CLIMATE DAMAGE CAUSED BY RUSSIA'S WAR IN UKRAINE

24 February 2022 – 23 February 2024

by Initiative on GHG accounting of war

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Executive Summary

Russia's 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. Beside causing damage to the natural environment of Ukraine, this war affects the global climate due to the release of significant amounts of carbon dioxide and other greenhouse gases (GHG) into the atmosphere.

With the war ongoing, GHG emissions have continued to grow, as is shown is the figure below. This fourth assessment concludes that GHG emissions, attributable to 24 months of war, have increased to **175 million tCO_2e**. In the early months of the war, the majority of the emissions were caused by the large scale destruction of civilian infrastructure requiring a large post-war reconstruction effort. Now, after two years of war, the largest share of emissions originate from a combination of warfare, landscape fires and the damage to energy infrastructure.

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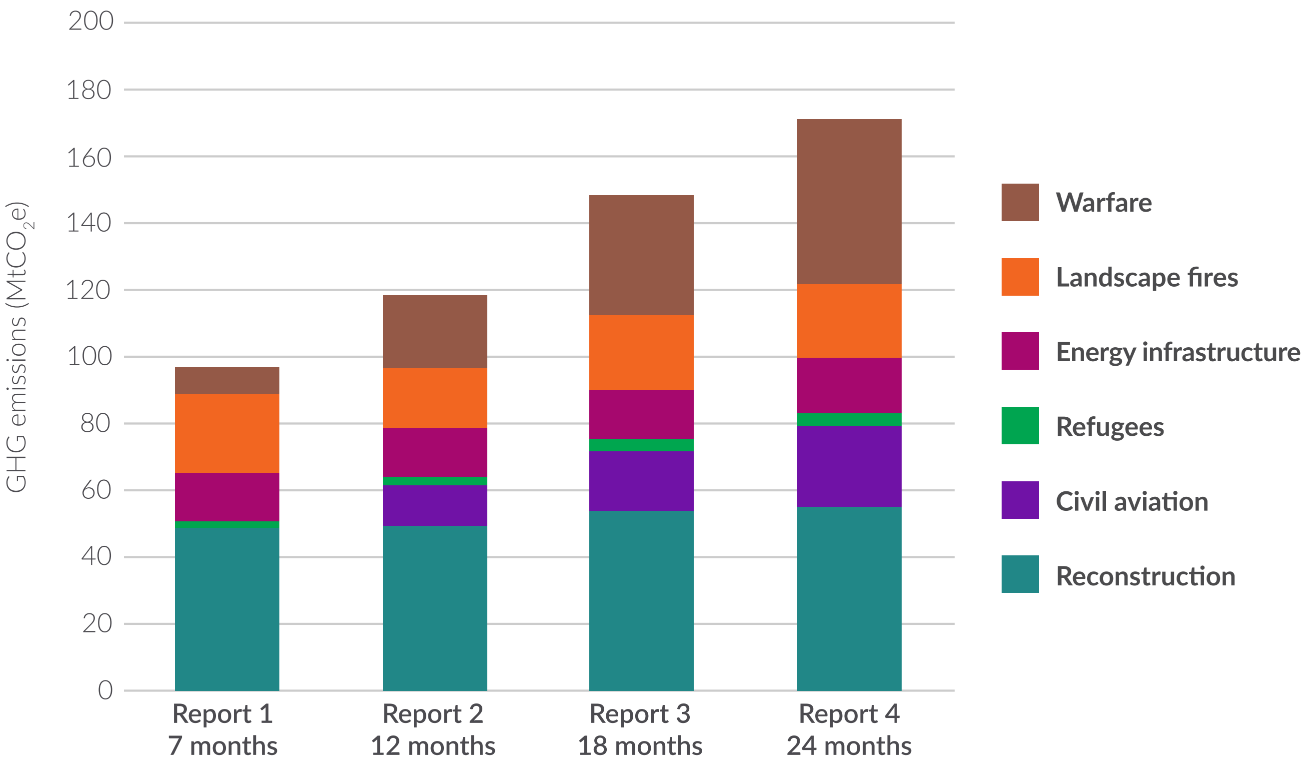
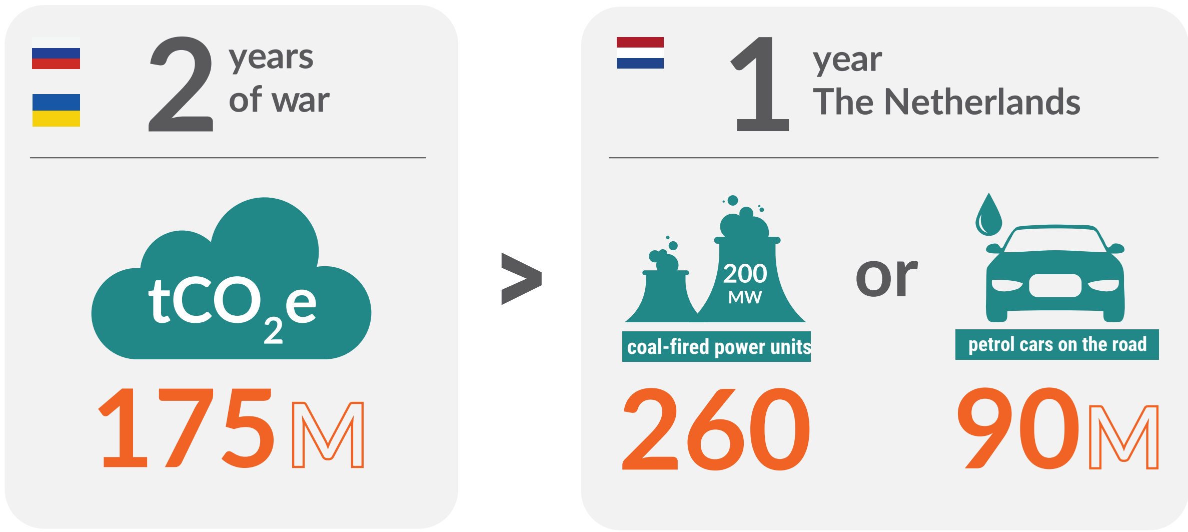


Figure 1. Growth of war emissions

175 million tCO_2e is more than the annual GHG emissions from a highly industrialized country like **The Netherlands**, putting **90 million new petrol cars** on the road, or building **260 coal-fired power units** of 200 MW each.

GHG emissions



The Russian Federation can be held accountable for these emissions and the resulting damage to the global climate as, without its act of aggression, these GHG emissions would not have happened. Applying the Social Cost of Carbon of 185 USD/tCO_2e, a measure to reflect damage for each tonne of emitted greenhouse gas, the total climate damage that the Russian Federation has caused after 24 months of the war amounts to **more than USD 32 billion**. For more details, see Chapter 2. The majority of the emissions originated from the territory of Ukraine, whereas a third of the emissions occurred elsewhere, showing that the impact of the war on GHG emissions is not limited to Ukraine.

As an **indirect** effect, the full-scale invasion has led to an insecure world with military spending on the rise, in particular on the European continent.[1] As militaries are responsible for 5.5% of global emissions,[2] an increase in military spending will inevitably lead to more military emissions worldwide.

Warfare

Emissions resulting from warfare continue to grow. The consumption of fuel has risen steadily with each passing month of the war both at the frontline and in the supply chain of the armed forces. Though the rate of artillery use decreased compared to the first year of the war, the production of large quantities of ammunition has significantly increased in Russia, Ukraine, and elsewhere to replenish dwindling stocks. The use of carbon-intensive explosives, steel, and other materials has increased for the production of ammunition. Both Russia and Ukraine have constructed and continued expanding and strengthening hundreds of kilometres of fortifications along and behind the frontlines. Ukraine has also implemented a large-scale programme of building protective layers for critical energy infrastructure and installing concrete shelters in cities and towns to protect civilians. The use of carbon intensive materials, such as steel and concrete, among other construction materials resulted in more carbon emissions. Additional GHG emissions are caused by manufacturing of military equipment that has been destroyed and damaged during the war, as well as long-distance arms deliveries by allies.

Total emissions: 51.6 million tCO_2e.

1. Military spending in Europe increased in 2023 with 16% compared to the previous year, https://www.sipri.org/publications/2024/sipri-fact-sheets/trends-world-military-expenditure-2023
2. Estimating the military's global greenhouse gas emissions, CEOBS, https://ceobs.org/estimating-the-militarys-global-greenhouse-gas-emissions/

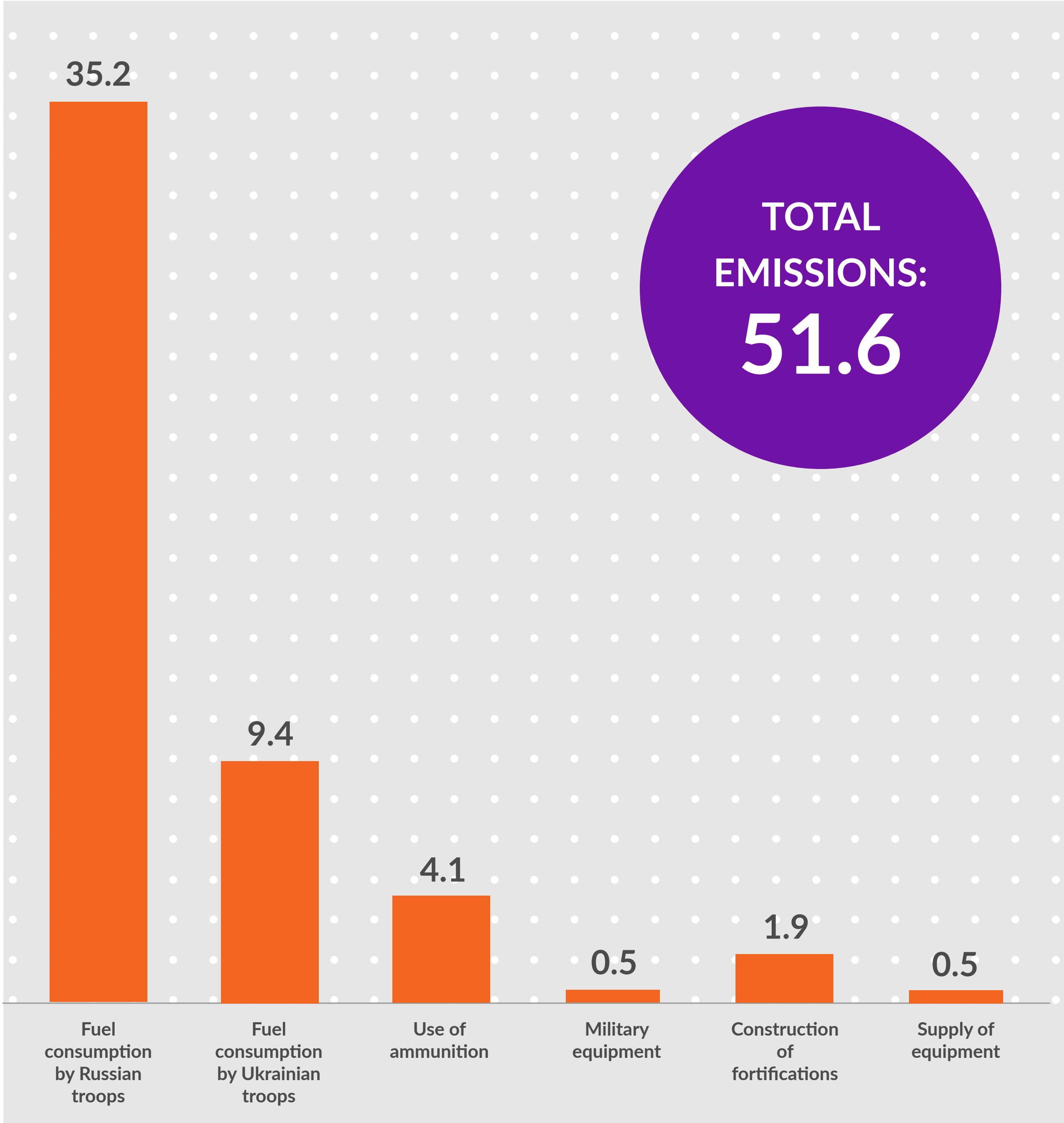


Figure 2. GHG emissions from warfare during 24 months

Landscape fires

Landscape fires are a normal phenomenon but the size and intensity of landscape fires in Ukraine during the past 24-month period increased significantly at both sides of the frontline: shelling and other warfare activities ignited fires and, in the absence of adequate fire-fighting capacity, these fires burnt uncontrolledly. This fourth assessment is based on a fully revised approach with manually mapped fires and a novel methodology to distinguish war-related fires from regular ones. **Total emissions: 22.9 million tCO_2e.**

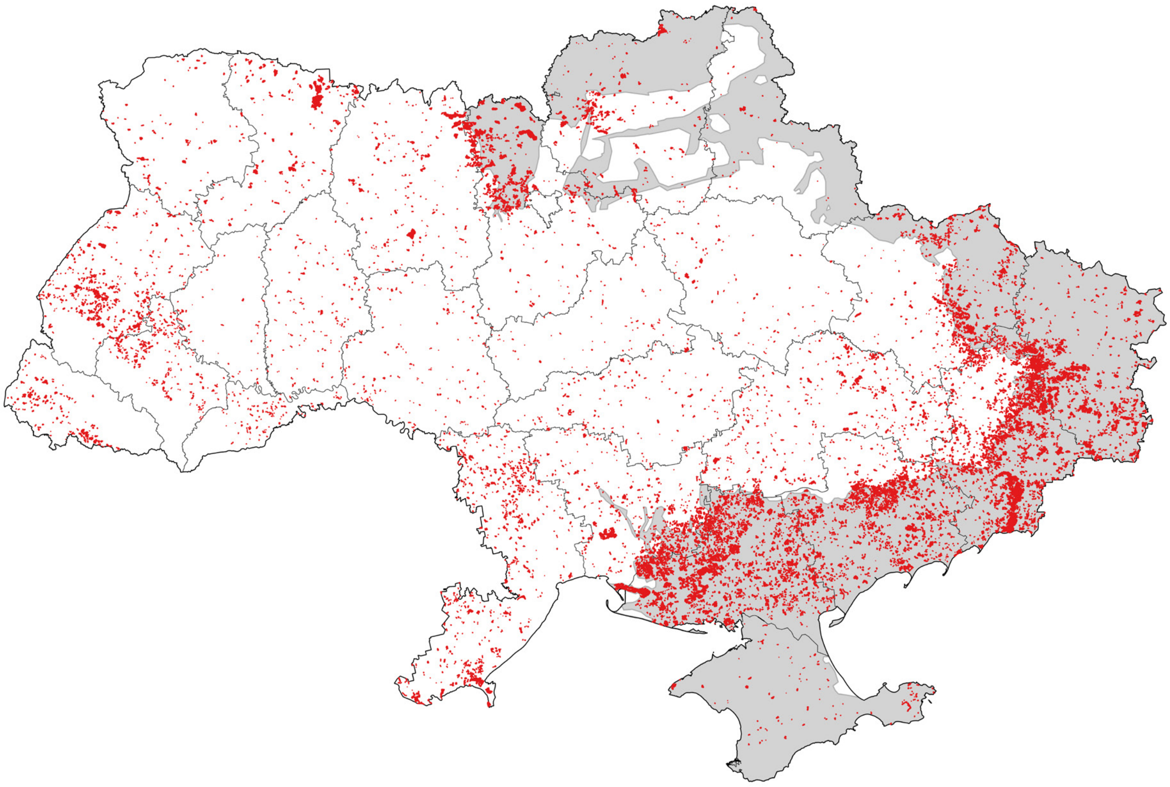


Figure 3. Landscape fires during 24 months of war with areas or armed conflict and occupied territories marked in grey

Energy infrastructure

In the first weeks of the war, Russia attacked many Ukrainian fossil fuel depots and refineries and many tonnes of oil products went up in flames causing significant GHG emissions. The large-scale attacks on the Ukrainian electricity network caused many uncontrolled leakages of SF_6, which is the strongest existing greenhouse gas. Additional GHG emissions were caused by the damage and destruction of natural gas transportation and distribution infrastructure in Ukraine and the long-term fire on natural gas production platform in the Black Sea. In this fourth assessment, these emissions have been estimate for the first time. They come on top of the sabotage of the Nord Stream 1 & 2 natural gas pipelines, which resulted in the biggest leak of methane, another potent greenhouse, ever observed. **Total emissions: 17.2 million tCO_2e**.

Aviation

The closure of the Siberian airspace by Russia to many airlines has cut important east-west air routes between Europe and Asia for many Western carriers. The closure of Ukraine's airspace to commercial traffic has also disrupted flight routes within Europe, in particular in the eastern part of Europe and between Russia and Turkey. Carriers have been forced to take detours resulting in longer flight times, as well as added fuel costs and higher GHG emissions. **Total emissions: 24 million tCO_2e.**

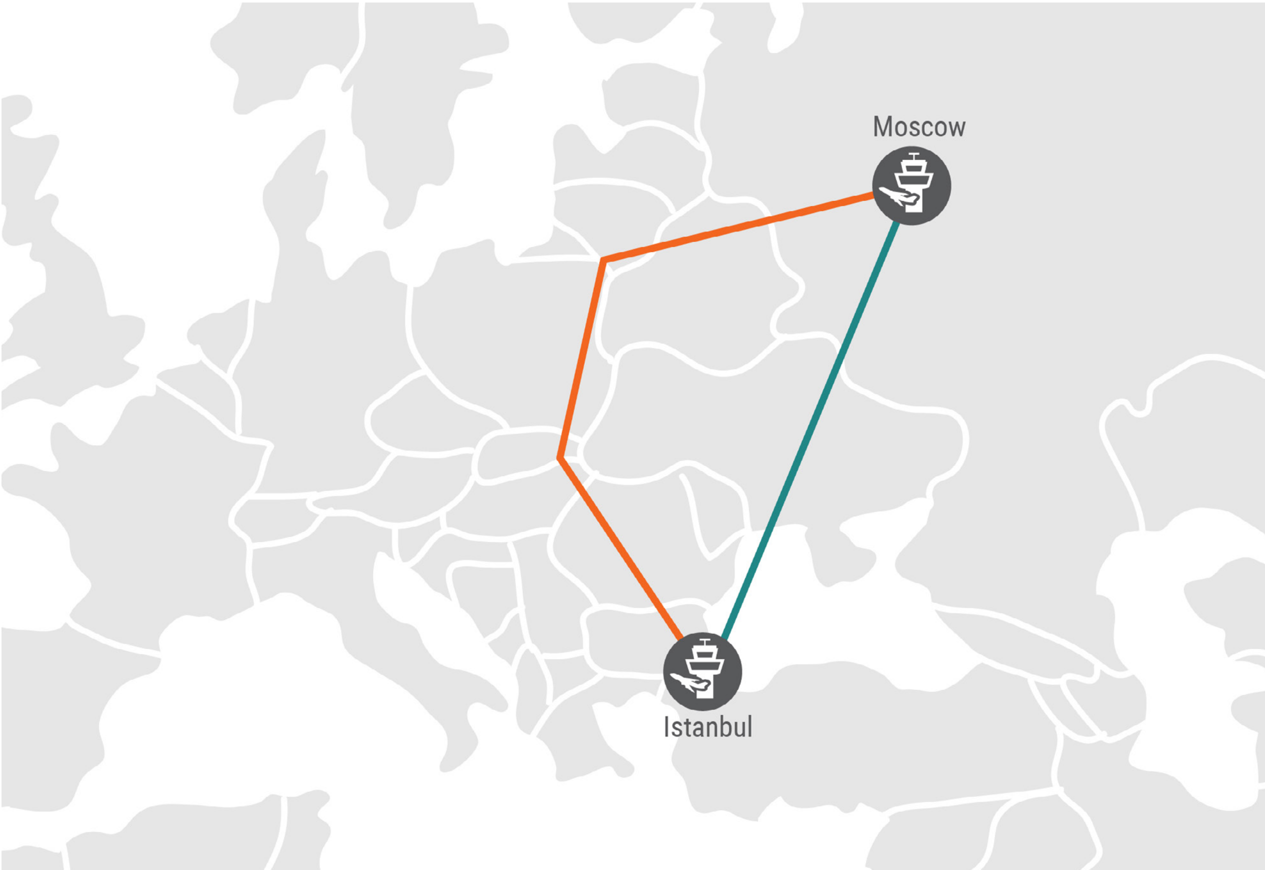


Figure 4. Pre- and post-invasion Turkish Airlines flight routes between Istanbul and Moscow. Source: FlightRader24

Reconstruction

The post-war reconstruction of damaged and destroyed civilian infrastructure will constitute a large source of emissions. Most of the damage was done in the first weeks of the war, but each day sees more infrastructure being damaged. The frontline has not moved significantly in the past year and the pace of destruction has slowed down. As noted in our previous assessments, the reconstruction of buildings and other infrastructure is highly carbon-intensive due to the use of large amount of concrete and steel. **Total emissions: 56.0 million tCO^2e.**

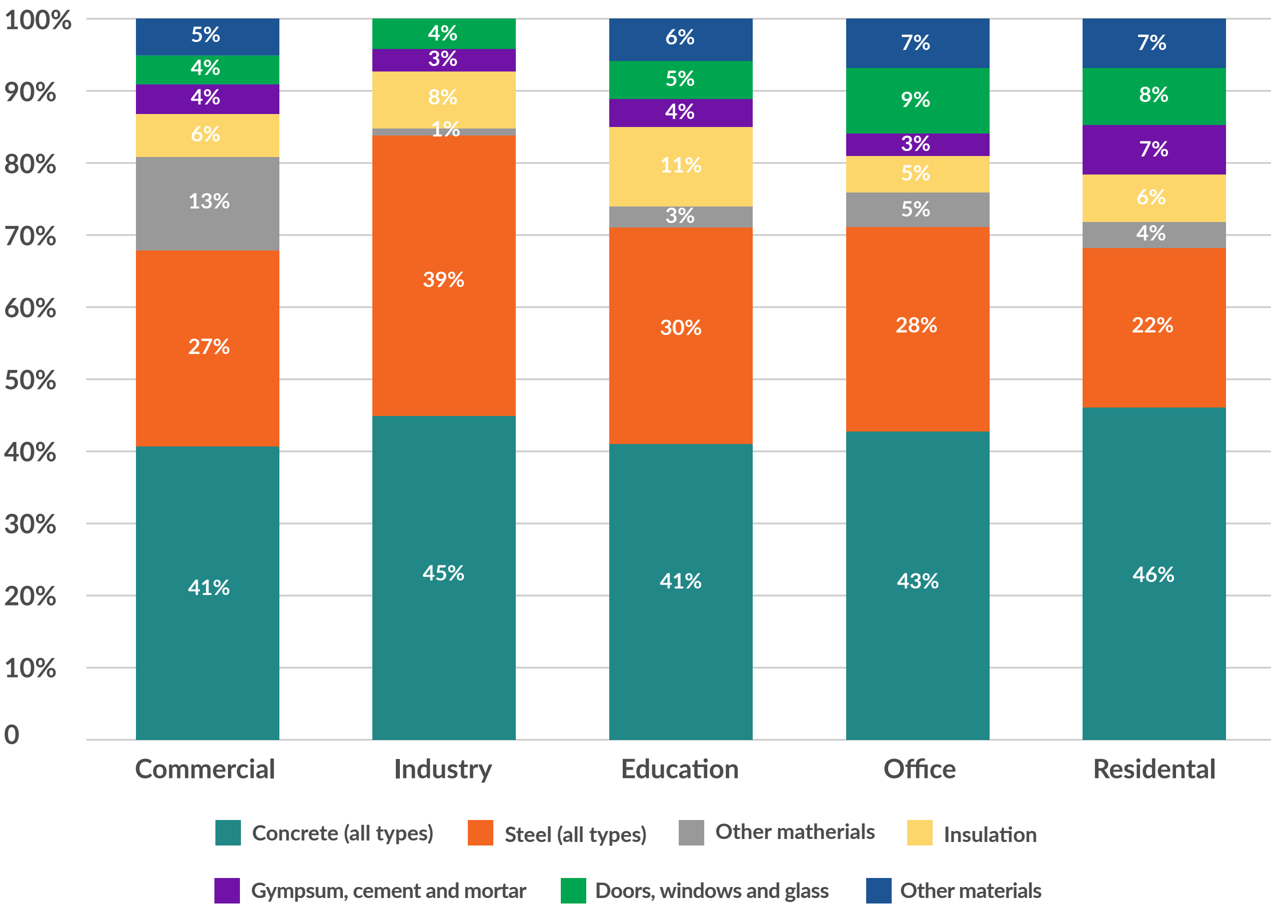
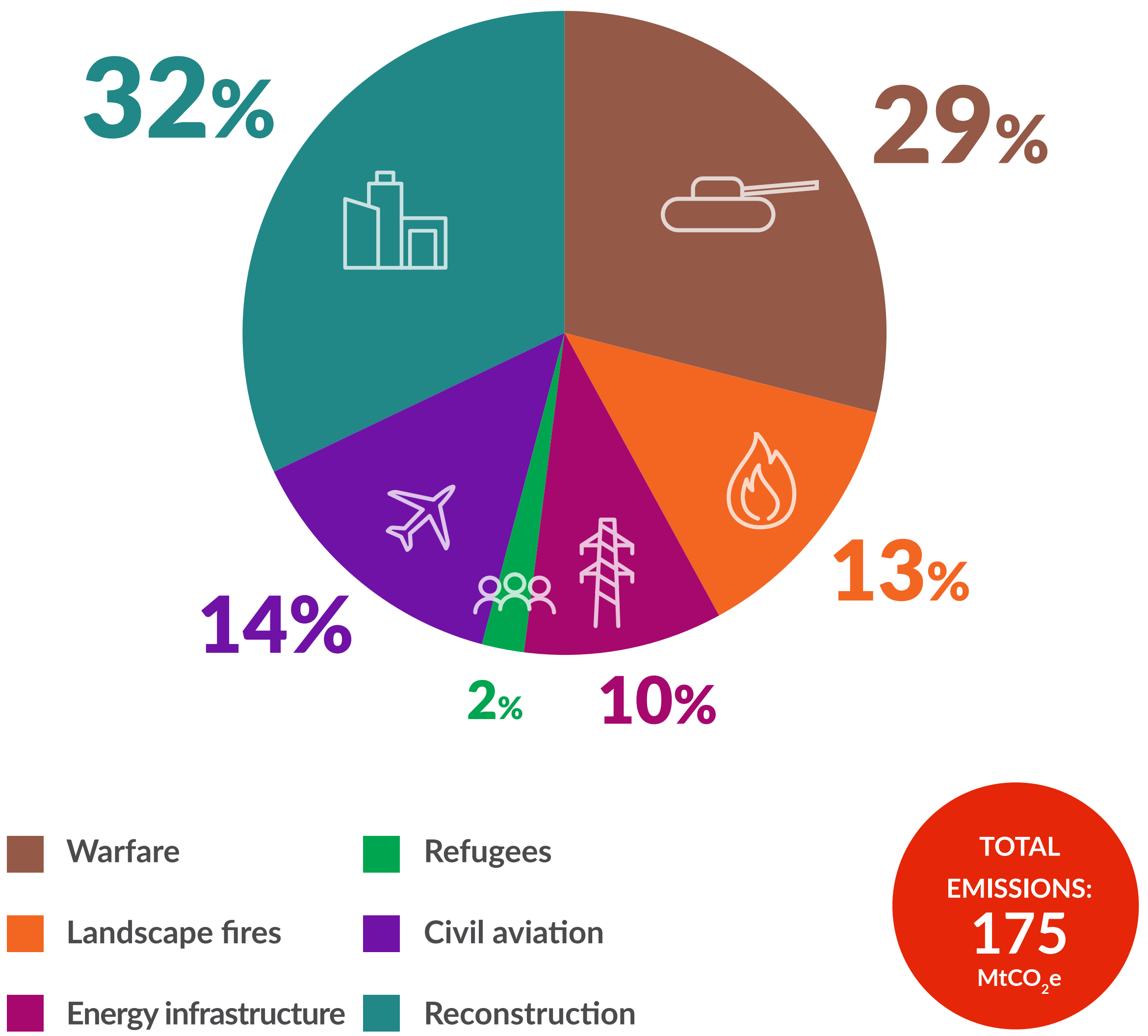


Figure 5. Embodied carbon content by material and building type

Breakdown of total emissions

The share of each sector is visualised in the pie chart below, while the absolute numbers are listed in the table. Whereas in earlier assessment reconstruction emissions where the largest contributor, in this assessment, reconstruction emissions are at par with warfare.



