,03 tonnes per m^2 (300 tonnes per ha).

Table 22. Emission factors for different land categories

Opportunities for a more detailed analysis of the areas affected by fires will be explored in future assessment reports (e.g. breakdown of forest fires by types of forests, types of fires, regions, etc.; identification of fires with the area of less than one hectare and use of alternative satellite data sources; analysis of combustible material content in built-up areas, etc.).

163. Methodology for calculating of unorganized emissions of polluting substances or mixtures of such substances into atmospheric air as a result of emergency situations and/or during martial law and determining the amount of damage caused, approved by the order of the Ministry of the Environment of April 13, 2022 No. 175, https://zakon.rada.gov.ua/laws/show/z0433-22#Text

REFUGEES AND IDPS

A. The number of people travelled; their departures and destinations
Displacements can be broken down into two main groups moving from, and within, Ukraine. Data on the refugees that left Ukraine for other countries was gathered and published by the UNHCR[164].

Data on internally displaced persons was gathered by the government of Ukraine and communicated to the Center for Environmental Initiatives Ecoaction.

B. Transport modes
The use of transport modes was assessed subject to standardised assumptions. The assumption was made that a combination of not more than two of the below transport modes was used for international travels to each destination country:

- Petrol car, 4 passengers
- National railways
- Bus
- Domestic flight (= short-haul flight, narrow-body aircraft)
- Long-haul flight, economy (wide–body aircraft)

The choice of a transport mode was determined by a distance to Ukraine and the availability of the relevant transport mode. We have assumed that, in many cases, the first half of the journey was done by petrol car. For the second half of the journey, we have assumed as follows:

- For countries neighbouring Ukraine: petrol car, 4 passengers
- For countries in North-West Europe: national railways
- For countries in South Europe, North Europe, the Baltic, the Caucasus, and islands states: domestic flight
- For the US, Canada and Australia: long-haul flight, entire journey
- For Russia and Belarus: bus, entire journey

We have not differentiated between various types of cars, fuel, or occupancies.

C. CO_2 emissions per person kilometre for each of those transport modes
To assess CO_2 emissions per person kilometre, we have used the 2019 data published by the UK Department for Business, Energy & Industrial Strategy: Greenhouse gas reporting: conversion factors 2019[165]. These factors may vary slightly depending on the country.

164. https://data.unhcr.org/en/situations/ukraine
165. https://ourworldindata.org/grapher/co2-transport-mode

CIVILIAN INFRASTRUCTURE

Determining the Carbon Emission Factor (CEF) for different facilities is an important component of the methodology. Regarding Buildings sector, the average size of each building was provided by the Kyiv School of Economics (in m^2/unit) and then multiplied by relevant specific carbon emission factor (in tCO_2e/m^2) to obtain the CEF (tCO^2e/unit). The embodied carbon approach is used to determine specific CEF. Under this approach, all emissions, both direct and indirect, are estimated over the whole life cycle of a facility, excluding, however, operational emissions (in the case of a building, operational emissions are, for example, heating). For buildings, the life cycle, according to EN-15978, is split as follows:

PRODUCT STAGE	Raw material supply	**A1**
	Transport	**A2**
	Manufacturing	**A3**
CONSTRUCTION PROCESS STAGE	Transport to building site	**A4**
	Installation into building	**A5**
USE STAGE	Use / application	**B1**
	Maintenance	**B2**
	Repair	**B3**
	Replacement	**B4**
	Refurbishment	**B5**
	Operational energy use	**B6**
	Operational water use	**B7**
END-OF-LIFE STAGE	Deconstruction / demolition	**C1**
	Transport	**C2**
	Waste processing	**C3**
	Disposal	**C4**

Table 23. Life cycle stages of buildings

Embodied carbon includes stages A1-A3, A4-A5, B4-B5, and C1-C4. In this assessment, we look into additional emissions of GHG, i.e. emissions that would not have occurred in the absence of the war. Therefore, stages B4-B5 are not taken into account as replacement and refurbishment of buildings would have also happened in the damaged or destroyed buildings. The End-of-Life stages C1-C3 will occur first, after which reconstruction stages A1-A3 and A4-A5 will happen. Operational carbon emissions from the Use stages B1-B3 and B6-B7 are omitted as well, as they would have happened in existing buildings as well.

To reflect the most recent construction practice used in the region to determine the Embodied Carbon Emission Factor of buildings, a database of One Click LCA[166], a software programme to perform Life Cycle Assessments (LCA) for buildings, was used. This database contains LCAs of recently designed buildings of different types in various countries. From this database, LCAs performed in 16 countries in Central and Eastern Europe in the past three years were selected to calculate an average CEF. Depending on the building type, the average was based on 4 to 100 building designs.

BUILDING TYPE	CEF ($kgCO_2e/m^2$)
Apartment buildings	575
Cultural buildings	474
Educational buildings	643
Hotels and similar buildings	401
Industrial production buildings	475
Office buildings	529
Retail and wholesale buildings	632
Warehouses	415

Table 24. Specific Carbon Emission Factor per building type for life-cycle stages A1-A3, A4-A5, and C1-C4

In Transport & Infrastructure sector, damaged roads represent a large share of the damage. A 2022 study estimated the life-cycle emissions of different types of roads[167]. Most of the roads in Ukraine are single-2 lane and only the construction stage is taken into account as road operation and maintenance emissions would happen on existing roads as well. For a single-2 lane road, embodied carbon adds up to 711 kg CO_2e per kilometre of road. The Kyiv School of Economics has classified all roads as damaged, not destroyed, so only a third of the construction emission factor is used. This is probably a conservative estimation given the fact that months of artillery cause significant damage to roads.

166. One Click LCA website: https://www.oneclicklca.com
167. Lokesh, K., Densley-Tingley, D. and Marsden, G. (2022), Measuring Road Infrastructure Carbon: A 'critical' in transport's journey to net-zero, Leeds: DecarboN8 Research Network, https://decarbon8.org.uk/wp-content/uploads/sites/59/2022/02/Measuring-Road-Infrastructure-Carbon.pdf

Asphalt pavement sub-systems	Dual-3 lane	Dual-2 lane	Single-2 lane
	tCO$_2$e per functional unit		
Material production	1,711	1,433	591.5
Material transport	313	201.3	100.7
Construction	70	37.6	18.8
Road operation (lighting only) (40 yrs.)	406.1	268.7	132.6
Maintenance (40 yrs.)	158.8	73.5	36.6
TOTAL EMISIONS	2,658.9	2,014.1	880.3

Table 25. Embedded emissions estimated for the different sub-systems of asphalt pavement (for different scales of construction) over an assumed time period of 40 years

For passengers vehicles, more research[64] is available to determine embodied carbon. For the purpose of this study, we have taken the lower end of estimations at 5.6 tCO$_2$e/vehicle. Within this category, there are other types of vehicles as well, like trolleybuses, trams, buses, and agricultural machines. The embodied carbon factor of passenger vehicles was used as a reference point and other factors were set relative to the average weights of other vehicles compared to a passenger vehicle. The KSE report does not separate vehicles as damaged or destroyed, so an average adjustment factor of 67% was used as some vehicles could be repaired.

168. https://www.hotcars.com/the-truth-about-the-carbon-footprint-of-a-new-car-that-no-ones-talking-about/