SECTOR	EMISSIONS 24 MONTHS ($MtCO_2e$)	PERCENTAGE, %
Warfare	51.6	29
Landscape fires	22.9	13
Energy infrastructure	17.2	10
Refugees	3.3	2
Civil aviation	24.0	14
Reconstruction	56.0	32
TOTAL	**175**	**100**

Table 1. Total GHG emissions after 24 months of war

1. Introduction

On 24 February 2022, the Russian Federation launched an unprovoked, large-scale invasion of Ukraine. Today, the war has been going on for more than two years, causing a humanitarian crisis with many people killed, injured, or fleeing their homes. The war has also damaged and destroyed civilian infrastructure including buildings, factories, and roads. In addition, the war has destroyed natural ecosystems and polluted the environment. Many industrial installations have been hit, leading to an uncontrolled release of chemicals. Forests and natural reserves have been damaged.

Many initiatives are tracking environmental damage. The Ministry of Environmental Protection and Natural Resources of Ukraine has launched a website[3] aggregating damage to the environment based on reports from local governments and individuals, who can report damages. The Conflict and Environment Observatory and Zoï Environment Network release regular briefings to assess different environmental types of damages like radiation, water or soil pollution.[4] Using an interactive map, the Center for Environmental Initiatives Ecoaction and Greenpeace collect and process data on local pollution incidents collected by individuals.[5]

Besides environmental pollution and land degradation in Ukraine, a direct effect of the war is the significant emissions of greenhouse gases (GHG). While the world is struggling to drastically reduce GHG emissions to limit the average global temperature increase to 1.5°C, additional war-caused emissions make it even more difficult to halt the climate crisis.

The **first assessment** of climate damage[6] was presented at the Climate Conference COP27 in Sharm-el-Sheik, Egypt on 9 November 2022,[7] 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.

The **second assessment** of climate damage[8] provided an update of these four emission sources, covering the first 12 months of the war, i.e. from 24 February 2022 to 23 February 2023, and was presented at the UNFCCC Climate Conference in Bonn, Germany, on 7 June 2023.[9] New sectors included the rerouting of flights due to airspace closures and the impact of the 2022 energy crisis on energy emissions in Europe. As it was argued, the energy crisis resulted in a significant reduction in gas consumption, but many other effects balanced out the emissions reductions. For more details, refer to the second assessment, Chapter 5.

3. https://ecozagroza.gov.ua/en
4. Conflict and Environment Observatory (http://www.ceobs.org/publications/) and ZOÏ Environmental Network (https://zoinet.org and https://ecodozor.org/index.php?lang=en)
5. https://en.ecoaction.org.ua/warmap.html and https://maps.greenpeace.org/maps/gpcee/ukraine_damage_2022
6. Climate Damage caused by Russia's war in Ukraine, first assessment. English: https://en.ecoaction.org.ua/climate-damage-caused-by-russias-war.html. Ukrainian: https://ecoaction.org.ua/vplyv-ros-vijny-na-klimat.html
7. The recording of the side-event: https://www.youtube.com/watch?v=ynQbzwxTnBw
8. Climate Damage caused by Russia's war in Ukraine, second assessment. English: https://en.ecoaction.org.ua/climate-damage-by-russia-12-months.html. Ukrainian: https://ecoaction.org.ua/vplyv-ros-vijny-na-klimat-2.html
9. The recording of the side-event: https://www.youtube.com/watch?app=desktop&v=6yW1hWQmgpc

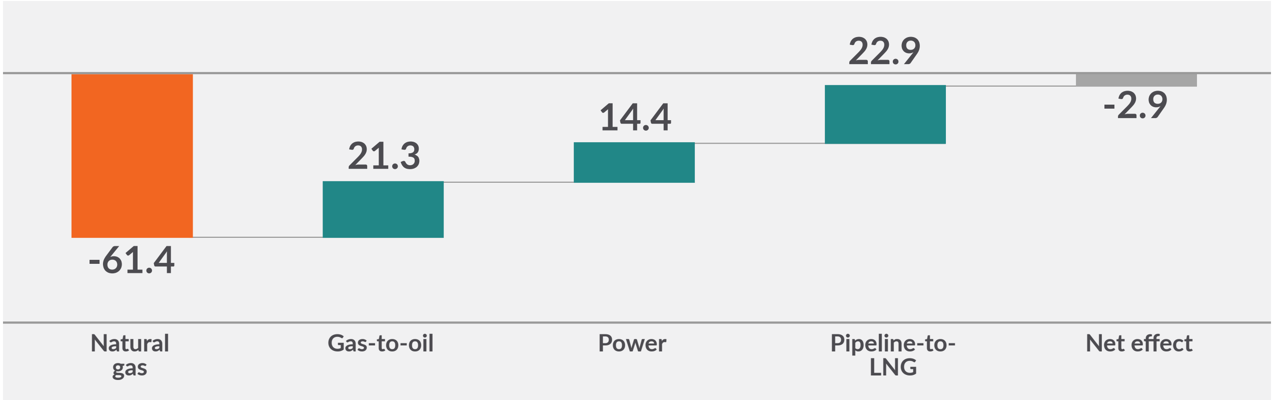


Figure 6. Year-on-year change (2021-2022) of emissions in the EU energy sector attributed to the war ($MtCO_2e$)

The second assessment also addressed the impact on overall emissions in Ukraine in 2022. Obviously, economic decline led to a decrease in country-wide emissions, but, as is being argued in Chapter 7 of the second assessment, many of the emissions shifted abroad together with the many refugees and shifted steel production. After the National Inventory Report (NIR) 2022 is published, expected in the course of 2024, the reduction of emissions within the territory of Ukraine will be visible. As much of Ukraine's territory is now occupied by Russia, it is difficult to obtain reliable emissions data from these parts.

Figure 7. Shifting of emissions from Ukraine

The **third assessment** of climate damage[10] provided updates of all emission sources, covering 18 months of the war, i.e. from 24 February 2022 to 1 September 2023, and was presented at the Climate Conference COP28 in Dubai, United Arab Emirates, on 4 December 2023.[11]

The main topic of the third assessment was an analysis of the possibilities to hold the Russian Federation accountable for the climate damage caused. A methodology was presented to express the climate damage in monetary terms, thus identifying the amount that should be paid by Russia as compensation. For more details, refer to the third assessment, Chapter 2.

The potential to reduce reconstruction emissions through a green recovery was discussed and quantified in Chapter 3 of the third assessment, showing several ways how post-war reconstruction emissions could be avoided.

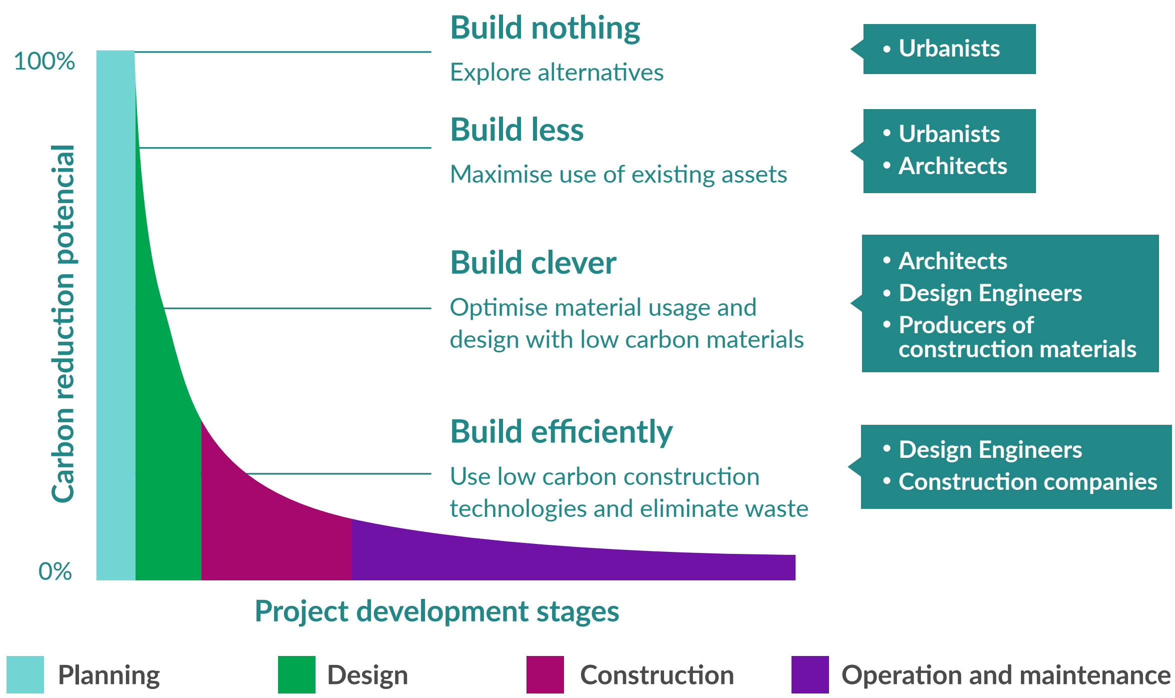


Figure 8. Potential to reduce embodied carbon and actors involved at different project development stages

This **fourth assessment** covers 24 months since the start of the war until 23 February 2024. The main changes compared to the third assessment are the following:

- The methodology to express the climate damage in monetary terms for each tonne of CO_2e, also known as the Social Cost of Carbon (SCC), was introduced in the third assessment. With new insights available, the SCC has been updated in this assessment and significantly revised upwards
- The warfare section has a better justification description of activity data, emission factors, and other assumptions
- The methodology and data sources to determine emissions from landscape fires have been fully renewed in cooperation with the Regional Eastern Europe Fire Monitoring Centre (REEFMC), the National University for Life and Environmental Sciences of Ukraine (NUBIP), and the Ukrainian Hydrometeorological Institute

10. Climate Damage caused by Russia's war in Ukraine, third assessment. English: https://en.ecoaction.org.ua/climate-damage-by-russia-18-months.html. Ukrainian: https://ecoaction.org.ua/vplyv-rosijskoi-vijny-v-ukraini-na-klimat.html
11. The recording of the side-event: https://www.youtube.com/live/beFON17SeUw?si=zd16Ilsc_BHrFO9S

- A new Energy Infrastructure sector has been introduced estimating emissions from damaged and destroyed fossil fuel infrastructure (oil depots, gas pipelines) and SF_6 emissions from high-voltage switches. This section also incorporates methane emissions from the sabotage of the Nord Stream 1 & 2 pipelines as was reported in previous assessments
- For the first time, the geographic location of war emissions is classified: governmental-controlled Ukraine, occupied Ukraine, Russia & Belarus, and the rest of the world.

GHG emissions have been derived from various parameters, such as fossil fuel consumption, areas affected by fires, or the number of damaged apartment blocks. The war is ongoing and much data are not available or their access has been restricted for security reasons. Visual inspection is often impossible due to safety reasons, qualified staff being mobilised, or the territory being occupied. Hence, remote sensing through satellites and reliance on indirect data are often the only available options. Estimates rely on assumptions, which are subject to revisions as more information becomes available.

In preparing the analysis, we have relied on official governmental information, 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 are working. 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.

2. Accountability

Climate change-related losses and damage or, shorter, climate damage refers to the negative consequences of climate change for human societies and the natural environment. Climate damage can result from sudden-onset events (climate disasters, such as cyclones) as well as slow-onset processes (such as sea level rise).[12] As climate change is caused by anthropogenic emissions of GHG, any additional emissions amplify the effects of climate change and increase the associated risks. Since the full-scale invasion, an additional amount of 175 million tCO_2e was emitted and, without doubt, this comes at a cost to the climate and therefore to society.

Social Cost of Carbon

Determining the climate damage caused by Russia's war requires putting a price tag for each tonne of CO_2e emitted. Today, there are several ways that GHG emissions are being priced: prices in cap-and-trade schemes or carbon offset schemes are determined by supply and demand, but these market-based carbon prices do not necessarily reflect the damage that carbon emissions are causing in the future. Similarly, carbon taxes are set by governments to stimulate investments in low-carbon technologies, but these are policy instruments and are not based on future damages caused by today's GHG emissions.

To determine the climate damage caused by this war, the proper indicator is the social cost of carbon (SCC). The SCC is a measure that represents today's cost of an incremental unit of carbon (or an equivalent amount of other greenhouse gases) emitted now, summing the full **global cost** of the damage it imposes over its whole lifetime in the atmosphere. This cost is global, as it adds up all damages globally, i.e. not only the damages in a country where the emissions have occurred. This measure includes the economic costs of climate change that could be felt in sectors as agriculture, energy services, labour productivity, and coastal resources, as well as non-market impacts, such as other types of human health risks (including mortality effects) and ecosystems.

Estimates of the SCC have varied over time, but the underlying scientific models have recently become more robust. A recent research, published in *Nature*, improved probabilistic socioeconomic projections, climate models, damage functions, and discounting methods that collectively reflect theoretically consistent valuation of risk, substantially increase estimates of the SCC. The research concluded that the preferred mean average SCC of USD 185 per tonne of CO_2 is the best available estimation of the SCC to date[13].

The United States is one of the few countries that use SCC in policy instruments.[14] The Environmental Protection Agency of the United States (EPA) has, similar to the research in *Nature*, reviewed the SCC in 2023 and significantly increased the SCC using a new set of Social Cost of Greenhouse Gas (SC-GHG) estimates.[15] These estimates are based on recent research by the US National Academies of Science, Engineering, and Medicine (2017).[16] The Social Cost of Carbon ($SC\text{-}CO_2$) is listed for each year in the period from 2020 up to 2080 in 2020 dollars.[17]

12. https://en.wikipedia.org/wiki/Loss_and_damage
13. Comprehensive evidence implies a higher social cost of CO_2, https://www.nature.com/articles/s41586-022-05224-9
14. https://en.wikipedia.org/wiki/Social_cost_of_carbon
15. EPA Ups Estimates for the Social Cost of Carbon, https://www.instituteforenergyresearch.org/regulation/epa-ups-estimates-for-the-social-cost-of-carbon
16. EPA's "Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances", https://www.epa.gov/environmental-economics/scghg
17. Annex A.5, Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances; https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf

For a 2% discount rate of future damages, the most commonly used discount rate, the SC-CO_2 is established as follows:

Emission year	SC-CO_2
2020	193
2021	197
2022	200
2023	204

Table 2. Social Cost of Carbon in 2020 USD per metric tonne of CO_2

As one can see, both the EPA and the publication in *Nature* come to similar conclusions regarding the SCC. As both prices are very similar, we take the lower (conservative) number, which is suggested in the *Nature* article, being **185 USD/tCO_2**.

With 175 million tCO_2e emitted during 24 months of the war, **the total climate damage amounts to over USD 32 billion.**

Geographical distribution of emissions

Some of the emissions presented in this report have taken place or will take place in Ukraine, either in areas under the Ukrainian government's control or in occupied territories, while other emissions have occurred or will occur elsewhere. From a climate damage perspective, the geographical location of emissions is not relevant: each tonne of GHG emitted, wherever in the world, contributes to climate change equally. Nevertheless, to understand the impact of the war on emissions worldwide, a geographical distribution of the war emissions is provided below.

Sector	Emissions (MtCO_2e)	Government-controlled Ukraine	Occupied territories[18]	Russia & Belarus	Rest of the world
Warfare	51.6	20%	55%	22%	3%
Landscape fires	22.9	50%	50%	-	-
Energy Infrastructure	17.2	11%	2%	2%	85%
Refugees	3.3	30%	5%	10%	55%
Aviation	24.0	-	-	10%	90%
Reconstruction	56.0	40%	40%	-	20%
TOTAL	**175**	**27%**	**36%**	**8%**	**29%**

Table 3. Geographical distribution of emissions for each sector

18. Including Ukrainian territories occupied by the Russian Federation before 24 February 2022.

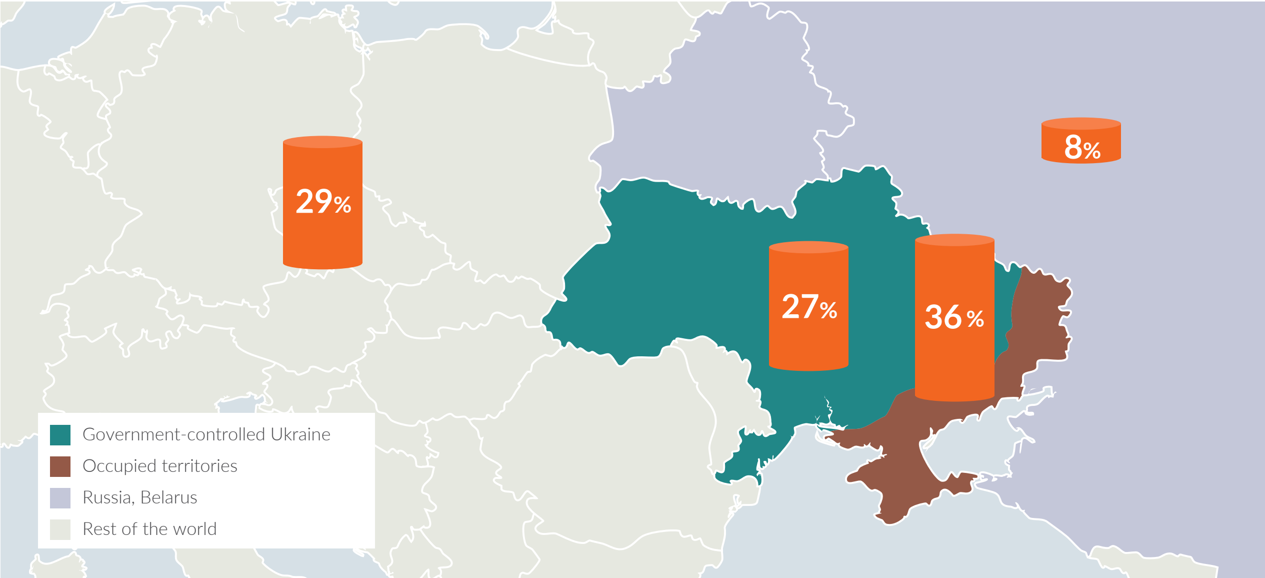


Figure 9. Geographical distribution of war emissions

The majority of these emissions (63%) originate from Ukraine, either from government controlled territories or occupied territories. However, a significant part (27%) was emitted in the rest of the world.

Some assumptions made while distributing emissions:

- Warfare:
  - It was assumed that 80% of the emissions from Russian fossil fuel occurred on the occupied territories of Ukraine and 20% on the territory of Russia; emissions from long-distance supply of military equipment occurred in the rest of the world.
  - For ammunition, it was assumed that 40% of emissions occur in Ukraine and 60% abroad due to significant reliance on military aid, while for Russia the distribution was 90% and 10% respectively (=North Korean and Iranian military aid).
  - Similar logic was applied for military equipment but with equal distribution between Ukraine and foreign countries for Ukrainian destroyed and damaged equipment, while 100% of emissions from Russian destroyed and damaged equipment were assumed to occur in Russia.
  - For fortifications, all emissions from the construction of Ukrainian fortifications were calculated for Ukraine, while for the construction of Russian fortifications, 20% of emissions were allocated to the occupied territories and the remaining 80% to Russia and Belarus, the latter which supplied many dragon teeth.
- Landscape fires: The renewed methodology mainly looks at landscape fires that occurred within an aggregated area of 30 km from the frontline. For simplicity, it was assumed that half of those emissions happened on the occupied side of the frontline, whereas the other half on the government-controlled side.
- Energy infrastructure: It was assumed that emissions from damaged Ukrainian fuel storage facilities, electricity infrastructure damage, and half of emissions from gas infrastructure damage occurred on the territory of Ukraine controlled by the government; the remaining half of emissions from natural infrastructure damage, emissions from gas flaring at the Black Sea platform, and 10% of emissions from combustion of fuel at Russian oil depots

were assumed to occur on the occupied territory of Ukraine; 90% of emissions from combustion of fuel at Russian oil depots were assumed to occur in Russia; emissions from the Nord Stream 1 & 2 pipelines occurred abroad.

- Refugees: Most transport was over land by car, bus, or train as Ukrainian airspace has been closed. Some refugees continued their travel by carbon-intensive flights abroad.
- Aviation: Most of the re-routings occur due to the closure of Russian airspace for Western airlines. Some re-routings happen between Russia and southwards avoiding Ukrainian airspace, estimated to be 10% of the total.
- Reconstruction: As most damages occurred in the currently occupied areas, we expect most of the construction activities post-war to happen in liberated areas. Many steel and cement factories in the occupied territories have been destroyed, so we expect these carbon-intensive materials to be mainly produced on the territory of Ukraine currently controlled by the government. Some less carbon-intensive materials might be imported from abroad.

Chronological distribution of emissions

Some of the emissions have occurred during the 24 months while others will happen in the future. This is mainly the case for reconstruction emissions, but also relevant for forests dying after intensive wild fires. The table below shows which emissions have occurred during the 24 months of the war and which will likely happen in the future.

Sector	Emissions ($MtCO_2e$)	Direct	Future
Warfare	51.6	100%	-
Landscape fires	22.9	40%	50%
Energy Infrastructure	17.2	100%	-
Refugees	3.3	100%	-
Aviation	24.0	100%	-
Reconstruction	56.0	10%	90%
TOTAL	**175**	**63%**	**37%**

Table 4. Chronological distribution of emissions

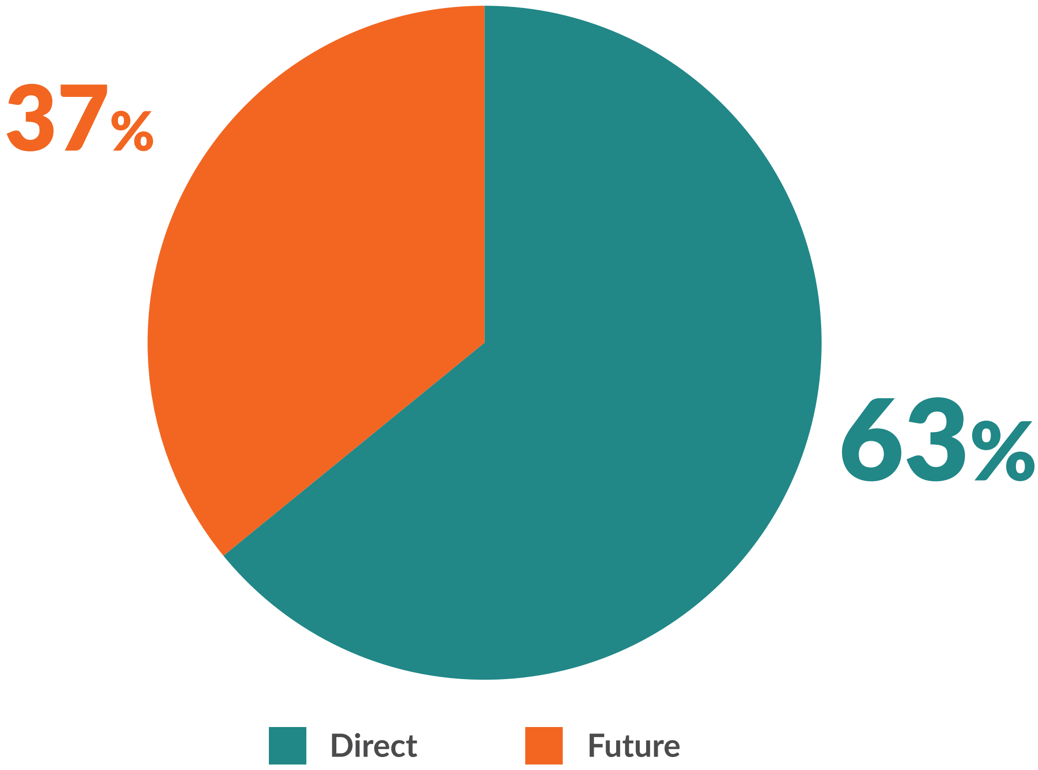


Figure 10. Distribution of emissions which occurred during 24 months of war and future emisisons

Some assumptions made while distributing emissions:

- Warfare: Production emissions of used ammunition or damaged and destroyed equipment (embodied carbon) could have happened before the war, during the war, or even afterwards. For simplicity, embodied carbon emissions are accounted for the moment the ammunition was used and the equipment was damaged or destroyed.
- Landscape fires: Some forests die after intensive fires and either decompose over time or the wood is being logged. In both cases, overtime, the biomass enters as CO_2 in the atmosphere.
- Reconstruction: Although the majority of reconstruction will happen post-war in some liberated territories, reconstruction activities have already happened.

3.1 Warfare

Warfare activities cause large volumes of GHG emissions due to the huge consumption of fuel and demand for carbon intensive materials and equipment.

The current assessment focuses on the four major components that determine the carbon footprint of warfare and are discussed in the subsections below:

- Fuel,
- Ammunition,
- Equipment, and
- Fortifications.

While fuel combustion represents direct GHG emissions from warfare (Scope 1), the majority of other sources represent indirect Scope 3 emissions (embodied carbon of military equipment, ammunition, and fortifications).

Most emissions will to some extent be reflected in the national inventories of various countries (e.g. Ukraine, Russia, or third countries manufacturing military equipment). Their attribution to warfare or military industries is lacking within the UNFCCC reporting process, however. Only emissions from military fuel in some cases are reflected separately in category 1.A.5 OTHER (Not elsewhere specified) of the common reporting framework. Emissions associated with the production of military equipment and explosives are hidden within the manufacturing, chemical, or energy sectors emissions.

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 achieve a high level of accuracy in the estimation of climate damage. The "fog of war" term, which is used to reflect the uncertainty in situational awareness experienced by military operations participants, is also relevant for the assessment of warfare-related GHG emissions. A step-by-step approach moving from a helicopter view of the key sources of warfare emissions to a gradual extension of the depth and scope of accounting is the only way forward. Finding partners is crucial for this exercise in order to bring together expertise from various fields (e.g. military, carbon accounting) and sectors (e.g. academics, OSINT community, think tanks, journalists, etc.). With the understanding of the scale and structure of warfare emissions, gradual improvement of the accuracy and a more robust justification of assumptions are possible.

Based on the ongoing research work related to the scale of warfare emissions, the following findings should be highlighted:

- Though the initiatives to increase the transparency of and assess to the data on the armed forces' climate impact have only started to gain attention,[19] it is nevertheless evident that even during the peacetime, due to the nature of their activities and operations, the **militaries are a significant source of GHG emissions**. Armed forces contribute at least 1% to the total national GHG emissions (see an overview of the studies on military GHG emissions in various countries in the Annex). During the war, the level of emissions increases manyfold due to the mobilisation of manpower, more intensive use of fuel, use of explosives and ammunition, construction of fortifications, and extended supply chains. Supply

19. 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

chain emissions could be two to five times higher than operational emissions of the military. Having in mind that in the course of a war, stocks accumulated during many years, and even decades, are being used and depleted, the impact of such upstream emissions could be even higher.

- **Fuel consumption is the most significant single source of GHG emissions** associated with the operation of the military and warfare. Modern armies are large consumers of fossil fuel even during peacetime due to the operation of high-tech equipment employed (planes, helicopters, ships, tanks, and armed vehicles) and various ancillary infrastructure (airstrips, roads, permanent bases, training grounds, and supply vehicles). Energy consumption of the military is high due to the prioritisation of superior combat performance of equipment, the need for rapid movement of troops, overall high-tech militarisation of the armed forces, and increasing their size rather than energy efficiency.[20] Consumption of fuels significantly increases during warfare and the rate of the increase depends on the share of forces committed to military action and duration and intensity of battles. The ratio between the different types of fuels depends on the types of operations the military is performing (e.g. reliance on aviation or ground forces).
- **Ammunition, missiles, and explosives also rely on the use of carbon intensive materials.** During the war in Ukraine, artillery is used at an immense scale resulting in the depletion of stocks built over decades and significant investment in the restoration and scaling up of production capacities. Interestingly, the effect of weapon systems on the battlefield is not related to the associated climate damage as small FPV drones allow destroying equipment at the scale similar to the effect of a high-intensity artillery use. The use of precision strikes capabilities, such as GPS guided artillery systems, allows achieving results with a much lower impact compared to the unguided artillery shells.
- Manufacturing of **military equipment is energy and carbon intensive**. Though the research on embodied carbon of military equipment is limited, it is likely to be significantly higher than that of the similar size civilian equipment. Warfare activities result in the destruction and damage of equipment, which requires additional investment in its replacement, and also leads to an overall militarisation of economies and investment in security due to increasing risks and instabilities.
- Fortifications are the basis of effective defensive operations as they allow for protection of soldiers and limit the possibilities of breakthroughs along the frontline. Though at the line of contact they are typically represented by trenches and dugouts, **the second and third lines of defence in the multi-layer fortification system also require significant volumes of carbon intensive materials**, such as concrete and steel. Attacks on critical energy infrastructure and civilian population in the cities throughout Ukraine resulted in the construction of protection structures far behind the frontlines, further increasing the demand for concrete, steel, and other materials.
- **The impact of the war in Ukraine will be long-lasting and felt worldwide** as though the armies initially relied on existing stocks, the scale of the war resulted in massive destruction of military equipment and depletion of ammunition stocks causing a large-scale increase in military production around the globe. Ukrainian domestic arms production was growing even at the beginning of the war and is expected to grow further in future years based on local resources and expertise as well as expansion of international cooperation and

20. 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

joint projects with leading international companies to reduce reliance on external security assistance in the long-term.[21] NATO allies also increase military spending with 18 countries expecting to reach 2% of GDP defence spending target in 2024, including NATO allies in Europe investing a combined total of USD 380 billion in defence, thus reaching 2% of their combined GDP.[22] Similarly, Russia's military spending reached 3.9% of GDP in 2023 and is expected to grow further.[23] Total global military expenditure reached $2.4 trillion in 2023 with an increase of 6.8% in real terms from 2022, which was the steepest year-on-year increase since 2009.[24] All this leads us to a less secure world with the rearmament of Europe and other regions and redirection of financial resources from climate action to militarisation. There are fragile lines between the strong militaries that can protect the international rule of law enabling countries to focus on climate action and the risk of new conflicts and wars that can cause a devastating damage to climate and environment.

Fuel — fossil fuels as an enabler of military equipment and source of GHG emissions

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 mobilisation 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. Moreover, fuel consumption related to warfare is also associated with activities away from the battlefield, including the long-distance supply of equipment and ammunition.

The most visible equipment using fossil fuels includes 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 logistics required to move people and cargo to the area of operations and throughout the theatre of military actions. 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[25] or even from the territory of Russia, where railway network, which is a key element of Russia's logistics, could operate more securely. This also means that there are significant volumes of fuels consumed even during the period when operational pauses occur at the battlefield (e.g. transportation activities for accumulation of reserves, logistics to support day-to-day operations of the military, relocation of equipment and personnel, etc.).

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21. ISW, Ukraine's Long-Term Path to Success: Jumpstarting a SelfSufficient Defense Industrial Base with US and EU Support, https://understandingwar.org/backgrounder/ukraine%E2%80%99s-long-term-path-success-jumpstarting-self-sufficient-defense-industrial-base
22. Secretary General welcomes unprecedented rise in NATO defence spending, https://www.nato.int/cps/en/natohq/news_222664.htm?selectedLocale=en
23. From scones to drones: inside Putin's arms race that is leaving the West behind, https://www.telegraph.co.uk/world-news/2024/01/26/russia-arming-itself-faster-than-nato/
24. Global military spending surges amid war, rising tensions and insecurity, https://www.sipri.org/media/press-release/2024/global-military-spending-surges-amid-war-rising-tensions-and-insecurity
25. See, for instance, the analysis of logistic networks in Luhansk region of Ukraine, https://twitter.com/NLwartracker/status/1627047617938223106

Large amounts of fuel consumption led to significant GHG 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 distances covered 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.

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 or procurement 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 and applying corresponding fuel efficiency factors.

Detailed information on the approaches applied in calculations and their results are provided in the Annex, while the final results are presented in the table below.

Emissions from fossil fuel consumption

Data	Russian Forces	Ukrainian Forces	Total
Assumed fuel consumption, Mt	8.9	2.4	11.3
Direct GHG emissions from fuel combustion (estimated using default emission factor for diesel fuel), Mt CO_2e	28.5	7.6	36.1
Upstream GHG emissions associated with fuel combustion,[26] MtCO_2e	6.7	1.8	8.5
Total GHG emissions from fuel combustion during warfare, MtCO_2e	**32.5**	**9.4**	**44.6**
Additional GHG emissions from long-distance equipment supply, MtCO_2e	**0.04**	**0.42**	**0.5**

Table 5. Total fuel consumption and GHG emissions

26. 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

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 details on the estimations based on different approaches and for the indicative bottom-up assessment of fossil fuel consumption during the war). Total emissions from fuel combustion during the warfare combined with the emissions associated with the long-distance supply of military equipment are estimated a **45.1 million tCO_2e**.

Ammunition and explosives — GHG emissions from manufacturing and use

The use of ammunition and explosives is decisive during warfare with volumes of fire power and precision being the key determinants of effectiveness.

There are various types of explosives employed by militaries (e.g. TNT, RDX, HMX, CL-20) and they are constantly looking for new, more efficient materials to meet specific KPIs, such as faster detonation speed, stronger explosive energy, or larger armour-penetrating power.[27]

Typical military explosives are organic chemicals, often containing only four types of atoms: carbon (C), hydrogen (H), oxygen, (O), and nitrogen (N). Upon detonation, heat releasing reactions transform nitrogen atoms into nitrogen (N_2) gas, while oxygen atoms combine with hydrogen and carbon atoms to form gaseous products (H_2O, CO, or CO_2). The explosives are divided into "low explosives" (e.g. nitrocellulose used in propellants) and "high" explosives (e.g. TNT and nitroglycerin) with latter having much higher speeds of the shock waves. "High" explosives are further divided into primary (detonated by simple ignition-spark, flame, or impact) and secondary ones (usually initiated by the shock created by a primary explosive).[28]

Manufacturing of explosives and ammunition is a carbon-intensive process, as many explosives are manufactured using carbon-intensive resources such as ammonia and nitric acid. Ammonia, for instance, is produced from hydrogen and nitrogen, where methane is used as the most common source of hydrogen and thus results in a significant carbon footprint. Though during the use phase there are also some emissions at the point of firing (e.g. due to the combustion of a propellant) and point of impact (e.g. due to the detonation of a warhead), the main climate footprint is associated with the manufacturing process and raw materials used.

Emissions during the use phase are also associated with large variations, and further research is required to understand the scale and composition of GHG emissions from explosions during warfare activities. In general, the gases formed during explosions could include nitrogen oxides (NO and NO_2), carbon monoxide (CO), carbon dioxide (CO_2), ammonia (NH_3), methane (CH_4), and others depending on the completeness of chemical reactions.

The emissions from detonation are roughly proportional to the weight of explosives used. The end products of explosive reactions are determined primarily by the oxygen balance of an explosive with the deficiency of oxygen (e.g. TNT) favouring the formation of carbon monoxide and unburned organic compounds and an excess of oxygen causing the formation of more nitrogen oxides and less carbon monoxide and other unburned organics (i.e. results in more complete oxidation of carbon to carbon dioxide). The composition of emissions from explosives detonation is influenced by many factors that are difficult to measure, and any estimates must be regarded as approximations that cannot be made more precise because explosives

27. The Pentagon is hurrying to find new explosives, https://www.economist.com/science-and-technology/2024/01/17/the-pentagon-is-hurrying-to-find-new-explosives

28. Oxley, J.C., 1998. The Chemistry of Explosives. In: Zukas, J.A., Walters, W.P. (eds) Explosive Effects and Applications. High-Pressure Shock Compression of Condensed Matter. Springer, New York, NY. https://doi.org/10.1007/978-1-4612-0589-0_5

are not used in a precise, reproducible manner.[29] Due to the impact of various factors (e.g. oxygen balance, presence of additives, nature, and stability of explosive ingredients, presence and type of confinement, and others), the measured concentrations of toxic gases from detonation reported in literature significantly differ.[30]

The climate impact thus depends on the mass of ammunition and explosives used during warfare. The assessment focuses on artillery shells as the most significant type of ammunition, but the analysis of its other types is provided to justify the adjustment factor to estimate total GHG emissions.

Artillery

Artillery is a key source of firepower during the warfare and is responsible for the largest share of explosives used and associated GHG emissions.

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,[31] while on average for 2022, some estimates reported relatively equal shares of both artillery ammunition types.[32] During the second year of the war, the prevalence of 155 mm calibre for Ukraine remained due to its dependency on the ammunition supply from partners.

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 months of the war, Russian artillery maintained a significant advantage over its Ukrainian counterparts on most engagements and at some points, the disparity reached 10:1, with Russia firing up to 50,000 or even 60,000 shells per day with larger variation and significantly lower numbers during some days. Russia relied on the quantity of shells to make up for the lack of precision strike capability.[33,34]

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.[35] 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 50 Russian warehouses were destroyed).

29. AP-42, CH 13.3: Explosives Detonation, https://www3.epa.gov/ttnchie1/ap42/ch13/final/c13s03.pdf
30. https://www.sciencedirect.com/science/article/pii/S2214914721001951
31. Комбриг 45-ої бригади Олег Файдюк: Нам однозначно треба більше гармат, https://www.pravda.com.ua/articles/2023/02/7/7388192/
32. 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
33. Ukraine Update: Russia was unprepared for a modern artillery war, https://www.dailykos.com/stories/2023/9/23/2194180/-Ukraine-Update-Russia-was-unprepared-for-a-modern-artillery-war
34. 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 the war, Russia alone used 7 million artillery rounds, excluding losses due to the destruction of warehouses, https://theins.ru/politika/254514
35. See https://twitter.com/TrentTelenko/status/1605644712458670080

Since then, there were growing reports of evolving artillery deficit for both Russian occupying forces[36] and the Ukrainian army. The intensity of artillery use decreased during the second year due to depleted stocks.

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.[37]

Reports from February 2023 stated that Ukraine asked for an increased artillery shells supply in the face of expected escalation and the average use level was about 5,000 shells per day.[38] At the same time, Russia was estimated to use four times more artillery shells while trying to gain territory in the east of the country and deploy tens of thousands of newly trained conscripts in the war.[39,40,41]

Since the start of Ukrainian counter-offensive in summer 2023, there was a significant focus on the destruction of Russian artillery guns with a high number of damaged equipment recorded both in official updates from Ukrainian armed forces and visually confirmed losses recorded in Oryx's list. This, along with the increased artillery use by Ukraine during the offensive operations, started reducing the disparity in fire intensity. According to some reports, amid the counteroffensive, Ukrainian guns were firing 6,000-8,000 shells per day[42] with similar volumes fired by Russia.

The relative parity in artillery use intensity with 7,000-8,000 shells fired per day reportedly remained during the following months[43] but by the end of 2023, the disparity became larger again with Ukraine firing 2,000 shells per day and Russia firing up to 10,000 shells per day.[44]

36. See, for instance: Russia Struggles to Maintain Munition Stocks (Part One), https://jamestown.org/program/russia-struggles-to-maintain-munition-stocks-part-one/
37. 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 its 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
38. Ukraine pleads for ammunition 'immediately' as Russia steps up attack, https://www.ft.com/content/817b7e61-9f09-494c-8f96-934810033b62
39. Nato is in ammunition race against Russia in Ukraine, says Stoltenberg, https://www.ft.com/content/3d3c9102-b8ef-4b1c-a8dc-6c844de71981
40. As of April 2023, Ukraine was reportedly using 7,700 artillery rounds per day, while Russia was firing three times more. Facing critical ammunition shortage, Ukrainian troops ration shells, https://www.washingtonpost.com/world/2023/04/08/ukraine-ammunition-shortage-shells-ration/
41. During the first quarter of 2023, the rate of Russian fire fluctuated between 12,000 and 38,000 rounds per day, but the number of days in which Russian fires exceeded 24,000 rounds became much scarcer. Meatgrinder: Russian Tactics in the Second Year of Its Invasion of Ukraine, https://rusi.org/explore-our-research/publications/special-resources/meatgrinder-russian-tactics-second-year-its-invasion-ukraine
42. Ukraine is firing shells faster than can be supplied. Can Europe catch up?, https://edition.cnn.com/2023/09/17/europe/ukraine-shell-supplies-intl/index.html; US faces hurdles in ramping up munitions supplies for Ukraine war effort, https://www.ft.com/content/b2c89d88-3e71-4787-920f-5385236aa684
43. The US Has a Defense Supply Chain Problem, https://www.bloomberg.com/news/articles/2023-12-07/arming-israel-ukraine-exposes-a-us-defense-supply-chain-problem; and NOV 14th update of the Russian artillery shell chart, https://twitter.com/HerrDr8/status/1724409456245563729 and https://twitter.com/HerrDr8/status/1744702462072652086
44. Yes, Ukraine can still defeat Russia – but it will require far more support from Europe. Jack Watling, https://www.theguardian.com/commentisfree/2023/dec/27/ukraine-russia-europe-support-kyiv; With Western aid stalled, Ukrainian troops run low on artillery shells, https://www.washingtonpost.com/world/2023/12/22/ukraine-ammunition-shortage-russia-war/; Here's How the Russian and Ukrainian War Efforts Compare, in 10 Charts, https://www.wsj.com/world/russia/heres-how-the-russian-and-ukrainian-war-efforts-compare-in-10-charts-1cf9a74f; Can Europe arm Ukraine—or even itself?, https://www.economist.com/europe/2024/01/14/can-europe-arm-ukraine-or-even-itself

At the beginning of 2024, the significant disparity remained[45] and grew even further with Ukraine being able to fire 1 shell for every 10 shells fired by Russia according to some reports.[46] Such developments were caused by the supply of large volumes of artillery shells by North Korea to Russia on one hand and delays in approving the next rounds of military aid to Ukraine on the other hand.

Assumptions on the artillery use rates applied in calculations are presented in the Annex and the summary is presented in the table below. About 18 million shells were estimated to be used during the two years of war.

TOTAL NUMBER OF SHELLS USED DURING THE ASSESSMENT PERIOD (24 February 2022 – 28 February 2024), million shells	
Assumed use of shells by Russia	13.1
Assumed use of shells by Ukraine	4.8
Total	**17.9**

Table 6. Estimated artillery ammunition use

GHG emissions from the use of ammunition were estimated using the emission factor for generic 155 mm ammunition as described in the Annex with the application of an adjustment coefficient to account for other types of ammunition and explosives.

Emission factors for 155 mm ammunition are based on the published extended environmental life-cycle assessment,[47] which takes into account the global warming impact of the manufacturing of ammunition and propellants, as well as emissions at the point of firing and at the point of impact. The data on CO_2 emissions during the use phase are based on real measurements during firing and detonation and are thus more accurate than the estimates based on a hypothetical chemical reaction assuming full combustion of explosive materials (i.e. leading only to the formation of the simple molecules of carbon dioxide, water, carbon, and nitrogen) as they better reflect non-optimal real-life conditions that result in various chemical reactions and formation of different substances.

SOURCE	TOTAL ($MtCO_2e$)
Manufacturing of ammunition (steel casing and explosives)	2.4
Manufacturing of propellants	1.0
Emissions at the point of firing	0.048
Emissions from detonation at the point of impact	0.003
Total GHG emissions	**3.5**

Table 7. Total GHG emissions from the use of artillery ammunition

45. Ukraine Tells Allies Troops Are Outgunned Three-to-One by Russia, https://www.bloomberg.com/news/articles/2024-01-31/ukraine-tells-allies-troops-are-outgunned-three-to-one-by-russia
46. Ukraine Withdraws From Besieged City as Russia Advances, https://www.wsj.com/world/europe/ukraine-withdraws-from-besieged-city-as-russia-advances-554644c0
47. 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

Other ammunition and explosives

Artillery shells have a decisive role in terms of fire power and volume, while other types of ammunition and explosives represent a significantly lower share in terms of volumes (see Annex for details). There is a large variation of explosives and ammunition used during the war (e.g. in terms of size and type of warhead, propellant and fuels used, type of explosive material, size of ammunition and mass of steel casing, etc.), but due to limited information and research on carbon footprint, a simplified approach was used relying on lifecycle assessment of artillery ammunition. Other types of ammunition and explosives were accounted for via a correction coefficient.

Based on the assumptions of volumes described in detail in the Annex, the ratio between the total weight of ammunition and explosives and the mass of artillery shells is 1.16. Taking into account additional types of ammunition and explosives (e.g. hand grenades and grenades for grenade launchers, anti-armour systems, ammunition for tank guns, other types of mines, missiles for air-defence systems, etc.), the adjustment factor of 20% has been used during the calculation to account for additional GHG emissions (compared to 30% used in previous assessments).

This approach does not take into account the difference in composition and carbon footprint of various types of ammunition and explosives but serves as a good indicator of the scale of impact.

Overall emissions associated with the use of all types of ammunition and explosives would be at least **4.1 million tCO_2e**, mostly represented by embodied carbon due to the use of carbon intensive materials during manufacturing.

The analysis also demonstrates a striking difference between some systems if the effect on the battlefield or destruction power are compared to the mass of ammunition and explosives used. FPV drones at the end of the second year of the war played a huge role on the battlefield while destroying or damaging a large number of tanks and armoured vehicles. At the same time, their contribution to the total weight of explosives and ammunition is negligible. Similarly, there is a significant difference in carbon intensity per military target achieved if regular artillery shells are compared with precision strike systems. This, however, does not undermine the decisive role of massive artillery fire under certain conditions, when the scale of fire destroys defensive lines and pressures a defending party to move further away or blocks the movement of an attacking party.

Equipment — embodied carbon in military equipment

Military equipment is the core of warfare activities, as it attacks the enemy, protects and supplies forces, builds fortifications, conducts surveillance, and executes many other tasks needed for the achievement of strategic and tactical goals.

Manufacturing of every piece of equipment and machines used during the war is associated with GHG emissions from the consumption of energy and various raw materials. 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, which are very carbon intensive. The amount of energy, materials, and GHG emissions associated with manufacturing process is proportional to the weight of machinery.

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. Military equipment stockpiles decreased during the war and many countries significantly increased manufacturing, sometimes even at the expanse of climate action.[48]

At the end of the second year of the war, Russia maintained a considerable number of military equipment involved in the warfare. Mobilisation of the defence industry and launch and expansion of production lines currently allows Russia to support its ongoing operations with the supply of 1,500 tanks and approximately 3,000 armoured fighting vehicles of various types per year. However, about 80% of them are not a new production but refurbishment and modernisation of declining pre-war stocks, which undermines the long-term capabilities of equipment supply at this scale.[49]

Ukraine has also been able to maintain and increase its inventory of combat equipment with the International Institute for Strategic Studies (IISS) estimating that at the end of the second year of the war, the number of the main battle tanks (MBTs) in service in the Ukrainian armed forces remains almost at the pre-war levels, while the number of armoured personnel carriers (APCs) and infantry fighting vehicles (IFVs) has increased due to Western support.[50]

Due to high carbon intensity and direct impact of warfare activities on increased equipment production, emissions associated with the manufacturing of equipment are included in the estimation of climate damage. Our assessments focus on destroyed and damaged equipment only; however, this is a conservative approach as evidence demonstrates that investment in new equipment could significantly exceed the rate of equipment destruction if a broader picture of militarisation in different countries is considered.

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 the manufacturing of military equipment, such as main battle tanks or other armoured vehicles. Producers of equipment are starting to

48. EU shifts spending focus from climate to defence, https://www.ft.com/content/c777a195-ccd5-43a3-95c4-18b05e1ef643

49. Russian Military Objectives and Capacity in Ukraine Through 2024, https://www.rusi.org/explore-our-research/publications/commentary/russian-military-objectives-and-capacity-ukraine-through-2024 (estimated military equipment available: approximately 4,780 barrel artillery pieces of which 20% are self-propelled; 1,130 MLRS; 2,060 tanks; and 7,080 other armoured fighting vehicles, primarily consisting of MT-LBs, BMPs, and BTRs, as well as 290 helicopters and 310 fast jets). Based on some reports, during 2023, Russia reportedly produced 1,530 tanks and 2,518 armoured fighting vehicles. See From scones to drones: inside Putin's arms race that is leaving the West behind, https://www.telegraph.co.uk/world-news/2024/01/26/russia-arming-itself-faster-than-nato. IISS analysis of satellite images provides similar data with the estimated (at least) 1,180 to 1,280 MBTs and around 2,470 IFVs and APCs reactivated from storage and manufacture of new tanks and other armoured vehicles, though precise numbers are not available. See Equipment losses in Russia's war on Ukraine mount, https://www.iiss.org/online-analysis/military-balance/2024/02/equipment-losses-in-russias-war-on-ukraine-mount/

50. Equipment losses in Russia's war on Ukraine mount, https://www.iiss.org/online-analysis/military-balance/2024/02/equipment-losses-in-russias-war-on-ukraine-mount/

report the carbon footprint but limit information to mainly Scope 1 and Scope 2 emissions and do not usually 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.

There are examples of companies, however, which report information on all Scope 3 categories of indirect emissions, and emissions from the use of sold products and purchased goods and services cover the most significant share (69% and 24% respectively).[51]

Data for civil machinery and equipment (e.g. tractors, farm implements, trucks, construction equipment, etc.) could serve as a proxy and demonstrate the scale of emissions associated with military equipment manufacturing. Therefore, indicative values derived from studies on civil equipment have been used as proxies for the assessment of emissions associated with the destroyed and damaged military equipment. However, even for civil construction and agricultural equipment, there is limited information on carbon footprint and embodied carbon values.

Manufacturing of military equipment is an energy- and resource-intensive process utilising special 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 a 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.[52] Carbon intensity of military equipment manufacturing is likely higher than manufacturing of civil equipment and machinery.

The value of 6 kgCO_2e per kg of machinery has been applied as an indicative carbon footprint of military equipment (see the Annex for details).

As of early April 2024, the list of lost equipment based on open-source intelligence data included more than 15,200 visually confirmed losses for Russia and more than 5,500 losses for Ukraine. About three quarters of entries represent destroyed and damaged equipment, while the remaining units were captured or abandoned.[53]

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

51. Rheinmetall, ESG Reporting 2023, https://www.rheinmetall.com/en/responsibility/esg-reporting
52. The environmental impacts of the UK military sector, https://www.sgr.org.uk/publications/environmental-impacts-uk-military-sector
53. 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

For damaged equipment, only one third of the estimated embodied carbon has been taken into account in calculations. Though this assumption is highly uncertain as some damaged equipment could require limited repair, the share of damaged equipment considered in calculation is only about 3%, so this does not have a significant impact on the results. The eleven categories of equipment included in the assessment represent 88% of the visually confirmed destroyed and damaged equipment for Russia and 79% for Ukraine.

Though the accuracy of the open-source assessment of losses is proving to be rather high, not all destroyed equipment is recorded on video or photo and can be visually confirmed. In particular, such data tend not to capture the destruction of equipment mostly operating behind the enemy lines, further than tanks and infantry-fighting vehicles, such as artillery and air defence systems.[54] In some cases, the analysis of high-resolution satellite images revealed a significant number of equipment losses not visible at videos or photos from locations of intensive battles. To account for this factor, it is assumed that actual losses are at least 20% higher than those visually confirmed.

For more detailed information on the indicative assumptions and results of GHG emissions calculation, see the Annex.

Data	Russian Forces	Ukrainian Forces	Total
Indicative mass of destroyed equipment, t	195,169	55,586	250,754
Indicative mass of damaged equipment (only one third accounted for in calculations), t	16,480	9,935	26,415
Total mass of equipment accounted for in embodied carbon calculation (including assumed 20% not visually confirmed), t	240,794	70,677	311,471
Total embodied carbon, tCO_2e	**1,444,766**	**424,062**	**1,868,828**

Table 8. Total GHG emissions from military equipment manufacturing

The mass of destroyed and damaged equipment of only key types accounted for in calculations exceeds 300,000 tonnes. GHG emissions associated with manufacturing of the military equipment destroyed and damaged during the war was estimated at **1.9 million tCO_2e**, including 1.44 million tCO_2e for Russian losses and 0.42 million tCO_2e for Ukrainian losses.

This is a very conservative value as it takes into account only the key types of large equipment and machinery and does not account for the dozens of types of specific machines used during the war and different pieces of small equipment. It also focuses only on the destroyed and damaged equipment, while the emissions associated with building up the stocks of military equipment in different countries are not accounted for.

The potential scale of the overall impact could be measured based on an alternative approach of estimating carbon footprint of the military aid supplied to Ukraine. Such carbon footprint could be preliminary assessed using the economic value of equipment provided and limited data on carbon emissions reported by manufactures. According to the Ukraine Support Tracker of the Kiel Institute for the World Economy[55], the military aid committed between 24 January

54. Equipment losses in Russia's war on Ukraine mount, https://www.iiss.org/online-analysis/military-balance/2024/02/equipment-losses-in-russias-war-on-ukraine-mount/

55. Ukraine Support Tracker of the Kiel Institute for the World Economy, https://www.ifw-kiel.de/topics/war-against-ukraine/ukraine-support-tracker/

2022 and 15 January 2024 and covering only heavy weapons (armoured vehicles, tanks, 155 mm and 152 mm howitzers, and MLRS) amounted to EUR 26.79 billion. At the same time, the reported emissions associated with fuel use (direct Scope 1 emissions), electricity consumption (indirect Scope 2 emissions), and purchased products and services (Category 1 of Scope 3 emissions) could be about 309 tCO_2e per million euro of sales.[56] This would result in about 8 million tCO_2e of total embodied carbon of heavy weapons committed as military aid to Ukraine.

There could be various reasons for the significant difference between the estimated carbon footprint of military aid and Ukrainian equipment damaged and destroyed during the war, including the fact that military aid provided is larger than the number of equipment destroyed, the difference between committed and delivered aid, and different approaches for estimation of GHG emissions. The scale of the difference, however, could also indicate that on average, the carbon footprint of military equipment per unit of weight is far larger than assumed in the assessment, which highlights the importance of further studies focused on the embodied carbon of military equipment.

56. Estimated based on the data on Scope 1 and 2 emissions intensity, Scope 3 emissions structure and sales reported by Rheinmetall, ESG Reporting 2023, https://www.rheinmetall.com/en/responsibility/esg-reporting

GHG emissions from construction of fortifications

Fortifications, including trenches, strongholds, and other elements, play a crucial role in defensive operations and are used at scale by both Russia and Ukraine.

Construction of trenches poses a significant negative impact on environment and biodiversity causing destruction of vegetation, including endangered species, since many natural protected areas were affected, disrupting topsoil layer, becoming a trap for many animals, and causing desertification and soil erosion with the affected area extending beyond the physical footprint of trenches.[57]

Construction of fortifications also contributes to climate damage, as they require energy and large volumes of carbon intensive materials. 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.

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, as well as with reinforced concrete panels in some cases. Trenches are made with the use of specialised military equipment, civil construction equipment, or hand tools. Apart from 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.

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 the main emissions resulting from fossil fuel consumption and calcination process during clinker production.

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. Though the first lines of defence reportedly do not typically have concrete elements, the next lines could have large strongholds with concrete-made fighting positions and trenches covered by concrete plates.[58]

In addition to concrete, the carbon footprint of fortifications includes embodied carbon of other materials, such as steel shelters and various steel elements used for fortifications, which would further increase the estimated carbon footprint.

57. Military fortifications in Ukraine – what comes next?, https://uwecworkgroup.info/military-fortifications-in-ukraine-what-comes-next/

58. See, for instance, photos from the early stages of trench construction with a concrete bunker visible on the background and later photos, where the concrete bunker is covered with soil, https://twitter.com/DefMon3/status/1695463250538709496. Also, examples of the analysis of heavily fortified positions with bunkers and covered trenches could be seen here https://twitter.com/emilkastehelmi/status/1695879651158052910, here https://twitter.com/solonko1648/status/1698037965862150412, and here https://www.wsj.com/world/europe/russia-defense-ukraine-trenches-dragon-teeth-visualized-614a4910

Fortifications built by Russian occupational forces

After the liberation of a significant part of the Ukrainian territory in autumn 2022, Russia has started preparation in the anticipation of a Ukrainian counteroffensive. Defence lines were formed both in Russia along the border with Ukraine and on the occupied territories of Ukraine behind the frontlines. Construction and strengthening of fortifications have continued throughout 2023 and at the beginning of 2024 with bolstering of existing trenches with wood, concrete, or metal structures.[59]

Numerous fortifications were constructed along the frontlines, which stretched over approximately 1,000 km on the east and south of the country.[60] The longest distance of fortified lines is represented by trenches of different depth and width.[61]

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. 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. Still, any efforts to map the fortifications based on satellite images and other evidences should not be treated as complete. As reports from the ground battles during the Ukrainian counter-offensive started to feed in media, it appeared that the scale of fortifications was even larger than assumed and not all the elements could be seen from satellite images and mapped. The first line of defence of the Russian forces was heavily fortified and each tree line among the fields has some kind of fortification structures and fighting positions. Also, some critical zones had much more intensive fortifications systems compared to what was mapped by open-source analysts.

"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.[62]

Both initial reports based on satellites images, photos, and videos, as well as additional footage from the battlefields, where the Armed Forces of Ukraine started to penetrate defensive lines, demonstrate that hundreds of kilometres of "dragon's teeth" lines were installed.

According to DeepState[63], the overall length of various fortification structures exceeded 6,000 km and the length of "dragon's teeth" lines was 1,184 km as of October 2023.

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.[64] Concrete is expected to be used actively for the third line of defence, as this requires planning, resources, and involvement of civilian machinery.[65]

59. See the 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 and https://twitter.com/bradyafr/status/1783813203790561306
60. See the following article for the visualisation 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/
61. See the following article for the description and visualisation of trenches and other elements of 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
62. See the 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; На шляху до моря, https://texty.org.ua/d/2023/way_to_sea/
63. DeepState, https://t.me/DeepStateUA/18121
64. See, for instance: https://twitter.com/TrentTelenko/status/1588626918651621377
65. https://t.me/DeepStateUA/18955

Fortifications constructed by Ukrainian defence forces

Ukraine also constructs fortifications on the liberated territories, territories along the border with Russia and Belarus, as well as along the frontlines. Fighting positions and shelters from reinforced concrete, as well as concrete walls were installed in many regions.[66] Field fortifications include not only concrete fortifications but also shelters from special steel modules that are installed underground.[67] Concrete is also used for fortifications along the frontlines on the east and south of Ukraine (shelters, firing positions, strongholds, etc.)[68].

At the end of 2023 and beginning of 2024, with intensified Russian attacks, Ukraine significantly extended its efforts to construct fortifications in the second and third lines of defence. More than UAH 20 billion were directed for the construction of fortifications in different regions in the first months of 2024 with the goal to construct efficient defensive lines at the length of 2,000 km.[69] Though there were many reports on the deficiency of fortification systems in some critical locations,[70] there was also significant progress made. The multilayered defence systems include trenches, dragon teeth protection lines, as well as concrete and steel bunkers as visible in the reports shared by the Ministry of Defence of Ukraine.[71] There are no exact figures on the number of dragon teeth units installed, but there were several news updates on the installation of 10,000-12,000 units per region in different regions along the frontline, as well as along the northern border and even in Odesa region. By the end of the second year of the war, there was an extensive network of fortifications both on the east and south of Ukraine.[72] According to the Ministry of Defence of Ukraine, during 2022-2023 more than 2,000 strongholds and firing positions have been equipped along the borders and lines of contact with a similar number expected to be constructed during 2024.[73]

Besides, concrete shelters are installed in cities to protect civilians from shelling.[74] Smaller shelters and fortification structures could have a weight of about 20 tonnes, while larger shelters

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66. See the examples of fortifications construction in Kyiv region (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/), Zhytomyr region (Держкордон на Житомирщині укріплюють “ДОТами” та габіонами, https://mil.in.ua/uk/news/derzhkordon-na-zhytomyrshhyni-ukriplyuyut-dotamy-ta-gabionamy), and Rivne region (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/), 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/
67. Інженери готують позиції за допомогою підземних модулів, https://mil.in.ua/uk/news/inzhenery-gotuyut-pozytsiyi-za-dopomogoyu-pidzemnyh-moduliv/
68. Overview of multilayered Ukrainian fortification structures, https://twitter.com/clement_molin/status/1745033008938102852; Military briefing: Ukraine digs deep as Russians advance, https://www.ft.com/content/b5b1b3d7-ca51-482a-a028-45a81816559a, See also examples of fortification structure, including concrete bunkers, published by the Ministry of Defense of Ukraine, https://www.mil.gov.ua/news/2024/02/23/u-2024-roczi-sili-oboroni-prodovzhuyut-buduvati-posileni-fortifikaczijni-sporudi/, https://www.mil.gov.ua/news/2024/02/23/rezultati-roboti-inzhenernih-pidrozdiliv-mou/
69. See, for instance, the Decision of the Cabinet of Ministers of Ukraine On Some Issues of Enhancing the State’s Defence Capability for the Period of Martial Law in Ukraine https://www.kmu.gov.ua/npas/deiaki-pytannia-pidvyshchennia-oboronozdatnosti-derzhavy-na-period-voiennoho-stanu-v--t291223 and relevant news reports at https://suspilne.media/697970-z-pocatku-roku-na-budivnictvo-fortifikacijnih-sporud-vidileno-20-mlrd-griven-smigal/ and https://suspilne.media/703236-situacia-na-fronti-zabezpecenna-vijsk-ta-fortifikacii-zelenskij-proviv-zasidanna-stavki/
70. See, for instance, https://twitter.com/Tatarigami_UA/status/1762930018819121615
71. See the photos of construction sites with visible concrete bunkers and other elements from different regions of Ukraine at https://www.mil.gov.ua/news/2024/03/08/roboti-z-budivnicztva-oboronnih-rubezhiv-vedutsya-bezperervno/, https://www.facebook.com/MinistryofDefence.UA/posts/pfbid0TkyiCxPnCZZhHvx2M3dLgC7ARF2ok77xGv1ZD47TpHFjBJ7apH7hiL8pL47e7Js4l, https://www.facebook.com/MinistryofDefence.UA/posts/pfbid0PpBbENDwGLAQP2NdFYHGzi4phRR9xEkZxbKPa4Gk6JWyfjRNrASnXNejvpRjy4snl, https://www.facebook.com/watch/?v=405845578760096, https://www.facebook.com/watch/?v=3702955573278518, https://www.facebook.com/MinistryofDefence.UA/posts/pfbid0iTh4ad1AkRdSpZAC8WNcBGanU15AX51b3qjxm7WyPsKg4MPDpmNMy4gtZ6UVaYVKl
72. See the maps at https://twitter.com/clement_molin/status/1764040806661300637 and https://twitter.com/clement_molin/status/1745033008938102852
73. Ministry of Defence of Ukraine, https://www.facebook.com/MinistryofDefence.UA/posts/pfbid0kPrFHXUcM8duM6LqUw4si1mN4Y7Eb6qTUd98YR3nsgAhxMrmXnmoSpMsM8JTyFtil
74. 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

weight around 70 tonnes. Hundreds of concrete shelters were installed in Ukrainian cities and villages. Apart from that, thousands of concrete blocks are used for the organisation of block-posts in cities and other locations. It is assumed that at least 40,000 tonnes of concrete were used for these needs.

In addition, after the extensive attacks on the energy system during the autumn and winter of 2022-2023, Ukraine devoted significant efforts to the protection of critical infrastructure, including electric substations and gas distribution substations. In particular, concrete-based protection structures were installed at 28 facilities with additional measures anticipated to protect 68 power transformers and 22 key substations.[75] Protection of just one transformer substation requires 613 tonnes of steel and 1,721 m^3 of concrete.[76] Based on preliminary data, the demand for concrete was estimated at 300,000 m^3; also, more than 200,000 tonnes of sand were used for gabions.[77] In addition, about 20,000 tonnes of steel were planned to be used for the protection of energy infrastructure.[78]

Assumptions used in calculations

The estimation of the carbon footprint of fortifications is very challenging during the war, as it is hard to collect activity data on the materials and energy used during construction. A detailed inventory is impossible to comply based on satellite data since most of the structures are hidden and covered by soil. Data on the quantities of materials used by militaries for the construction of fortifications are not available, while a detailed analysis of a sample of fortification lines with the description of the number and characteristics of shelters, strongholds, and other parameters of fortifications with further extrapolation on the overall length of fortification lines is not possible to conduct during the war. High-level estimations using satellite data for "dragon teeth" and general assumptions for other concrete structures were made, while more studies would likely be possible only after the end of the war.

For comparison, the Baltic Defence Line planned to be established on the border between Estonia, Latvia, and Lithuania and Russia and Belarus could have approximately 2 concrete bunkers, 35 m^2 each, per kilometre (i.e. about 600 bunkers planned for the 300 km border stretch between Estonia and Russia), making the total potential number of bunkers almost 4,500 units[79].

The general assumption applied for concrete use is 80 tonnes of concrete per kilometre of the frontline for each side (e.g. two bunkers requiring 40 tonnes of concrete for each per km). The following assumptions were made:

- 1,000 km of the frontline with concrete structures for Russian forces (east and south of Ukraine) – 80,000 tonnes of concrete;
- 2,000 km of defence lines with concrete structures for Ukrainian forces (north, east and south of Ukraine) – 160,000 tonnes of concrete.

Additional information is provided in the table below.

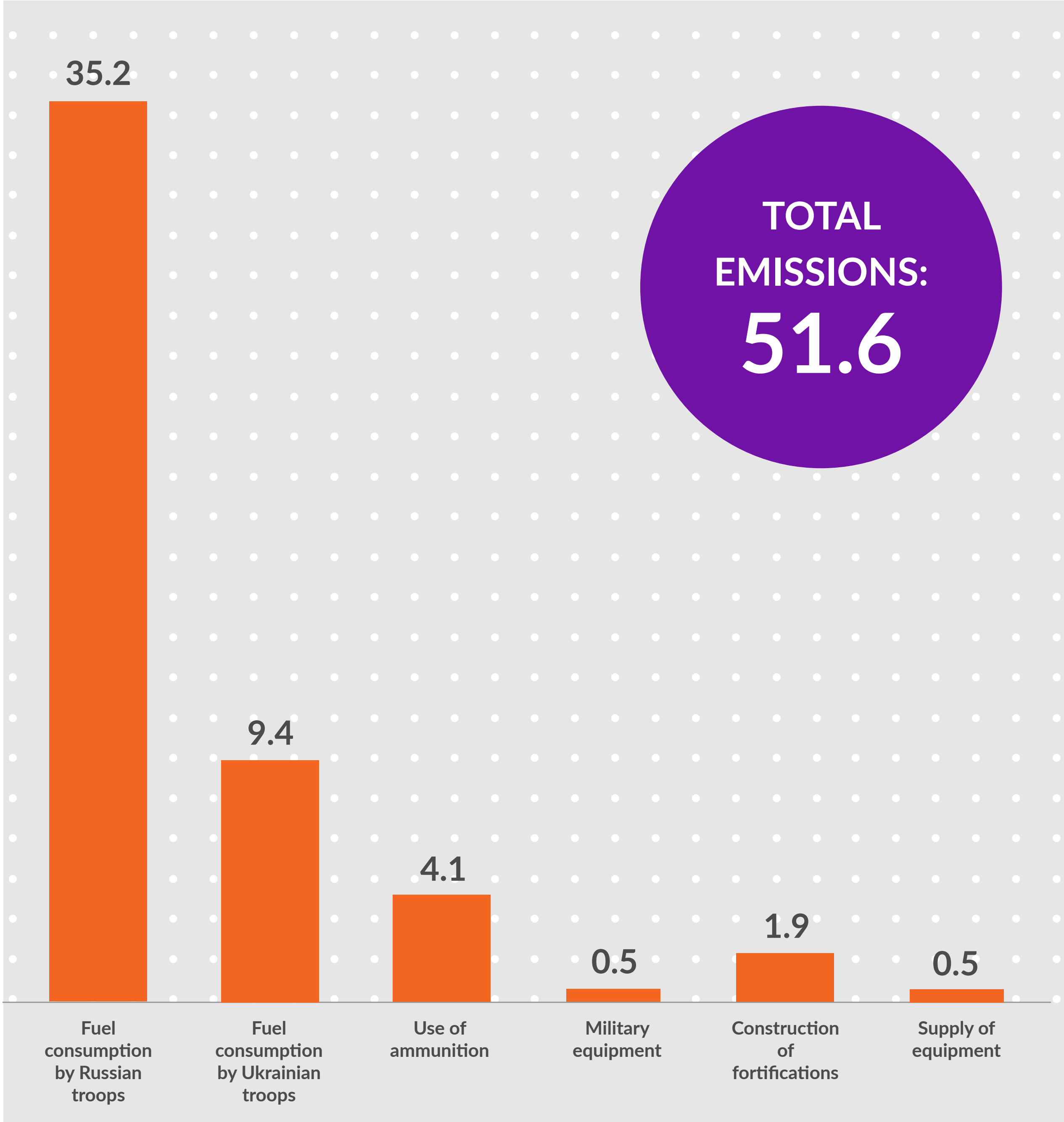
75. Агентство відновлення реалізує трирівневу систему захисту енергетичної інфраструктури – Найєм, https://interfax.com.ua/news/economic/953814.html
76. Укренерго реалізує проєкт захисту критично важливого обладнання підстанцій, https://ua.energy/zagalni-novyny/ukrenergo-realizuye-proyekt-zahystu-krytychno-vazhlyvogo-obladnannya-pidstantsij/
77. Керівник "Укренерго" Володимир Кудрицький: "Висновок ДАСУ нічого спільного з аудитом немає, це більше схоже на профанацію, або на якусь атаку", https://mbiz.censor.net/resonance/3451467/kerivnyk_ukrenergo_volodymyr_kudrytskyyi_vysnovok_dasu_nichogo_spilnogo_z_audytom_nemaye_tse_bilshe
78. Агентство відновлення та USAID спільно працюють над пасивним захистом енергооб'єктів, https://mtu.gov.ua/news/35002.html
79. Fearing Russia, the Baltic states improve their defences, https://www.economist.com/europe/2024/02/10/fearing-russia-the-baltic-states-improve-their-defences

Data	Russian Forces	Ukrainian Forces	Total
Dragon's teeth used	900,000	100,000	1,000,000
Concrete used for dragon's teeth manufacturing, t	1,080,000	120,000	1,200,000
Concrete used for other fortification structures, t	80,000	160,000	240,000
Concrete used for shelters and check-points, t	N/A	40,000	40,000
Concrete used for the protection of critical infrastructure, t	N/A	720,000	720,000
Total amount of concrete used for fortifications, t	1,160,000	1,040,000	2,200,000
Assumed concrete density, t per m^3	2.4		
Total amount of concrete used for fortifications, m^3	483,000	433,000	916,000

Table 9. Assumptions used for the calculation of carbon footprint

Assumed emission factor for concrete is 0.5 t per m^3 based on the B40 concrete class composition.[80] Total carbon footprint of fortifications is estimated at **0.46 million tCO_2e**.

80. Carbon footprint of concrete depends on its class, which determines cement strength and content. Based on available specifications, fortifications are build using high-strength concrete of class B40 (C32/40). The carbon footprint was defined 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 m^3 of concrete) and emission factors provided by Concrete Embodied Carbon Footprint Calculator for concrete with such composition using data from the ICE database, https://circularecology.com/concrete-embodied-carbon-footprint-calculator.html. Results provided by Concrete Embodied Carbon Footprint Calculator: 496 kg CO_2e / m^3 concrete or 0.206 kg CO_2e / kg concrete. Cement (CEM I) is responsible for 86% of the estimated carbon footprint. The exact value of carbon footprint from concrete production would depend on the type of cement used, technology of cement manufacturing (e.g. fuel used as energy source, use of "wet" or "dry" technology process, energy efficiency of the plant), as well as technical specifications of concrete used for the manufacturing of different fortification structures.



SOURCE OF EMISSIONS	$MtCO_2e$
Emissions from fuel consumption by Russian troops	35.2
Emissions from fuel consumption by Ukrainian troops	9.4
Emissions from the use of ammunition	4.1
Emissions from the construction of fortifications	0.5
Emissions associated with military equipment manufacturing	1.9
Emissions associated with long-distance transportation of military equipment	0.5
TOTAL	**51.6**

Table 10. Total GHG emissions from warfare

3.2 Landscape Fires

Introduction

According to the UN Food and Agricultural Organisation's (FAO) definition, landscape fires are human-related land-use fires, prescribed management fires, and wildfires burning in the live and dead vegetation of natural, cultural, and urban-industrial landscapes.[81] In Ukraine, only some agencies collect statistical data on fires – but most of them do not cover all landscape fires. Hence, assessment of war-related emissions from all types of landscape fires in this report is based on fire statistics of the Regional Eastern Europe Fire Monitoring Center (REEFMC), which is financially supported by Zoï Environment Network.[82]

Before the war, there were numerous, mostly human-related, ignition sources in the landscapes of Ukraine: starting from intentional burning of crop residues on fields to fires on small patches of land ignited by rural populations near their villages and negligence fires from citizens (or their cars) that visit forests. Among several Ukrainian state agencies, only the State Agency of Forest Resources of Ukraine has a complete system of forest fire management in place: from prevention and detection to response and suppression (around 10.6 million ha of forest lands). The vast majority of agriculture and swallow lands and pastures (more than 40 million ha) are not covered by regular fire management activities.

The war has also affected the amount and areas of fires and related CO_2 emissions via the direct impact of shelling, presence of large numbers of soldiers and various potential sources of ignition, occupation of territories, and reduction in existing technical and human capacity of landscape fire management in Ukraine. On top of that is climate change and extreme fire weather events that increase the risks of uncontrollable burning, especially along the frontline, where there is no response from fire brigades.

The war has essentially redistributed fire locations all over the country. Now, most of the fires (more than 60%) occur along the frontline — from Kharkiv region in the north to Kherson region in the south. Some fires are still occurring in western regions around the Carpathians due to agriculture burnings, but these are not related to the war. Burning of agricultural residues in some parts of the country was reduced significantly due to the presence of territorial defence checkpoints and air defence forces, in particular close to the frontline.

An increasing number of fires in the occupied areas as well as along the frontline are related to an almost completely dismantled fire management infrastructure: destroyed forest ranger district offices and loss of staff, defunct fire detection towers and cameras of video surveillance, fire engines, fire roads and ponds, and dangerous circumstances for firefighters. The absence of fire weather monitoring, weak or absent response, and contamination by unexploded ordinances are the main drivers leading to increasing fire areas. Mobilising of many foresters to the Ukrainian army and donation of fire pickup trucks to the army weakened fire management capacity all over the country and indirectly increased fire areas. Late responses very often lead to high intensity fires, while there is a ban for aviation suppression due to threats from rockets, especially near the frontline.

War-related limitations in forest and fire management are caused by labour shortage and reduced technical capacity, late response and low effectiveness of the initial fire response, and the absence of fire suppression from the air.

81. FAO Fire Management Voluntary Guidelines, https://www.fao.org/4/j9255e/j9255e00.pdf
82. https://nubip.edu.ua/node/9087/2

Methodology

The methodology presented below consists of the following steps:

1. Mapping of fires
2. Buffer zone delineation
3. Biomass loss and GHG emissions
4. Attribution
5. Results

Step 1: Mapping of fires

As the first step of the methodology, in the period from 24 February 2022 to 23 February 2024, all fires in the territory of Ukraine were delineated by visual inspection of Sentinel 2 time series. The MODIS-based MOD14/MYD14 Fire and Thermal Anomalies[83] product was used to identify dates and locations of potential fires. This product represents an active fire as a centroid of a 1 x 1 km pixel, i.e. one pixel may contain more than one small fire.

Next, pre- and post-fire image mosaics were created for each fire location. Sentinel 2 images were screened from clouds and cloud shadows and then composed into median mosaics. A time window for image mosaicing was 10 days before and after the fire. However, if there were not enough high quality observations, the time window was extended. A group of trained photo interpreters analysed Sentinel 2 mosaics within 1 km of the fire location to identify active fires or recent burn scars and the fire perimeters were outlined manually. A SWIR2-NIR-red band combination was used to provide a good contrast between live and burned vegetation.

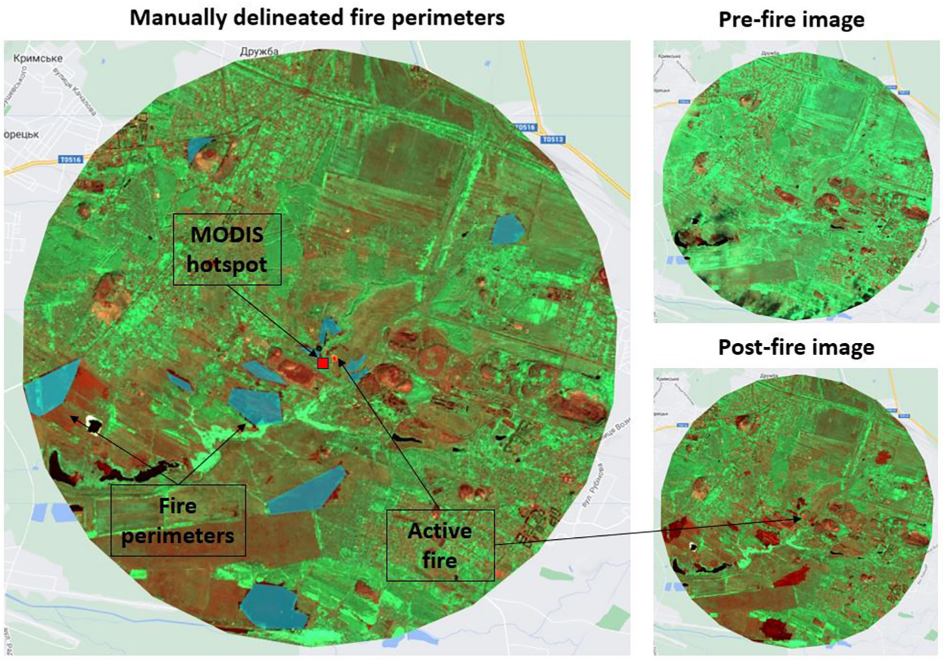


Figure 11. An example showing an active fire on Sentinel 2 image mosaic. Fire perimeters were created using post-fire spectral changes

83. https://modis.gsfc.nasa.gov/data/dataprod/mod14.php

Step 2: Buffer zone delineation

As the second step, a buffer zone was established. This study used daily frontlines created by Zoï Environment Network. Based on the daily progression of the frontline since 24 February 2022, three zones were delineated:

- Zone 1: Ukrainian territory not impacted by the ground-based warfare, i.e. outside of the 30-km buffer zone
- Zone 2: Accumulated 30-km buffer zone on both sides of the moving frontline
- Zone 3: Occupied territories, including those territories occupied since 2014 but outside of the 30-km buffer zone

As for the buffer zone, a cumulative buffer of 30 km on both sides of the frontline for a given date is used. Thus, the buffer refers to the maximum area of direct war impact observed since the beginning of the invasion. Some areas of Ukraine have been liberated since then, but these areas are not accessible for fire fighters due to the presence of mines or unexploded ordnance. Therefore, we *accumulate* a 30-km buffer zone during the 24 month period.

Step 3: Biomass loss and GHG emissions

In the third step, carbon emissions from fires are determined for different landscape categories as follows.

Carbon emissions from forest fires

To estimate carbon emissions from forest fires, species and age structure of forest stands were determined. The age and species composition of forest stands were determined to significantly affect the formation of total biomass volumes and determine the specifics of biomass losses as a result of forest fires of different severities. Based on the data of the last forest assessment in Ukraine,[84] the ratio of age groups was also determined for each region of Ukraine: young, middle-aged and premature, mature, and overmature. Further, the total volume of biomass within the classified forest stands was estimated using mathematical models.[85] The models were selected considering the dominant tree species within a specific region: coniferous (pine, spruce) and broadleaf (oak, beech, hornbeam, robinia, birch, aspen, and alder). Different types of forest fires, i.e. surface, canopy (crown), or combined ones, can form different degrees of damage: low (damage to the upper layer of the litter, ground cover, and undergrowth and slight burning of the bark of tree stems), medium (damage to the bark of tree stems and lower branches of the crown, destruction of trees of categories IV and V according to the Kraft scale), and high (destruction of a significant number of elements of the forest stand). Coefficients of forest biomass losses due to forest fires are presented in the annex.

The volumes of carbon emissions resulting from forest fires were calculated using the following equation:

$$C_{em} = M_{fr} \times K_{cf} \times K_{lf} \quad (1)$$

where C_{em} is the volume of carbon emissions, t; M_{fr} is the mass of individual fractions of biomass in the mass of dry matter, t; K_{cf} is the coefficient of carbon content in a unit of biomass (bark, branches of the crown — 0.5; leaves, living ground cover, litter — 0.45); and K_{lf} is the burnt factor coefficient (a coefficient that takes into account the loss of biomass (within fractions) as a result of the damage (completely or partially) by a forest fire of various severity).

84. Handbook of the Forest Fund of Ukraine, 2012
85. P.I. Lakyda et al. (2013), A.Z. Shvidenko et al. (2014), R.D. Vasylyshyn (2016) and A.M. Bilous (2018).

Future biomass losses and, hence, GHG emissions for forest stands adversely affected by fires were estimated based on expert assessments of potential post-fire stand losses. The predicted death of forest plantations due to the impact of high-intensity fires is as follows: young and middle-aged plantations — 100%, ripe and overripe ones — 90%; of medium-intensity fires: young and middle-aged plantations — 80%, ripe and overripe ones — 50%; of low-intensity fires: young and middle-aged plantations — 30%, ripe and overripe ones —15%.

Carbon emissions from cropland fires

Determination of the dominant species structure of the sown areas of crops was done based on area distribution by crop structure. According to the Ministry of Agrarian Policy and Food of Ukraine, wheat, barley, sunflower, and corn dominated the crop structure, covering almost 85% of the sown areas. The following ratios of the mentioned crops were used: wheat — 37.3%, barley — 10.8%, sunflower — 26.1%, and corn — 25.8%.

Estimation of the yield and volume of crops biomass

The yield of the mentioned crops (in tonne/ha) within each region was determined based on national statistics data[86]. The amount of biomass was determined using the coefficients of the total yield of surface and root residues of crops depending on main products yield.[87] The coefficients used in the work are presented in the table below.

Crops	Coefficient of the total yield of by-products, stubble, and root residues	Non-marketable biomass remaining on the field, %	
		by-products	stubble and root residues
Wheat	1.5	53	47
Barley	1.3	52	48
Sunflower	3.5	50	50
Corn	1.4	58	42

Table 11. Coefficients of the total yield of surface and root residues of crops depending on the harvest of the main products[88]

The calculations assumed that not only by-products, but also the main crop would be lost due to fires in the buffer zone during May and July 2022, as a high density of shelling was observed and the crop could not be harvested. The volumes of carbon emissions caused by cropland fires were calculated as follows:

$$C_{em} = B_{pl} \times K_{cf} \times K_{pf} \quad (2)$$

where C_{em} is the volume of carbon emissions, t; B_{pl} is the plant biomass in a completely dry state, t; K_{cf} is the coefficient of carbon content in a unit of biomass (0.45); and K_{pf} is the coefficient that considers fire severity (low — 0.9; medium and high — 1.0).

86. Verner, I.E. (Ed.). (2021). Statistical yearbook of Ukraine 2020. https://ukrstat.gov.ua/druk/publicat/kat_u/2021/zb/11/Yearbook_2020_e.pdf

87. Kokhana, A.V., & Glushchenko, L.D. (Eds.). (2015). Current situation and ways to improve soil fertility in Poltava region in modern conditions of agricultural production. https://dspace.pdau.edu.ua/server/api/core/bitstreams/505eccad-4804-4c9b-bc88-12317e089c9b/content

88. Source: A.V. Kokhana & L.D. Glushchenko (2015)

Carbon emissions from fires in other natural landscapes

Using the official website of the State Statistics Service of Ukraine for geodesy, cartography, and cadastre, the regional structure of other landscape types was determined. The regional structure of landscapes, in addition to forest areas and arable land, also includes hayfields, fallows, and pastures. Based on the Land Directory of Ukraine data,[89] the share of each of the listed types of agricultural landscapes within each region was calculated. Productivity and biomass volumes were determined by landscape types. The productivity of the mentioned types of landscapes (in t/ha) within each region was estimated based on scientific data from numerous botanical and ecological publications and grouped by natural zones of Ukraine. The yield values used are presented in the table below.

Natural zone	Dry matter yield, t/ha				
	hayfields	pastures	fallows	bushes	wetlands
Steppe	2.7	2.4	1.8	8.7	8.0
Forest steppe	4.2	3.8	2.8	9.5	8.0
Ukrainian Polissia	3.8	3.4	2.5	9.2	8.0
Ukrainian Carpathians	3.2	2.8	2.1	8.9	8.0

Table 12. Productivity of certain types of landscapes within natural zones [90]

Biomass losses are differentiated depending on the level of site damage and landscape type. Equation 2 was used to estimate carbon emissions from fires within other natural landscapes.

As a result of applying the described algorithm by category (forest fires, cropland fires, and fires in other natural landscapes), burned areas by burn severity classes, biomass and carbon losses and GHG emissions were determined.

Carbon emissions from fires in urban areas

Emissions from fires in urban areas were estimated using the data provided in the Methodology for calculating of unorganised 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[91]. The methodology provides for an emission factor of 2.64 tCO_2e per tonne of material and gives an example of a shopping mall with combustible material content of 300 t/ha. Based on this, the emission factor of 792 tCO_2e/ha was estimated for fires in build-up areas.

The area of fires in urban areas was first estimated based on land category classification and then adjusted based on the analysis of the samples of areas classified as urban territory to account only for a fraction of the territory occupied by buildings and other structures.

89. Land Directory of Ukraine, https://agropolit.com/spetsproekty/705-zemelniy-dovidnik-ukrayini--baza-danih-pro-zemelniy-fond-krayini
90. Source: A.M. Bilous (2018), M.I. Stakal (2020), V.I. Grigoriev et al. (2021)
91. Methodology for calculating of unorganised 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

Step 4: Attribution

The fourth step of the methodology is to attribute fires in the buffer zone to the war, i.e. we must demonstrate that these fires were not caused by other natural factors or typical human activities. Using previous years as a reference is problematic due to significantly different weather conditions. Over the past two years, precipitation has been higher compared to the preceding 10-12 years, which experienced only one instance of annual precipitation exceeding the climate normal, with severe droughts recorded from 2018 to 2021. Establishing similarity between the weather conditions in earlier and recent years assumes that historical fires were caused by similar conditions, which is not accurate.

The past decade has seen significant changes in Ukraine, including climate shifts, alterations in land cover, changes in legislation, and shifts in agricultural practices. Additionally, the lack of detailed historical fire mapping further limits the use of previous timeframes for war attribution.

Therefore, for a more reliable estimation, we have proceeded with the assumption that weather conditions most similar to those in the buffer zone occurred in Ukrainian territories not directly impacted by the war (Zone 1) during, or very close to, the same day of fires. To enhance this method further, we have aggregated data over calendar seasons to achieve a more precise attribution.

There are a few widely used weather-related indices to forecast fire danger. Among them, the most used and available at the Copernicus data service[92] is the Canadian Forest Fire Weather Index (FWI). FWI serves to quantify the meteorological factors conducive to both the ignition and spread of fires. It is computed in three tiers. In the first tier, three dimensionless moisture codes are derived: the Fine Fuel Moisture Code (FFMC) corresponds to daily moisture levels in litter up to 2 cm deep, utilising air temperature, relative humidity, precipitation, and wind speed; the Duff Moisture Code (DMC) assesses moisture levels over approximately two weeks in litter and soil layers 5-10 cm deep, using air temperature, relative humidity, and precipitation; and the Drought Code (DC) represents moisture levels over around two months in litter and soil layers 10-20 cm deep, employing air temperature and precipitation data. In the second tier, the Build-up Index (BUI) and Initial Spread Index (ISI) are determined from the codes derived in the first tier. The BUI, derived from DMC and DC, reflects the cumulative fuel available for burning due to prolonged drying. The ISI, calculated using FFMC and wind speed, indicates how rapidly a fire can propagate. In the final tier, the FWI is computed from BUI and ISI, indicating both the fire danger based on meteorological conditions and the potential intensity of a fire if ignited.

The FWI is dimensionless and is categorised as such classes of fire danger:

- Low: <11.2
- Moderate: 11.2-21.3
- High: 21.3-38.0
- Very High: 38.0-50.0
- Extreme: ≥ 50.0

During the two-year period under consideration, the categories of fire danger based on FWI were assigned to all the fires across Ukraine's territory taking into account their geographical locations. The key attribution assumption was that, in case of a no-war scenario, the same weather conditions (presented by FWI) on the same land cover in the same season of the same year should cause the same area of fires across Ukraine. Therefore, all additional fires in the buffer zone can be attributed to the war.

92. Database of Copernicus: https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-fire-historical-v1?tab=overview

To calculate the attribution factor, the same land cover areas were needed for both territories — not war impacted territories and the 30-km buffer zone. To achieve this, Zone 1 was divided into 50 km-side squares with land cover values for each.

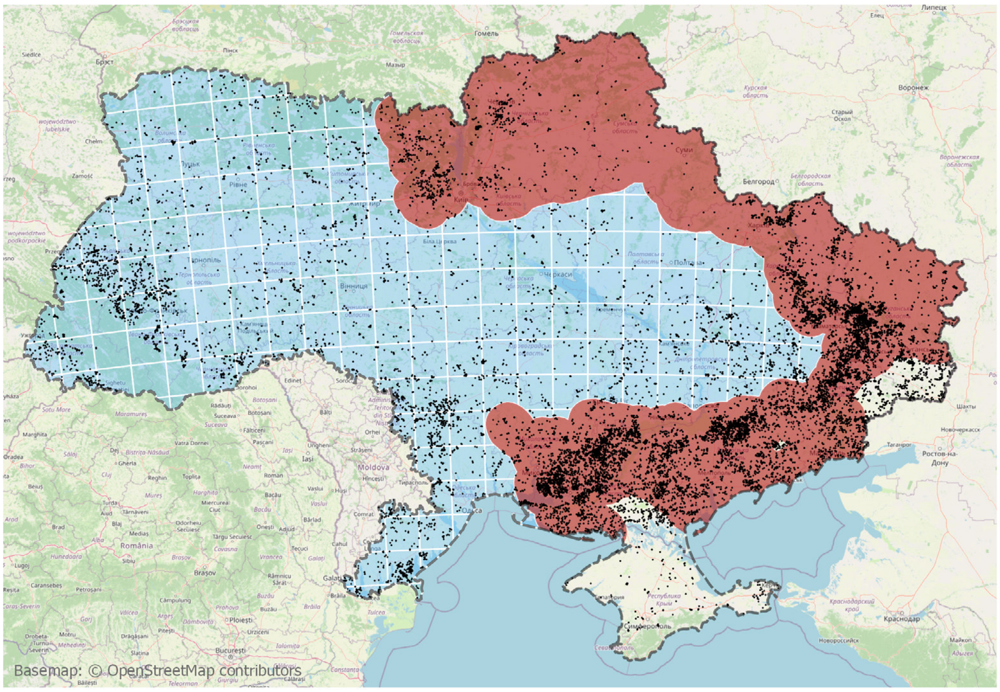


Figure 12. 50 x 50 km squares in zone 1

Then, for each land cover (agricultural lands, coniferous forests, deciduous forests, and other plantations), random squares in government-controlled Ukraine (Zone 1) were selected entailing the same area as in the buffer zone.[93] An example of selected areas (blue) within Zone 1 with an approximately equal amount of agricultural lands in the 30-km buffer zone (red) is presented in the figure below.

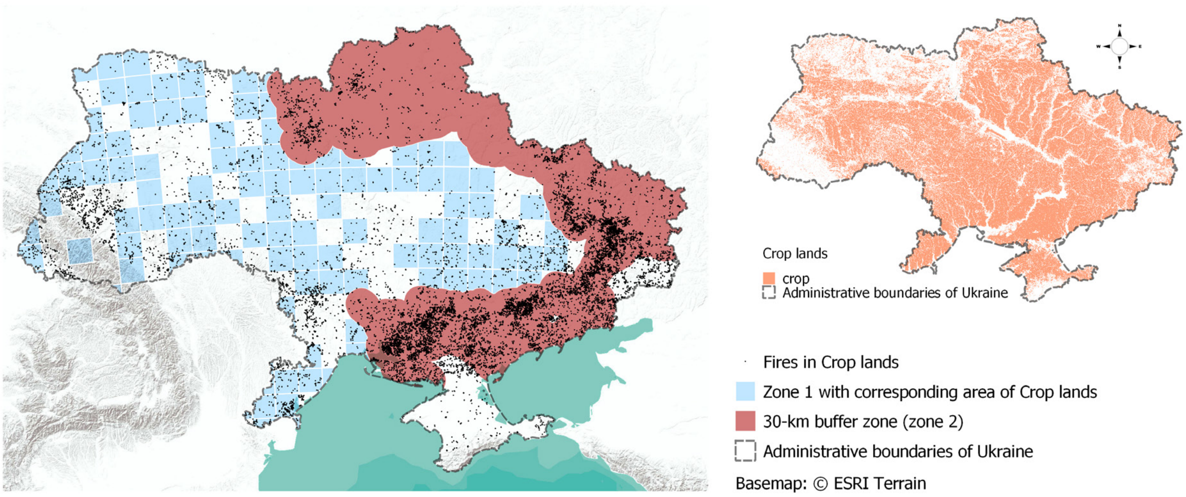


Figure 13. The estimated area of crop lands in Zone 1 (blue squares) compared to the 30-km buffer zone

For this, we estimated part of each land cover under fires in both zones with the subdivision into five classes of FWI and four calendar seasons: spring, summer, autumn, and winter.

In order to estimate war-related emissions from landscape fires, the total amount of GHG emissions released by fires in the buffer zone should be multiplied by attribution coefficients for each land cover, season, and FWI class.

93. This study used a 20-m spatial resolution land cover map produced by the SFI project using Sentinel 2 imagery https://www.sfi-ukraine.org.ua/en/

Results

Step 1: Mapping

The total area of natural landscape fires in Ukraine during 2022-2023 reached 1,202.9 thousand ha. The majority of the affected territories were agricultural lands (croplands), accounting for 633.7 thousand ha, and other natural vegetation (abandoned lands), amounting to 445,907 thousand ha. Forest fires burned 116.3 thousand ha. In total, about 27 thousand fires were detected during the two-year period. A significant share of these fires occurred within the buffer zone, comprising 74% of the total fire-affected area, while 67% of all fires occurred in occupied territories.

Apart from natural landscapes, urban areas were mapped as well, resulting in 6.4 thousand ha in the buffer zone and 0.5 thousand ha in Zone 1. This urban landscape type consists of mixed uses, like buildings, roads, vegetable gardens, or other natural vegetation. For this study, we only looked into buildings within the urban land cover.

To estimate the area of buildings footprint within the total urban area, we used a set of 400 reference points. These reference points were randomly distributed within the "urban" land cover class across Ukraine and allowed us to estimate the share of buildings with an accuracy of 5%.[94] For visual interpretation, we used the latest high-resolution Google Earth Pro imagery. The reference points were classified into four categories observed within the urban area: 1) buildings; 2) roads and infrastructure; 3) natural unproductive areas; and 4) vegetation. The proportional distribution of these categories showed that buildings occupy 29% of the total urban area in the land cover map.

Thus, it was concluded that fires within urban areas resulted in 29% x 6.4 thousand ha = 1.856 thousand ha of burnt buildings.

Step 2: Buffer Zone (Zone 2)

The buffer zone is an accumulated zone 30 kilometres away from the moving frontline. The result is provided below.

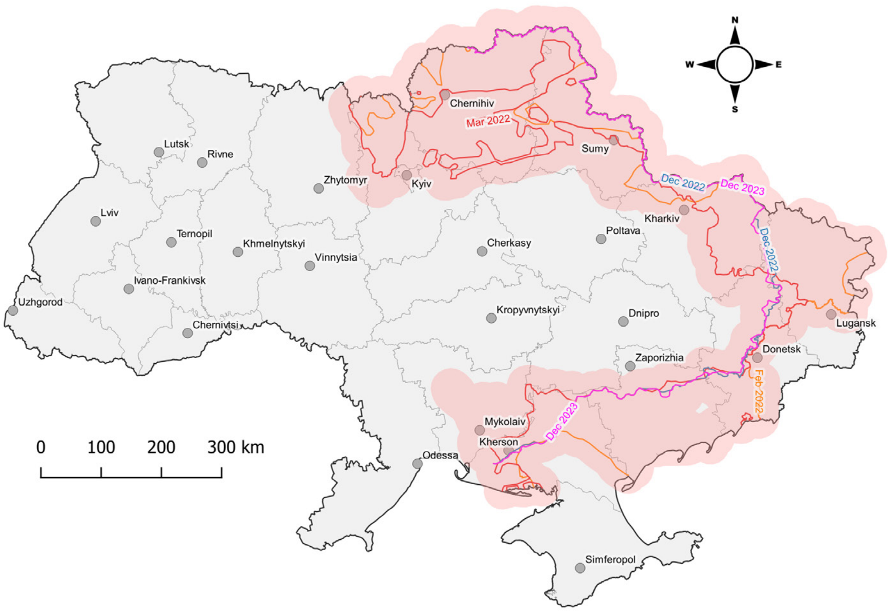


Figure 14.The accumulated buffer zone as of 30 December 2023 overlaid on the selected frontlines of 2022-2023

94. Olofsson, P., Foody, G. M., Herold, M., Stehman, S. V., Woodcock, C. E., & Wulder, M. A. (2014). Good practices for estimating area and assessing accuracy of land change. Remote Sensing of Environment, 148, 42–57. https://doi.org/10.1016/j.rse.2014.02.015

Step 3: Carbon Emissions

The total loss of biomass due to natural landscape fires on the territory of Ukraine during the 24 months of the full-scale war amounted to almost 6 million tonnes of carbon. As a result, total volume of GHG emissions amounted to more than 15 million tCO2e. Damage to forest plantations caused by forest fires can also lead to forest death and its decomposition in a period of up to five years. Therefore, future losses of damaged forests biomass will lead to the loss of more than 11 million tonnes of carbon and result in GHG emissions of more than 18 million tCO2e. Almost 85% of all GHG emissions originate from the buffer zone.

Land cover type	Area covered by fires (thousand ha)	Immediate loss of biomass (thousand tonne of dry matter)	Immediate GHG emissions (thousand tonne of dry matter)	Future losses of forest biomass (thousand tC)	Future GHG emissions from forests losses (thousand tCO_2e)
Zone 1					
Wetlands	20.39	156.91	259.22		
Other vegetation lands	133.85	433.32	715.83		
Deciduous forests	27.38	141.95	212.04	2831.09	4662.80
Croplands	131.53	398.85	658.89		
Coniferous forests	3.18	32.29	50.45	294.72	485.41
TOTAL	**316.33**	**1163.33**	**1894.43**	**3125.81**	**5148.21**
Zone 2 (30 km buffer zone)					
Wetlands	14.09	106.80	176.44		
Other vegetation lands	277.57	822.62	1358.94		
Deciduous forests	27.59	148.10	221.49	2869.09	4725.40
Croplands	502.19	3150.92	5205.19		
Coniferous forests	58.19	542.38	847.50	5127.56	8445.09
TOTAL	**879.63**	**4770.82**	**7809.56**	**7996.65**	**13170.49**
Total territory of Ukraine					
Wetlands	34.48	263.72	435.65		
Other vegetation lands	411.43	1255.94	2074.77		
Deciduous forests	54.97	290.05	433.53	5700.18	9388.20
Croplands	633.72	3549.77	5864.08		
Coniferous forests	61.37	574.67	897.96	5422.28	8930.50
TOTAL	**1195.97**	**5934.16**	**9705.99**	**11122.46**	**18318.70**

Table 13. Total biomass loss and GHG emissions after 24 months of war before attribution

Step 4: Attribution

In general, most obtained attribution coefficients in the table below are close to 100%, demonstrating that almost all emissions from fires in the buffer zone can be attributed to the war. Negative coefficients appeared during the autumn seasons for low and moderate FWI and when fire areas in Zone 1 exceeded fire areas in the buffer zone. Herewith, those areas are extremely small, which could be seen in the annex, where a more detailed information on the relative area under fires in both zones is presented for the considered land covers, seasons, and FWI classes. Therefore, their additional effect on the attributed emissions is within the uncertainty of the applied methods of estimation.

Season	FWI classes	Crop lands, %	Coniferous forests, %	Deciduous forests, %	Other vegetation lands, %
Spring 2022	low	58.0	92.6	56.9	64.3
	moderate	60.2	96.2	66.3	62.7
	high	70.0	81.6	85.3	92.7
	very high	64.0	100.0	100.0	99.9
	extreme	100.0	100.0	100.0	100.0
Summer 2022	low	95.8	100.0	97.0	98.6
	moderate	72.6	99.9	90.6	96.2
	high	93.5	99.0	98.6	92.2
	very high	89.1	100.0	99.2	97.6
	extreme	90.0	99.9	99.9	98.8
Autumn 2022	low	88.1	73.1	60.8	73.7
	moderate	-20.0	-99.4	-97.7	46.2
	high	98.2	100.0	100.0	97.8
	very high	100.0	0.0	100.0	100.0
Winter 2022/23	low	95.8	100.0	99.9	98.6
Spring 2023	low	76.4	99.5	75.4	75.1
	moderate	89.4	100.0	98.8	97.6
	high	23.0	100.0	100.0	99.7
Summer 2023	low	73.6	99.6	95.1	99.2
	moderate	74.6	99.7	82.0	96.0
	high	95.2	99.4	99.4	98.9
	very high	92.8	100.0	87.9	99.1
	extreme	99.4	100.0	100.0	100.0
Autumn 2023	low	40.6	-100.0	-88.1	25.2
	moderate	-13.5	70.7	-77.8	5.2
	high	86.8	99.9	95.2	90.0
	very high	96.6	99.7	99.7	90.9
	extreme	99.7	100.0	99.3	100.0

Table 14. Attribution coefficients in %

Applying the attribution coefficients to the buffer zone results in the following emissions that can be attributed to the war.

Land cover	Area covered by fires (thousand ha)	Immediate loss of biomass (thousand tonne of dry matter)	Immediate GHG emissions (thousand tonnes CO_2e)	Future losses of forest biomass (thousand tonne of dry matter)	Future GHG emissions from forests biomass losses (thousand tCO_2e)
ZONE 2 (30-km buffer zone)					
Wetlands	10.74	81.54	134.70		
Other vegetation lands	225.73	661.75	1093.18		
Deciduous forests	20.12	109.88	164.39	2163.25	3562.87
Croplands	423.74	2750.14	4543.12		
Coniferous forests	56.57	525.47	821.13	4968.26	8182.72
TOTAL	**736.9**	**4128.78**	**6756.52**	**7131.51**	**11745.60**

Table 15. Carbon loss and GHG emissions in the buffer zone attributed to the war

The resulting GHG emissions from natural landscape fires amount to 6757 million tCO_2e emitted directly during fires and 11.746 million tCO_2e resulting from the future emissions of dead forests together totalling 18.503 million tCO_2e.

GHG emissions from build-up areas

The total emissions from buildings fires within the urban land cover type are calculated by multiplying 1.856 thousand ha of burnt buildings by an emissions factor of 0.792 tCO_2e/ha, which results in 1.470 million tCO_2e with 100% of the fires attributed to the war.

Indirect impact

Whereas fires in the buffer zone can be directly attributed to the war as described above, in the territories not directly impacted by the warfare (Zone 1), the impact is more difficult to attribute. Cruise missiles and drones have caused damage far behind the frontlines, even in the west of Ukraine close to the Polish border, and may have ignited wildfires. However, the major impact of the war in Zone 1 is reduced firefighting capabilities to do reconnaissance with drones and respond and extinguish fires that have had regular or non-regular causes. Contrary to the buffer zone, these fires are in most cases accessible, but fire management activities are limited due to the lack of fire fighters as many men and women enlisted in the army. Extinguishing fires from the air can be hampered as airspace is often closed by order of the army or by Ukrainian authorities.

Moreover, many fire trucks and other firefighting equipment have been brought to the war zone to assist in firefighting activities in urban areas. According the data from the Kyiv School of Economics, Ukraine had a total of 4,216 firefighting trucks, of which 1,629 have been damaged or destroyed.[95] This is a destruction rate of 38%. These numbers comprise fire trucks used for both urban and landscape fires. Fighting urban fires is prioritised by the authorities; hence, most likely, even less fire trucks will be available to extinguish natural landscape fires. Nevertheless, we use this figure as a proxy to estimate the reduction in firefighting capabilities and to estimate the emissions from fires that are indirectly caused by the war, realising that the uncertainty of this estimation is higher compared to the emissions directly caused by the war in the buffer zone.

The immediate and future GHG emissions in Zone 1 were estimated to be 2.35 million tCO_2e and 5.15 million tCO_2e respectively (see table 13). Attributing 38% of these emissions to the war results in an additional 0.893 and 1.957 million tCO_2e respectively.

Source	Zone	Immediate emissions	Future emissions	Total
Natural landscapes	2	6757	11.746	18.503
Built-up areas	2	1.470	-	1.470
Indirect impact	1	0.893	1.957	2.850
TOTAL	**1 & 2**	**9120**	**13.703**	**22.823**

Table 16. Overview of GHG emissions from landscape fires ($MtCO_2e$)

95. Annex 10 of the Report on damages to infrastructure from the destruction caused by Russia's military aggression against Ukraine as of January 2024, KSE, https://kse.ua/wp-content/uploads/2024/05/Eng_01.01.24_Damages_Report.pdf

3.3 Energy infrastructure

Energy and fossil fuel infrastructure is often among the priority targets during warfare as its destruction undermines the capacity of adversaries to conduct military operations either directly due to the destruction of fuel reserves near the frontlines or indirectly by degrading the economy to reduce the ability to support and finance the war. Besides, energy and fossil fuel infrastructure could be located along the frontlines and be unintentionally damaged by ongoing combat activities or during missile and drone attacks on the cities across Ukraine. This section covers, apart from the damage to energy infrastructure directly linked to the warfare activities, the damage to the Nord Stream pipelines.

Nord Stream

The sabotage of the Nord Stream 1 & 2 pipelines on 26 September 2022 is not directly related to the warfare activities, but it has been included in this assessment as by principle we include all GHG emissions that would not have occurred without the act of aggression by the Russian Federation.

After the sabotage, the leakage continued for about a week. On 30 September 2022, GHGSat, using a high-resolution satellite, measured the emissions rate from the Nord Stream 2 leak in the Baltic Sea at the rate of 79,000 kg/h, which was the largest emission source detected by the company so far. There were no signs of leakages on satellite images from 3 October, confirming the statement of the Danish Energy Agency that pipelines in the Nord Stream 1 and Nord Stream 2 stopped releasing gas as of 2 October.[96]

The Danish Energy Agency estimated that in the worst case, the leaks from the Nord Stream 1 & 2 pipelines would result in approximately **14.6 million tCO_2e** GHG emissions (equivalent to 778 million standard cubic meters of natural gas). The calculation assumed that all the natural gas that was in the three pipelines was released into the atmosphere.[97]

The leaks were located in international waters and are thus unlikely to be reflected in any national emission inventories.

Black Sea offshore gas infrastructure

The Conflict and Environment Observatory (CEOBS) published a case study estimating GHG emissions from the damaged Black Sea gas infrastructure[98]. An attack resulting in heavy damages was reported on 20 June 2022, and the fire on one drilling platform was visible on satellite images for many months after the event.[99] The natural gas platforms were used for surveillance purposes by Russia and therefore were attacked and later recaptured by Ukraine with one of the platforms starting to burn during the combat events. According to the estimates made by CEOBS, uncontrolled gas flaring between June 2022 and November 2023 resulted in the combustion of 189.2 million m^3 of natural gas.

96. GHGSat measures its largest emission from a single source ever from Nord Stream 2 leak, https://www.ghgsat.com/en/newsroom/ghgsat-nordstream/
97. 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
98. Case study: Emissions from damaged Black Sea gas infrastructure, https://ceobs.org/ukraine-conflict-environmental-briefing-the-climate-crisis/#8
99. See examples of satellite images from August 2022, https://twitter.com/bradyafr/status/1561012683817865223, and December 2022, https://twitter.com/wammezz/status/1617496877468983296

The volume of natural gas has been estimated using the data collected at night by the VIIRS instrument and processed by special tools to define the temperature and radiant heat of the flare, which allows estimating the flaring volume. Since analysis is based on satellite data for cloudy days (32% of the time period), the linear interpolation between the nearest two good observations was applied. The conversion to flaring volume relies on the coefficients published in scientific literature, which results in significant uncertainty. Based on the range of coefficients, the flaring volume could be estimated at 164.1 to 193.7 million m^3 of natural gas.

The obtained results (approx. 325,000 m^3/day for the low-end estimate) are significantly higher than the reported well production capacities for the Black Sea wells (up to approx. 200,000 m^3/day). Though this could possibly be partly explained by the differences in standard operations and uncontrolled flaring, the result still indicates a significant level of uncertainty and requires further research.

Based, on CEOBS estimates, at least **0.34 million tonnes of CO_2e** have been released due to the natural gas flaring (the estimated range is 0.30-0.35 million tCO_2e). The actual climate impact could be even higher considering the incomplete combustion of natural gas, potential methane leakage, as well as the fact of continued natural gas flaring beyond November 2023, as no engineering solutions could be put in place to stop the gas flow and fire.

Apart from GHG emissions, the event has also resulted in water pollution in an environmentally sensitive area with a 7 km^2 oil slick visible on satellite images.

Onshore gas production and transportation infrastructure

During the two years of the war, there were dozens if not hundreds of cases of damage to gas transportation pipelines and gas distribution network. Emissions from such events depend on pipeline size and response measures undertaken. Emissions could be higher in case of damaging large high-pressure gas transportation pipelines affecting the long sections of the network. Typically, such damage is accompanied by fire, while methane is combusted into CO_2 emissions. Suspension of the flow as part of response measures limits the volume of gas lost to the amount held in the damaged section. Damage to small-diameter distribution networks results in lower volumes of natural gas losses though it could be also associated with methane leakage into the atmosphere when pipes are mechanically damaged but no gas ignition occurs causing a higher climate impact.

Though damage of natural gas infrastructure occurs frequently, there is no detailed inventory of such events available for our analysis. Still, information on previous accidents could predict the scale of potential emissions and factors influencing the scale of damage. For instance, a risk assessment study for a gas pipeline section with a diameter of 300 mm and pressure of 4.5 MPa at a section of 3 km, resulted in the estimated potential loss of 8,000 m^3 of natural gas in case of immediate closure of the flow, increasing to 20,000 m^3 for 30 minute response time and 55,000 m^3 for 80 minute response time.[100] There could be dozens of similar large-scale events during the war and hundreds of small-scale events. The response measures are typically slower during the war due to safety risks and other limitations causing higher natural gas losses.

An interactive map of potential cases of environmental damage from the warfare activities maintained by the Centre for Environmental Initiatives Ecoaction[101] with more than 1,600

100. Babadzhanova, O., Pavlyuk, Y., & Sukach, Y. (2019). ФАКТОРИ, ЩО ОБУМОВЛЮЮТЬ ПОЖЕЖНУ НЕБЕЗПЕКУ ЛІНІЙНОЇ ЧАСТИНИ МАГІСТРАЛЬНОГО ГАЗОПРОВОДУ. Пожежна безпека, 18, 27-34, https://journal.ldubgd.edu.ua/index.php/PB/article/view/1044

101. Ecoaction, https://ecoaction.org.ua/warmap.html

records contains at least 277 events that mention the damage to natural gas infrastructure. This includes damage to large-diameter high-pressure pipelines, small distribution networks, distribution units, gas processing plants, and other infrastructure. The information for the map is collected by volunteers based on the news and announcements of official authorities and certainly does not cover all the events leading to natural gas flaring or leaks.

Climate damage depends on the number of accidents, volume of natural gas losses, and proportion between natural gas combustion and leakage. For the purpose of initial assessment, the overall impact is assumed to be below **0.1 million tCO_2e**. Detailed data could be available after the war, as the Ministry of Energy of Ukraine has approved a special methodology for the estimation of natural gas losses as a result of warfare activities.[102] The methodology assumes the assessment of the volume of natural gas losses (leaks) after the damage of natural gas pipelines and other infrastructure due to warfare activities. Operators of natural gas distribution grids are expected to provide information to the Ministry of Energy of Ukraine on a monthly basis, including estimated volumes, information on warfare activities, confirmation of relation between the damage to natural gas infrastructure and warfare activities, duration of gas leakage and other details. The information, however, is not currently available and the data are unlikely to allow distinguishing natural gas losses caused by gas combustion and venting into the atmosphere.

Oil depots and oil refineries

From the first hours of the war, fuel storage facilities in Ukraine were under attack by Russian forces. Between the start of the large-scale war and the end of March 2022, at least 15 oil products storage facilities in different regions across Ukraine were attacked leading to large-scale fires.[103] Data on the damage of such attacks, as well as detailed information on further attacks during the two years of the war are not available. Still, only during a single event on 24 March 2022, when an oil depot in Kalynivka town near Kyiv was targeted, 22 tanks with oil products were affected and 5,800 tonnes of fuel burnt during the fire that lasted for 5 days.[104]

Attacks on fuel storage infrastructure continued. Two large-scale examples include an attack in June 2022 in the Dnipropetrovsk region, when oil products storage tanks with an overall capacity of almost 9,000 m^3 were destroyed,[105] and an attack in February 2024 in Kharkiv city, when oil tanks with a capacity of about 6,000 m^3 were affected.[106] In the latter case, 3,800 tonnes of fuel were reportedly stored and lost at the depot with more than 1 ha of land contaminated and fuel partly leaked into the nearby river (Nemyshlia River).[107]

As reported in our second assessment, GHG emissions from oil products that burnt as a result of rocket attacks were about 0.5 millions tCO_2e based on the data sourced from the EcoZagroza portal (the official platform of the Ministry of Environmental Protection and Natural Resources of Ukraine).[108] This is equivalent to about 144 thousand tonnes of fuel burnt or

102. Наказ Міністерства енергетики України від 11.07.2023 № 216 «Про затвердження Методики визначення вартості втрат (витоку) природного газу у разі пошкодження газопроводів та газорозподільних станцій, завданих Україні внаслідок збройної агресії Російської Федерації», https://zakon.rada.gov.ua/laws/show/z1555-23#Text

103. Аналітична довідка про пожежі та їх наслідки в Україні за 3 місяці 2022 року, https://idundcz.dsns.gov.ua/upload/6/2/1/7/8/8/XphKg30Ai9vGQwOfXkyehPgvP9FayYEVHyWC1P8F.pdf

104. Ecoaction volunteers recorded 1,500 cases of potential environmental damage from war. Is there a chance for recovery?, https://en.ecoaction.org.ua/1500-cases-environmental-damage-war.html

105. Аналітична довідка про пожежі та їх наслідки в Україні за 12 місяців 2022 року, https://idundcz.dsns.gov.ua/upload/1/6/0/8/6/7/7/analitychna-dovidka-pro-pojeji-122022.pdf

106. Аналітична довідка про пожежі та їх наслідки в Україні за 2 місяці 2024 року, https://idundcz.dsns.gov.ua/upload/2/0/6/1/9/6/1/analitychna-dovidka-pro-pojeji-022024.pdf

107. У Харкові через удар по нафтобазі забруднено 10 тис. кв м землі, https://www.pravda.com.ua/news/2024/02/12/7441556/

108. Climate damage caused by russia's war in Ukraine: 24 February 2022 – 23 February 2023, https://en.ecoaction.org.ua/climate-damage-by-russia-12-months.html

approximately 170,000 m^3 of fuel. As of 18 March 2024, the EcoZagroza portal[109] provides a figure of 723 thousand tonnes of oil and oil products burnt during the war. However, such estimate is in our view too high as the likely losses between the first and the second year would not be that different.

For the purpose of this assessment, we conservatively assume that 200,000 tonnes of fuel burnt due to the attacks on Ukrainian oil products storage facilities. The associated GHG emissions constitute 786,000 tCO_2e when accounting for both direct emissions from combustion and upstream emissions from fuel production (based on the emission factor for diesel fuel).

On the territory of Russia and occupied territories of Ukraine, at least several dozens of attacks on oil products storage facilities and oil refinery plants were reported during the first two years of the war. Detailed information on such events is provided in the Annex. Though information on the damage assessment in general and amount of fuel burnt in particular is limited, based on the data available from news reports it could be assumed that reservoirs with over 100,000 m^3 of fuel storage volume could have been destroyed or damaged during these events. During a single night in April 2024, fires at two fuel storage facilities reportedly destroyed 26,000 m^3 of fuel.[110] For the purpose of assessment, we use a value of 100,000 m^3 or 84,300 tonnes of fuel burnt as a result of attacks. The associated GHG emissions constitute about 331,000 CO_2e when accounting for both direct emissions from fuel combustion and upstream emissions from fuel production (based on emission factors for diesel fuel).

Total GHG emissions resulting from the attacks on oil depots and refineries amount to at least **1.1 million tCO_2e**.

SF_6 emissions from electric equipment

Electricity transmission networks rely on switchgear to protect electrical equipment against overload and short circuit currents (circuit breaking) as well as to interrupt the load current (load breaking). Sulphur hexafluoride, or SF_6, is used for high-voltage and medium-voltage switchgear for insulation (e.g. gas-insulated switchgear) and breaking (circuit breakers and load break switches) due to its unique characteristics (high electronegativity and density), but it also has the largest global warming potential of all GHG (GWP_{100} = 22,800). Even under normal conditions, emissions of SF_6 occur due to leaking (gas leaks can occur at flanges, fittings, seals, or other elements and new SF_6 needs to be added to maintain the required pressure) or poor gas handling practices during equipment installation (new closed-pressure switchgear is only partially filled with SF_6 and additional volume is added during installation to reach the required pressure), maintenance, and decommissioning. Fires or other catastrophic events can cause sudden and severe damage to equipment and SF_6 emissions.[111]

High-voltage and medium-voltage substations in Ukraine were among the priority targets during the intensive attacks on the energy system in the 2022-2023 autumn-winter period and some attacks were also reported later during 2023 and early 2024.

In Ukraine, SF_6 is used for transmission and distribution of electric power in switching systems and high-voltage equipment (50-380 kV), as well as in medium-voltage systems (10-50 kV). Under normal conditions, SF_6 emissions are relatively small but there was a steady growing trend from 9,700 tCO_2e in 2010 to 48,900 tCO_2e in 2021 due to an increased number of

109. https://ecozagroza.gov.ua/damage/air

110. Sources: SBU drone attack destroys 26,000 cubic meters of Russian fuel in Smolensk Oblast, https://kyivindependent.com/sources-sbu-drones-attack/

111. Overview of SF6 Emissions Sources and Reduction Options in Electric Power Systems, https://www.epa.gov/eps-partnership/overview-sf6-emissions-sources-and-reduction-options-electric-power-systems

gas-insulated high-voltage circuit breakers in operation in the electric networks in Ukraine. All SF_6 is imported to Ukraine in the volumes necessary for the production of its own gas-insulated equipment (about 20% — for transformers and gas-insulated switchgears), annual assembly and installation of new equipment, as well as repair and normal operation of the existing fleet of gas-insulated equipment (over 65%). As of late 2021, the total amount of SF_6 in operated gas-insulated equipment in Ukraine was 426 tonnes (mostly in the high-voltage equipment) and annual SF_6 emissions were estimated at 2.15 tonnes SF_6 or 48,940 tCO_2e. An emission factor of 0.5% (i.e. 0.5% of the gas contained in the system is assumed to be leaked during the year) is applied for the purpose of national inventory for both production and operation stages of gas-insulated equipment.[112]

Overall, there are 137 high-voltage substations in Ukraine and 445 transformers (110-750 kV).[113]

There is no information on SF_6 import volumes during the war or detailed results of damage assessment that could allow estimating SF_6 emissions during the war. Based on available reports, almost half of the high-voltage network facilities were damaged during the intensive attacks on the energy system of Ukraine.[114] Ukrenergo has also reported that during the 2022-2023 heating season, 1,200 missiles and drones were used to attack energy facilities, which resulted in the damage to the high-voltage infrastructure by 43%. At least 42 high-voltage transformers were destroyed and damaged and about 500 units of different equipment were supplied by international partners to support the recovery work.[115]

Though the level of damage could vary and there is no information on the damage specifically for the SF_6-insulated switching gear, we assume that at least 10% of SF_6 contained in the system could have been emitted during the attacks. This results in the emission of 42.6 tonnes of SF_6 or about **1 million tCO_2e**.

Overall emissions from energy infrastructure damage

The overall emissions from energy and fossil fuel infrastructure damage are estimated at **17.16 million tCO_2e**.

SOURCE OF EMISSIONS	$MtCO_2e$
Sabotage of the Nord Stream 1 & 2 pipelines	14.6
Gas flaring at the Black Sea gas platforms	0.34
Damage to natural gas transportation and distribution infrastructure	0.1
Attacks on oil depots and refineries	1.12
SF_6 emissions from electric equipment	1.0
TOTAL	**17.16**

Table 17. Total emissions from damaged and destroyed energy infrastructure

112. Ukraine's Greenhouse Gas Inventory 1990-2021 (2023), https://unfccc.int/documents/628276

113. Ukrenergo, https://ua.energy/infografika_nova/

114. Голова правління НЕК «Укренерго»: «Ми маємо для кожного об'єкта протокол реагування на обстріли і як відновлювати цей об'єкт», https://mind.ua/publications/20267506-golova-pravlinnya-nek-ukrenergo-mi-maemo-dlya-kozhnogo-obekta-protokol-reaguvannya-na-obstrili-i-yak

115. Ukrenergo, https://ua.energy/dlia_zmi/proon-ta-yaponiya-dostavyla-v-ukrayinu-potuzhni-avtotransformatory-z-metoyu-bezperebijnogo-energozabezpechennya-dlya-bilsh-nizh-piv-miljona-lyudej/ and https://i-visti.com/news/13010-v-ukrenergo-pdbili-pdsumki-nayvazhchogo-opalyuvalnogo-sezonu-v-storyi.html

3.4 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.

Since the previous update of this report, there have been no major further displacements due to the acts of war. Most IDPs and the majority of refugees seem to have settled in the places they have moved to. About 700,000 refugees have returned home.

In all of our reports, we have broken down emissions as a result of displacement in three main categories: transport emissions from Ukrainians fleeing out of Ukraine, transport emissions from internal displacement, and emissions from displacement of Russians leaving Russia to avoid draft into the military, prosecution, or for other reasons.

Refugees

Data on refugees have been drawn from UNHCR.[116] The total number of refugees from Ukraine in Europe amounted to 5.9 million by mid-April 2024, compared to 6.6 million by the end of March 2023. The number of registered refugees have decreased by approximately 700,000, suggesting people have returned home. We have assumed these 700,000 people have moved back home and further added the emissions of their return travel to the emissions as a result of displacement. Applying the earlier assumptions regarding travel modes, empty return transport, and home visits, emissions related to movements of refugees have amounted to 2.77 million tCO_2e.

IDPs

Data on IDPs have been collected by the International Organization for Migration (IOM), a UN body, through its Displacement Tracking Matrix (DTM).[117] By June 2023, the DTM reported 5.088 million IDPs in Ukraine in addition to 4.757 million returnees. The number of 5 million IDPs in 2023 was confirmed by the Kyiv School of Economics in July 2023, quoting the Ministry of Social Policy in Ukraine.[118] Hence, for transport movements of IDPs, we have assumed a total of 9.845 outbound movements and 4.757 million return movements, a total of 14,602,000 movements. We estimate an average movement to be 400 km, with an emission of 40.9 gCO_2e/pass km, as per our initial estimates resulting in emissions related to the movements of IDPs amounting to 0.24 million tCO_2e.

Russians

Russians leaving Russia are not tracked by either of the two UN organisations, the UNHCR or the IOM. An article on Wikipedia[119] reports a total of 900,000 individuals having left Russia until October 2022, quoting a variety of sources. Russians have left for a/o Turkey, Georgia, Armenia, Serbia, Kazakhstan, the United Arab Emirates, Finland, and many other countries. While no exact numbers are available on the distribution between different countries, we

116. See https://data.unhcr.org/en/situations/ukraine

117. See https://dtm.iom.int/ukraine

118. Report on damages and losses to infrastructure from the destruction caused by Russia's military aggression against Ukraine as of June 2023; Kyiv School of Economics (July 2023). https://kse.ua/wp-content/uploads/2023/09/June_Damages_ENG_-Report.pdf

119. See https://en.wikipedia.org/wiki/Russian_emigration_following_the_Russian_invasion_of_Ukraine

estimate the emissions conservatively by assuming 700,000 of them left by airplane over a distance of 4,000 km (representing an average of trips from Moscow to Antalya (Turkey), Belgrade (Serbia), Almaty (Kazakhstan), and Dubai (UAE)), while 200,000 individuals left by a 4-person car over a distance of 2,500 km (representing trips from Moscow to Tbilisi (Georgia), Yerevan (Armenia), or Astana (Kazakhstan). Resulting emissions amount to 0.25 million tCO_2e.

Total refugees and IDPs emissions

SOURCE OF EMISSIONS	GHG emissions ($MtCO_2e$)
International refugees from Ukraine	0.77
Transport returning empty to Ukraine	0.77
Refugees in Europe visiting Ukraine	1.24
Internal Displaced Persons in Ukraine	0.24
Russians leaving Russia	0.25
TOTAL	**3.27**

Table 18. Overview of transport emissions from refugees, IDPs and Russians

Please see the annex for more details regarding the calculation methodology.

3.5 Aviation

Russia's war in Ukraine has had a significant impact on aviation. The closure of Ukraine's airspace to commercial traffic and 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 resulting in longer flight times, as well as added fuel costs and higher GHG 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 has 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.[120]

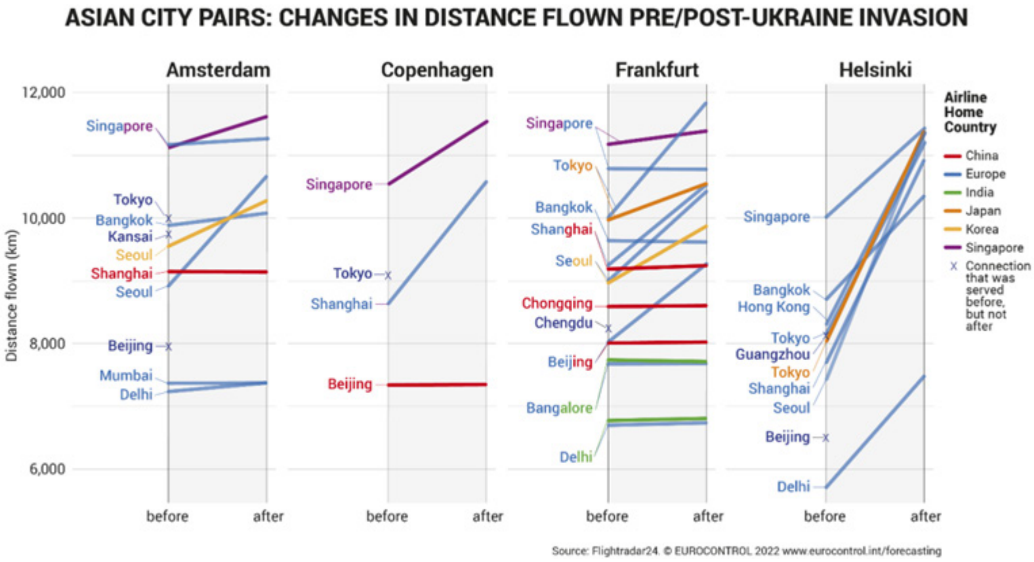


Figure 15.Asian City Pairs: Changes in distance flown pre/post-Ukraine invasion

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, which is not the case for China Airlines still using the Russian airspace.

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

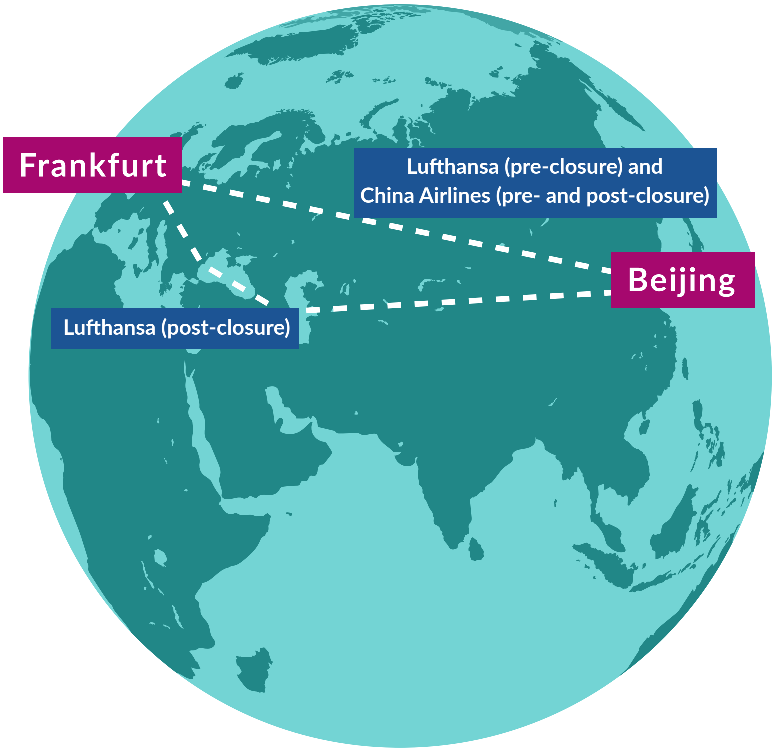


Figure 16. The flight path between Frankfurt and Beijing for China Airlines and Lufthansa. Source: FlightRadar24

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.[121] 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.[122]

Figure 17. Flying route from London to Tokyo

121. Eurocontrol data snapshot, 23 March 2022, https://www.eurocontrol.int/publication/eurocontrol-data-snapshot-28-how-re-routing-around-ukraine-disrupting-traffic-flows

122. Airlines chart new paths to avoid Russian airspace, https://www.pointhacks.com.au/news/airlines-avoid-russian-airspace/

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.[123] 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 has been extended by at least 1,800 miles and four flight hours, taking the flight in the opposite north-eastern 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.[124] The impact has been also felt with regard to intra-European flights. The 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 managed 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 their 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.[125] 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.

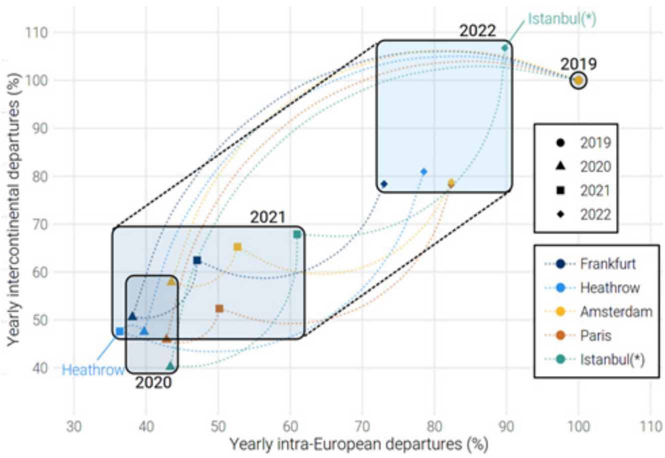


Figure 18. Path to recovery for the top 5 airports (in 2019)

123. Japanese Airlines Cancel, Reroute Flights Scheduled to Fly Over Russia, 3 March 2022, https://www.travelpulse.com/News/Airlines-Airports/Japanese-Airlines-Cancel-Reroute-Flights-Scheduled-to-Fly-Over-Russia

124. Ibid.

125. 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

Some of the European data also show the potential redirection of passenger flows. For example, the number of yearly intercontinental departures from Istanbul grew disproportionately in 2022 compared to other European hubs.[126]

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%.[127] 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 CO_2 emissions assigned to each state as per ICAO rules when compared to 2019 data.[128] The data demonstrate 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.

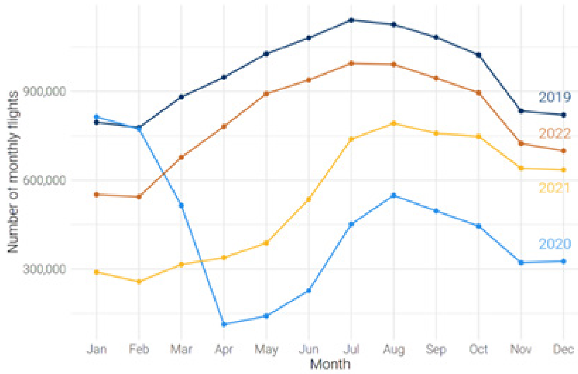


Figure 19. Network traffic as monitored in the Eurocontrol member states

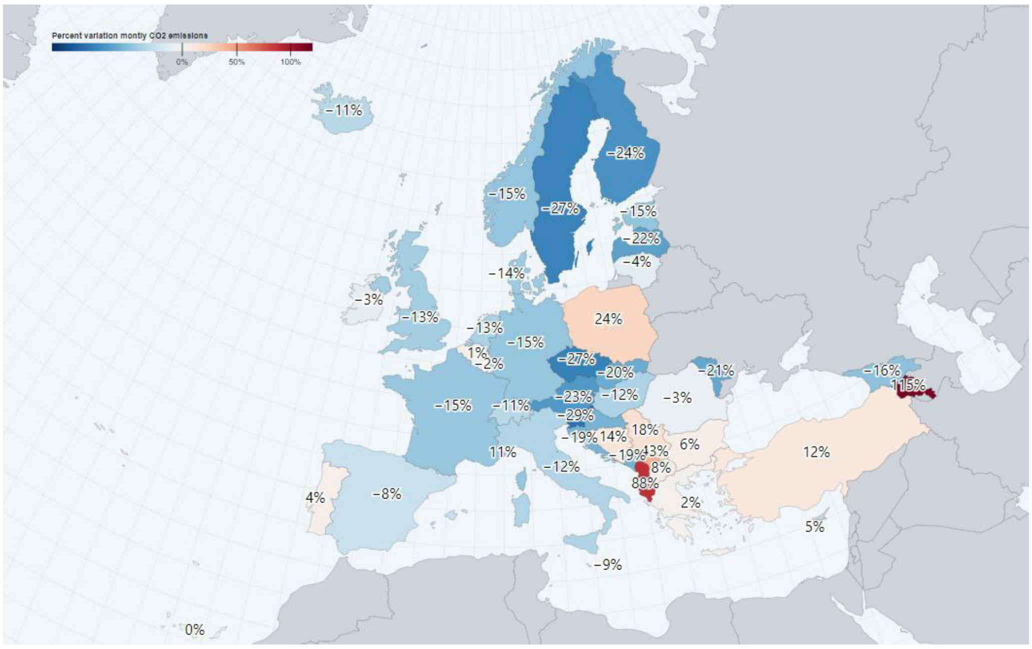


Figure 20. Percent variations in monthly CO_2 emissions, March 2021 to April 2023

126. Eurocontrol data snapshot, 18 January 2023, https://www.eurocontrol.int/publication/eurocontrol-data-snapshot-28-how-re-routing-around-ukraine-disrupting-traffic-flows

127. Eurocontrol data snapshot, 23 March 2022, https://www.eurocontrol.int/publication/eurocontrol-data-snapshot-28-how-re-routing-around-ukraine-disrupting-traffic-flows

128. Euroconrol, accessed May 2023, https://ansperformance.eu/efficiency/emissions/

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_2 (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 the improvements in aircraft and flight efficiency.

Nonetheless, if air traffic intensity is assumed to be constant between 2021, 2022, and 2023, the incremental increase that could be potentially attributed to re-routings, among other factors, over the period of 24 February 2022 to 23 February 2024 could reach just over **24 million tCO_2**, based on the Eurocontrol data.[129]

129. This number only reflects carbon dioxide and no other GHG. Also, non-CO_2 impacts (e.g. radiative forcing by contrails) have not been taken into account

3.6 Reconstruction

Destroyed or damaged civilian infrastructure is an important component of the climate damage caused by Russia's war in Ukraine. Many buildings, like apartment blocks, hospitals, kindergartens, and commercial and industrial buildings, have been damaged or destroyed. Utilities, roads, vehicles, and industries suffered significant damage.

Some of the reconstruction works are already happening, mainly in the liberated areas north of Kyiv, east of Kharkiv, or in Kherson region. The majority of rebuilding or reconstructing efforts, mainly in the eastern and southern parts of the country, will happen only after the end of the hostilities when a secure environment can be guaranteed.

From the beginning of the full-scale invasion, Ukrainian volunteers and authorities started to collect and assess, in a systematic way, information about the damaged or destroyed facilities, including the destruction of assets and infrastructure in those territories that where occupied after 24 February 2022. The Kyiv School of Economics (KSE) is aggregating this information coming from different Ukrainian ministries, other governmental sources, or from open sources. Where information is not available or restricted due to security reasons, KSE uses estimations to provide a comprehensive picture. Their overall damage assessment has been carried out in accordance with the methodology of the World Bank with monetary damages representing the replacement value. The KSE report is the basis for our estimations.

For this fourth assessment, we have used the KSE report on damage and losses assessment for the period of 24 February 2022 – 31 December 2023.[130] This reporting period is shorter than ours (which runs until 23 February 2024), but since there has not much additional damage in that period, there will only be a slight underreporting of reconstruction emissions.

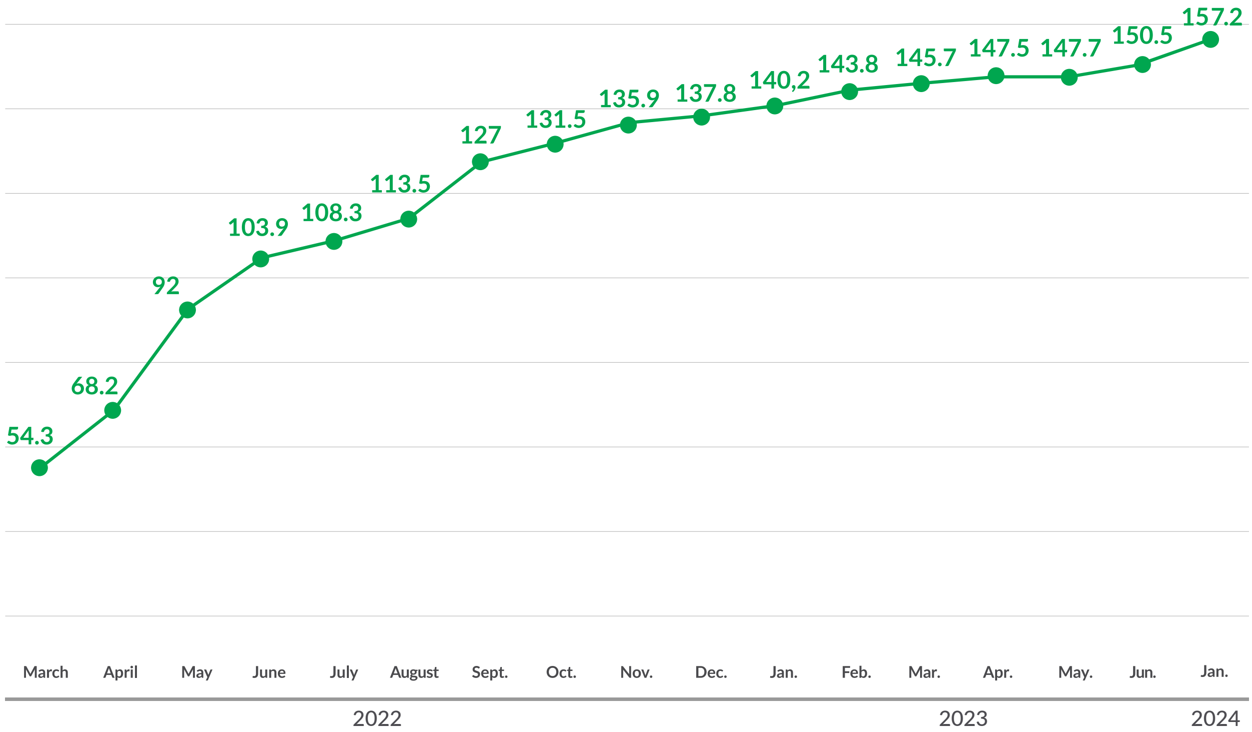


Figure 21. Dynamics of the aggregate assessment of direct damages to Ukraine's infrastructure. Source: KSE

130. Report on damages and losses to infrastructure from the destruction caused by Russia's military aggression against Ukraine as of the beginning of 2024, https://kse.ua/wp-content/uploads/2024/05/Eng_01.01.24_Damages_Report.pdf

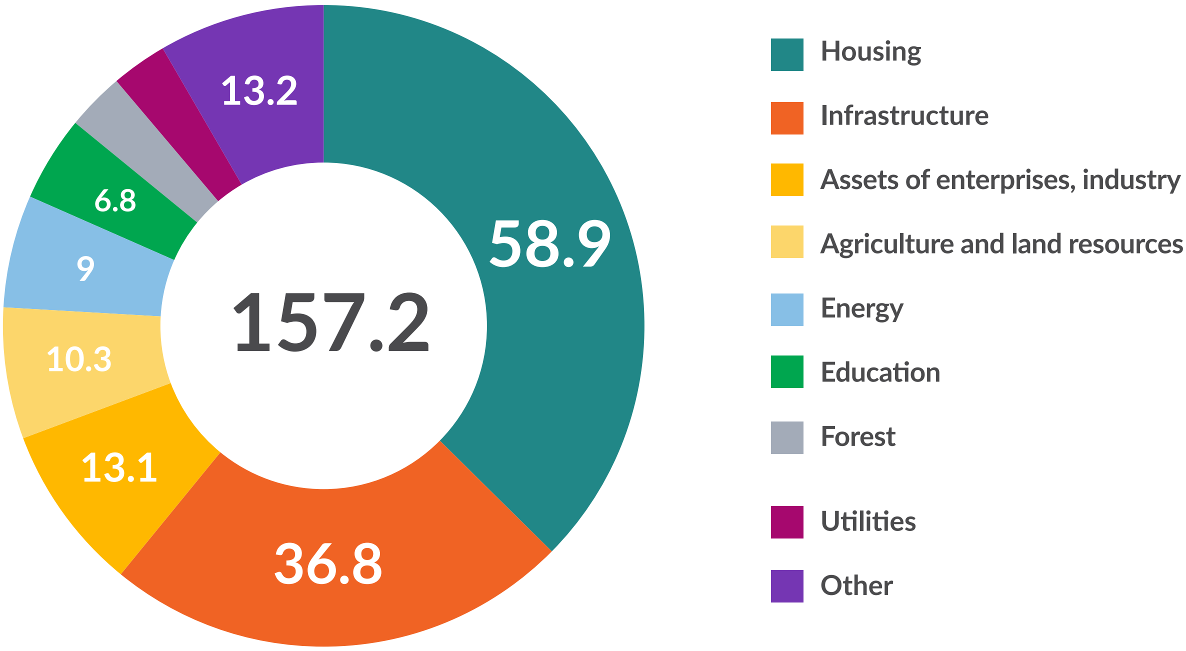


Figure 22. Direct damages by type of property, billion USD

The largest damage in monetary terms was faced by the residential sector (housing) followed by infrastructure. Most damage was done during the first four months of the war, while in the following 20 month period, the growing rate of damages decreased, as shown in the figure above. This is mainly caused by the fact that the frontlines have hardly moved and, where objects were located close to the frontlines, many objects had already been destroyed during the first months.

For example, below is a list of the residential sector units (housing stock) that existed in Ukraine before the war (first column), of which some unis were either damaged (second column) or destroyed (third column). Similar lists are provided for each type of property. The damage caused by the destruction of the Nova Kakhovka dam in June 2023 was assessed in more detail (fourth column).

	Stock (units)	Destroyed (units)	Damaged (units)	Damaged following the Kakhovka Dam destruction
Apartment buildings	180,003	6,862	19,276	1,001
Private houses	9,163,897	66,693	118,480	35,426
Dormitories	7,114	135	390	1

Table 19. Overview of residential housing available before the war (stock) and units destroyed or damaged during the 24 months of war

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

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

- The first category, Buildings, comprises residential sector, health care, social sector, education and science, culture, religion, sports, tourism, and retail. These objects mainly include buildings.
- The second category, Transport & Infrastructure, 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, Industry & Utilities, comprises the energy sector, industry and business services, digital infrastructure, and utilities. These objects mainly include machinery and equipment combined with buildings (factories) 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 and would have happened in the destroyed buildings as well.

For the category of Buildings, the embodied carbon is based on the average buildings' areas, data on which were provided by the Kyiv School of Economics[131]. For each type of building (e.g. apartment buildings or schools), 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 & Infrastructure, embodied carbon factors were considered for different types of objects, like tCO_2e/km of a damaged road or tCO_2e of a damaged car, using public sources.

For the category of Industry & 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).

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 100% of the embodied or spend-based emission factor is therefore applied. For damaged property, a generic factor of 33% was applied to the embodied carbon factor unless a pro rata adjustment could be derived from replacement value for destroyed and damaged property.

131. Many objects are in the occupied territory or close to the frontline and therefore cannot be inspected. Revision of the methodology in subsequent assessments by KSE led to a reduction of average areas, in particular in the housing and educational sector. As a consequence, reconstruction emissions have been adjusted accordingly.

The results over the 24 months of the war are provided in the table and graph below.

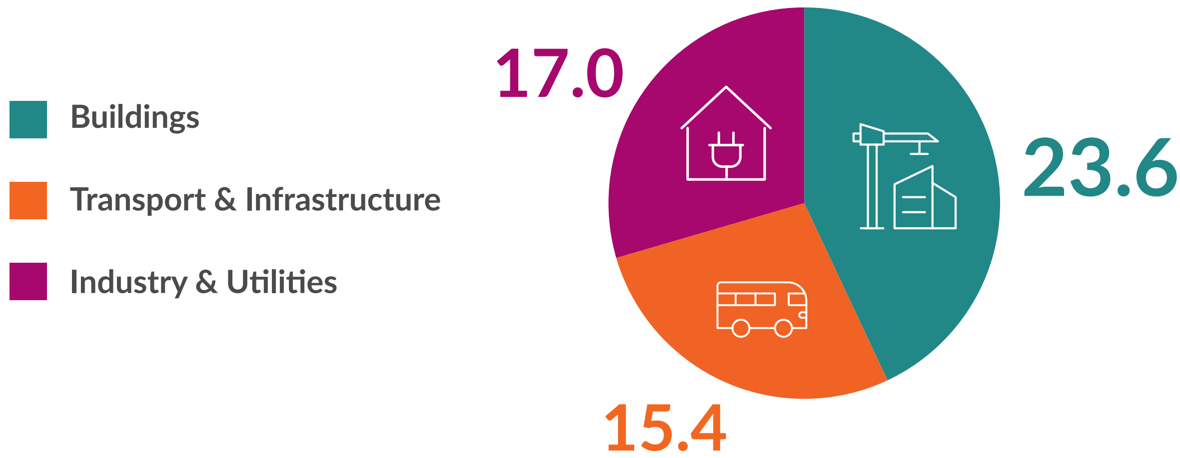


Figure 23. Distribution of emissions from civilian infrastructure reconstruction by category ($MtCO_2e$)

CATEGORY	EMISSIONS ($MtCO_2e$)	PERCENTAGE (%)
Buildings	23.6	42%
Transport & Infrastructure	15.4	27%
Industry & Utilities	17.0	30%
TOTAL	**56.0**	**100%**

Table 20. Overview of emissions from civilian infrastructure reconstruction

ANNEX:

Methodological components

Table of Contents. Annex

A1. Warfare

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).

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
– end of May 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

7 PHASE

End of May, 2023 –
August, 2023

UKRAINE'S COUNTER-OFFENSIVE

Beginning of counteroffensive operations on the south of Ukraine with gradual restoration of control over some areas. Intensive fighting on the frontlines and destruction of logistic hubs, artillery, and air defence systems by the Ukrainian army. Relatively high losses of equipment by both parties. Shelling, bombing, and missile attacks on Ukrainian settlements, especially, cities and villages near the frontlines.

CLIMATE IMPACT

8
PHASE

September 2023 – February 2024

NEW RUSSIAN OFFENSIVE OPERATIONS

Intensification of offensive operations by Russia with the aim to occupy additional lands in Donetsk region and regain territories liberated during the summer counter-offensive. Regaining control over the large share of the Black Sea territorial waters by Ukraine and starting cargo transportation via temporary corridors. Intensive missile and drone attacks during winter

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[132] arrived at an astonishingly high estimate of the global military carbon footprint equal to 2,750 million tCO_2e or 5.5% of total global emissions. This figure includes operational emissions equal to 500 million tCO_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,[133] for instance, the life cycle GHG 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).

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. [134]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 the 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.

132. 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

133. 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

134. The environmental impacts of the UK military sector, https://www.sgr.org.uk/publications/environmental- impacts-uk-military-sector

For the European Union, the carbon footprint of military expenditure in 2019 was estimated at approximately 24.8 million tCO_2e.[135] 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 of financial years 2001-2018 were 1,267 million tCO_2e. The emissions from overseas contingency operations (war-related emissions from 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.[136] The average annual value over this 18 year 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[137] 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.[138]

135. 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

136. 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

137. 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 was about 7 billion tCO_2e

138. 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

How much fuel is used? Different approaches to the estimation of warfare-related fuel consumption

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 south-western part of the country (Bryansk, Belgorod, Voronezh, Kursk, Rostov, Krasnodar, and Smolensk), as well as occupied Crimea.[139]

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.[140]

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 2022.[141]

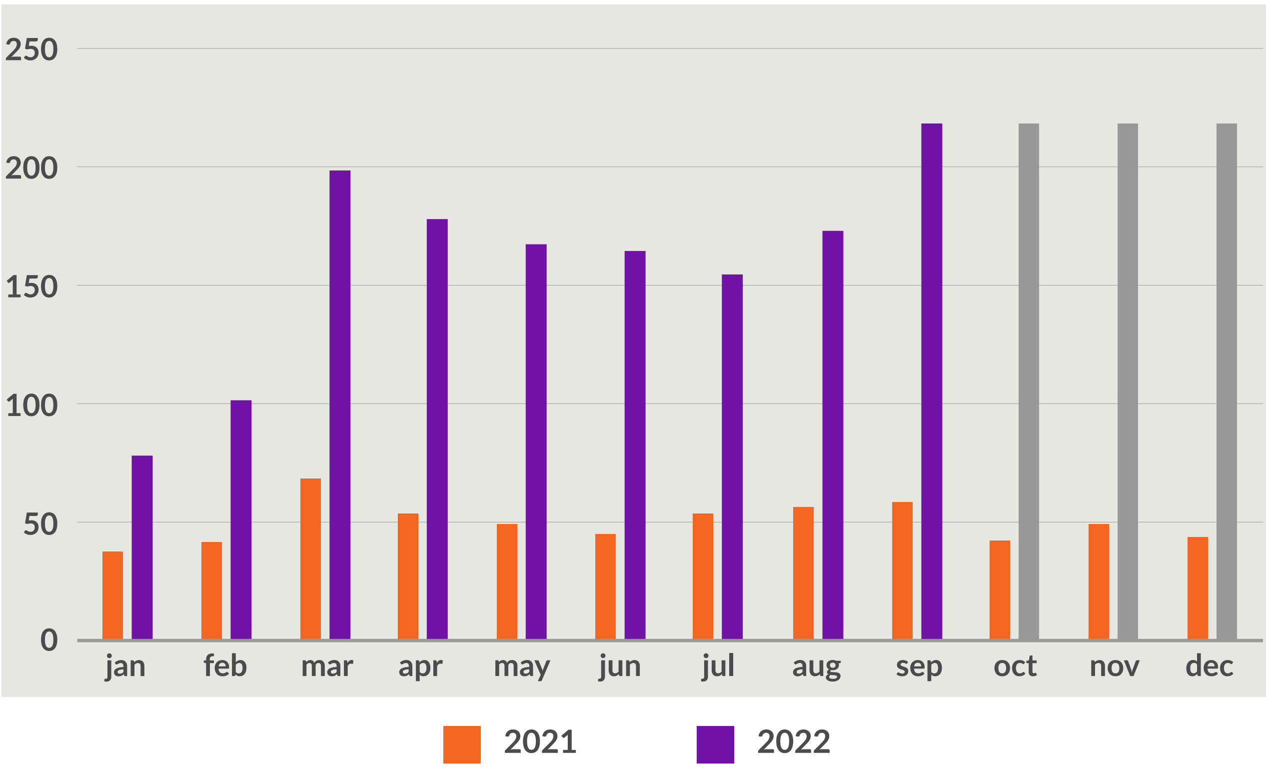


Figure 24. Increase in fuel supply to the regions bordering Ukraine, by months, 1,000 t

139. Russia Boosts Flow of Fuel to Troops at Border, https://www.energyintel.com/0000017f-0ebd-dfa7-a5ff-9fbf3c920000

140. 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

141. Supply in Q4 2022 is assumed based on the data for September and marked grey; this is a conservative estimate taking into account mobilisation 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 of 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 (difference between 2022 and 2021)	966
Estimated additional fuel supply by railway during 2022 (difference between 2022 and 2021 assuming that fuel supply during October-December was the same as during September 2022)	1,483
Assumed fuel supply via other routes	30%
Estimated total fuel consumption due to the war in 2022	1,927
Assumed additional monthly fuel supply for warfare activities applied for further periods (January 2023 – February 2024) estimated as an assumed increase in railway supply during September-December 2022 and a 30% additional supply by other routes	220
Estimated total fuel consumption due to the war – up to February 2024	5,004

Table 21. 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 of increased fuel supply for September-December 2022 (220 kt of additional fuel supply per month via different routes) have been extrapolated to the months of 2023 and 2024. Fuel consumption for the two years of the war using a supply-based approach is estimated at 5 million tonnes. The results of this approach are used as a lower end of the range of potential fuel consumption during the warfare by Russian forces.

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 mechanisation 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.[142] Other reports put estimated daily fuel consumption at 16[143] and 27.3[144] 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[145] 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 mobilisation announced in September 2022.[146] By September 2023, the number of personnel in occupational forces has increased to 420,000[147] and then further grew to 470,000 soldiers by February 2024.[148] Despite taking significant casualties, the Russian Group of Forces was nevertheless growing in size during the second year of the war.[149]

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 values of 190,000 soldiers for the first year of the war and 326,000 soldiers for the second year have been applied. The value of 83.3 litres of fuel per soldier per day has been used. As of the end of February 2024, the estimated amount of fuel consumption using this approach was 12.9 million tonnes.

The results of this approach are used as a higher end of the range of potential fuel consumption during the warfare by Russian forces.

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 8.9 million tonnes of fuel during the 24 months of the war (372 kt of fuel per month or an equivalent to 4.5 million tonnes of annual fuel consumption).

Data	Based on fuel supply estimates	Based on manpower estimates	Average
Fuel consumption during the two years of the war, Mt	5.0	12.9	8.9

Table 22. Fuel consumption estimates

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

142. Deloitte, Energy Security. America's Best Defense, https://legacy-assets.eenews.net/features/documents/2009/11/11/document_gw_02.pdf
143. The World's Biggest Fuel Consumer, https://www.forbes.com/2008/06/05/mileage-military-vehicles-tech-logistics08-cz_ph_0605fuel.html
144. U.S. military in Iraq feels gouge of fuel costs, https://www.nbcnews.com/id/wbna23922063
145. 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/
146. 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
147. В Україні перебуває понад 420 тисяч російських окупантів – ГУР, https://www.pravda.com.ua/news/2023/09/10/7419172/
148. Характер дій РФ з гучною назвою "наступи" передбачає затяжну війну, і це противник намагається нам нав'язати, жертвуючи величезною кількістю своїх людей - заступник начальника ГУР МО, https://interfax.com.ua/news/interview/968704.html
149. Russian Military Objectives and Capacity in Ukraine Through 2024, https://www.rusi.org/explore-our-research/publications/commentary/russian-military-objectives-and-capacity-ukraine-through-2024

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 2.8 times higher than Ukrainian ones.[150]

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.[151] 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.

NIR category 1.A.5.b – Other (mobile combustion)	Emissions, 1000 tCO_2e	Fuel use, TJ	Fuel use, 1000 t
2020	448.03	6,159.43	140
2021	383.15	5,273.48	120

Table 23. Ukraine's National Inventory Report (NIR) data for 2020-2021

The data for 2022 would be available only in the second half of 2024, but pre-war data indicate annual fuel consumption in the range of 120-140 thousand tonnes.

Fuel procurement data could serve as an additional source of information on fuel consumption. Though there could be some discrepancies between the time of procurement and time of use, they give a good indication of the overall fuel demand and fuel needs structure. According to the study of the Defence Procurement Reform Project, there was a significant decline in fuel procurement volumes in 2021 due to delays and unsuccessful tenders, with the total volume dropping from 204 to 89 thousand tonnes in 2020 and 2021 respectively. [152]The total sum of tenders conducted reached only UAH 2.65 billion compared to the initial planned volume of UAH 5.06 billion. Based on the actual average cost of the fuel procured and initial plans on procurement volumes in monetary terms, the planned volume was around 170 thousand tonnes or much closer to the 2020 volumes. Diesel and jet fuel have the largest share in overall fuel consumption, while the share of petrol is about 15%.

Fuel type	2021	2022
Petrol, t	25,726	18,937
Diesel, t	119,250	24,230
Jet fuel, t	59,320	46,230
Total, t	**204,296**	**89,397**
Total per month, t	**17,025**	**7,450**

Table 24. Fuel procurement data during 2020-2021
(Source: Defence Procurement Reform Project)

150. According to OSINT sources, as of 14 April 2024, Russia has lost 15,400 units of equipment and Ukraine has lost 5,556 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

151. Ukraine. 2022 National Inventory Report (NIR), https://unfccc.int/documents/476868

152. Підсумкове аналітичне дослідження про стан закупівель Міністерства оборони України та сектору безпеки і оборони за період 01.01. - 31.12.2021 року, https://drive.google.com/file/d/1Tuj7QaV2pxJ8wrokpn0iZGpltwonjT26/view

Though the estimates vary in different sources and due to different reasons, indicative pre-war military fuel consumption could be assumed at the level of about 150 thousand tonnes per year.

Since the beginning of the war in February 2022, consumption of fuel for military purposes in Ukraine has increased significantly, both directly by the military and by various civilian vehicles supporting military activities (e.g. transportation of vehicles and other supplies to the frontlines by thousands of volunteers), logistics, and other needs.

Fuel procurement data during the war are limited and fuel for military needs could be purchased by various entities, including the Ministry of Defence of Ukraine, various military units, regional state administrations, businesses, volunteers, etc.

Starting from the end of 2023, the procurement system became more centralised, as the procurement agency of the Ministry of Defence of Ukraine "State Logistics Operator" started active operation. In January-February 2024, it conducted tenders for the supply of almost 100,000 of fuel[153], including:

- 73,867 tonnes of diesel fuel (75% of the total),
- 15,402 tonnes of petrol (16% of the total), and
- 8,910 tonnes of jet fuel (9% of the total).

Though the fuel was expected to be supplied in March 2024, it is not known for which period these volumes were expected to cover demand.

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 per year (100 thousand tonnes per month). This represents an eightfold increase compared to the indicative pre-war fuel consumption volumes, which could be assumed reasonable taking into account active hostilities and mobilisation of defence forces. For comparison, in 2022 Ukraine imported 7.3 million tonnes of oil products[154] (assumed annual fuel consumption represents 16% of oil products import).

Overall fuel consumption during the 24 months of the war is estimated at **2.4 million tonnes**. Ukrainian fuel consumption could be likely verified after the end of the war.

153. See reports at https://statewatch.org.ua/publications/strong-za-sichen-2024-roku-dot-uklav-22-kontrakty-naybilshyy-z-iakykh-na-zakupivliu-palyva-na-3-25-mlrd-hrn-monitorynh-analitychnoho-tsentru-statewatch-strong/, https://statewatch.org.ua/publications/strong-monitorynh-zakupivel-dot-za-period-z-19-23-liutoho-strong/, https://prozorro.gov.ua/tender/UA-2023-12-22-020921-a?lot_id=825234c8566943feb7a743ea9cdd3757#lots, https://prozorro.gov.ua/tender/UA-2023-12-22-020760-a?lot_id=fade02d-fb4b749cdb50e4268cef21733, https://prozorro.gov.ua/tender/UA-2024-02-19-013742-a?lot_id=7ef42747684c40d6865e4affe-ae199e2#lots

154. Україна у січні скоротила імпорт нафтопродуктів та вугілля, https://ua-energy.org/uk/posts/ukraina-u-sichni-skorotyla-import-naftoproduktiv-ta-vuhillia

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 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 and validate the feasibility of assumed fuel consumption volumes.

Fuel consumption by aviation

Aviation is often considered as a main single fuel consumer in the course of 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,[155] 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", 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, the 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 a minimum of 96 sorties per day. Apart from 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 frontlines during the Russian offensive in Donbas between April and July 2023, and in defensive operations against Ukrainian counter-offensives in Kherson and Kharkiv since September 2023.

Based on other sources, the number of sorties during the initial stages of the war was even higher and reached 200[156] – 300[157] sorties per day but reduced to dozens missions per day by the end of 2022. In July 2022, the Air Force Command of the UA Armed Forces reported that the number of sorties of Russia's operational and tactical aviation has exceeded 6,400[158]

155. 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

156. 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/

157. Defence Intelligence, https://twitter.com/DefenceHQ/status/1599656741381328896

158. 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/

(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.[159] For comparison, Ukrainian aviation conducted 5-10 sorties per day[160] at the beginning of the war, while during the first year of the war fighter jets conducted over 5,300 sorties[161] (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.[162] In 2023 (as of 28 April), additional 132 missiles were launched by strategic bombers during the five waves of attacks,[163] bringing the total number to 956 missiles. The number of launches per sortie depends on the type of strategic bomber involved, types of missiles used, weapon load on board, and other factors (e.g. Tu-95MS can carry six or eight missiles depending on their type[164]). The number of launches, however, could be significantly lower than the maximum carrying capacity. For instance, during the attack on 9 March 2023, 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.

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 tempo- rary bases from the long-range precision artillery strikes (at 100+ km)[165]
Specific fuel consumption[166]	5.6 l 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 25. Information on assumed aviation activity data and estimated fuel consumption[167]

159. 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
160. 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/
161. Force Command of UA Armed Forces, https://www.facebook.com/kpszsu/posts/pfbid0Yu8ga2bNGzkVmqDA5Co5YMxa2qViwncJH-8FBB1jrNZEfwfXxNFRmSGiCfRezVUwGl
162. See the infographic shared by the Minister of Defence, https://twitter.com/oleksiireznikov/status/1611449870040109058
163. See https://twitter.com/MassDara/status/1634300311744438272 for the estimates as of 10 March 2023. On 28 April, 23 missiles were launched
164. 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
165. See, for instance, the geolocation of firing points of Mi-28 helicopters operating near Donetsk city and basing in Tahanrog city (100+ km), https://twitter.com/RedIntelPanda/status/1678936580965187584
166. 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)
167. All assumptions are indicative to demonstrate potential fuel consumption volumes

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

Fuel consumption by ground-based equipment

The majority of fuel is consumed by ground forces; however, it is very difficult to determine a 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.[168] 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 initial stages of the war were organised 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.[169]

Typical BTG structures provide a lower number of equipment and vehicles operated by a 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.[170] Fuel carried by a BTG is expected to be sufficient for one resupply round and support of one day of combat operations. Russian logistic channels must supply fuel to over 100 BTGs in addition to a number of paramilitary groups.[171] Fuel is consumed in large quantities during combat marches conducted by

168. 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.

169. Getting to Know the Russian Battalion Tactical Group, https://rusi.org/explore-our-research/publications/commentary/getting-know-russian-battalion-tactical-group

170. See 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

171. 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

BTGs and manoeuvring in the course of offensive and defensive operations (e.g. envelopment, encirclement, breakthrough, frontal attack, and evasive movement).[172]

DATA	1 BTG	100 BTGS	150 BTGS
Fuel in fuel tankers, t[173]	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 26. Estimated fuel consumption by BTGs[174]

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[175] 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.[176]

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.[177]

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.[178] 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.

172. 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

173. 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

174. All assumptions are indicative to demonstrate potential fuel consumption volumes

175. Nicolas J. Fiore, Defeating the Russian Battalion Tactical Group, https://www.benning.army.mil/ArmoreARMOR/content/issues/2017/Spring/ARMOR%20Spring%202017%20edition.pdf

176. 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

177. 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.

178. 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

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 27. Fuel use efficiency for some typical military equipment [179]

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.[180] 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 have grown to almost three quarters of the active ground forces.[181],[182]

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".

Assuming that BTGs involved in the war could require about 1 million tonnes of fuel per year, the total fuel consumption would be 4 million tonnes, which is broadly in line with the average estimate of annual fuel consumption by Russian forces (i.e. 4.5 million tonnes). Though the bottom-up assessment is focused only on indicative figures, it demonstrates the feasibility of the estimates derived using the fuel supply data and number of personnel involved.

Emissions from long-distance arms deliveries

Long-distance supply of military aid, especially when reliant on air transport, creates additional fuel demand and GHG emissions, which are not accounted for in the estimation of warfare-related fuel consumption described above.

Western partners of Ukraine have delivered more than 150,000 tonnes of various military material to Ukraine by the end of May 2023 with reported total value of almost USD 75 billion at that time. Equipment has been delivered from nearly 50 different countries and lightweight munitions sent at the start of the war have given way to more heavy equipment, such as tanks,

179. 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

180. 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

181. 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/

182. 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

MLRS, artillery, etc.[183] Since that time, the monetary value of military aid provided to Ukraine increased by about 50% and amounted to almost USD 96 billion as of September 2023[184] and USD 112 billion as of January 2024.[185] Thus, the estimated arms delivery could have increased to about 220,000 tonnes. There is no information on the amount of equipment supplied by each particular country and delivery routes, though the main partners disclose a detailed list of equipment provided.[186] Most significant volumes of arms were provided by the United States.

Supply of various military equipment from different locations across the globe is a complicated logistic task, which could involve different types of transport and different routes; hence, special units were formed to coordinate this work.[187]

At the beginning of the war, military aid consisted mainly of smaller equipment, such as small arms munitions and anti-tank equipment, and was delivered predominantly by air. Later, military aid started to increasingly include heavy equipment — first, older Soviet systems from various countries and then, more modern Western systems. At this stage, sea transportation was also involved in the delivery of military aid to Ukraine via Poland and other countries. Air transport has been used not only for transatlantic deliveries but also for some deliveries within Europe.[188] Railway transport has been actively used to deliver cargo from ports to the border of Ukraine as well as for cargo transportation within Europe and from Western Ukrainian borders to the battlefield, training grounds, or other locations.

The choice of delivery method for the transatlantic route (i.e. via cargo plane or by ship) typically depends on how urgent the supply of cargo is. Cargo planes (e.g. military cargo planes like C-17s or contracted civil planes like Boeing 747s) offer the fastest delivery option but they also incur the highest costs. The preference, whenever possible, is given to cargo ships as a less expensive option.[189] Still, very significant volumes have been delivered by air. At the initial stages of the war, roughly 8 to 10 flights full of supplies and equipment for Ukraine are landing in Eastern Europe daily.[190] As of July 2022, more than 800 flights have transported equipment to the Ukrainian border covering the distance of over 1.4 million kilometres of airspace.[191]

Of course, not all equipment provided by the US, for instance, has been physically transported from the US to Ukraine, as some equipment could have been available in Europe while other collected from different countries around the globe. At the same time, there could be additional flights within the US and to other countries to collect different equipment for further delivery.

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183. Russia recruited operatives online to target weapons crossing Poland, https://www.washingtonpost.com/world/2023/08/18/ukraine-weapons-sabotage-gru-poland/

184. How Much Aid Has the U.S. Sent Ukraine? Here Are Six Charts, Last updated on September, 21, 2023, https://www.cfr.org/article/how-much-aid-has-us-sent-ukraine-here-are-six-charts

185. Ukraine Support Tracker of the Kiel Institute for the World Economy (Data on reported military aid bilateral commitments converted to USD), https://www.ifw-kiel.de/topics/war-against-ukraine/ukraine-support-tracker/

186. Germany – Military support of Ukraine, https://www.bundesregierung.de/breg-en/news/military-support-ukraine-2054992; Research Briefing "Military assistance to Ukraine since the Russian invasion" Published 4 October, 2023, https://commonslibrary.parliament.uk/research-briefings/cbp-9477/; US - U.S. Security Cooperation with Ukraine, https://www.state.gov/u-s-security-cooperation-with-ukraine/

187. Inside the multinational logistics cell coordinating military aid for Ukraine, https://www.defensenews.com/global/europe/2022/07/21/inside-the-multinational-logistics-cell-coordinating-military-aid-for-ukraine/

188. See the examples of reports on military aid delivery from Spain https://babel.ua/en/news/84361-spain-sent-five-planes-with-ammunition-for-large-caliber-artillery-to-ukraine; and Italy, https://www.itamilradar.com/2023/07/16/italian-military-aid-to-ukraine-by-air-in-the-first-half-of-july/

189. How a Military Base in Illinois Helps Keep Weapons Flowing to Ukraine, https://www.nytimes.com/2022/07/03/us/ukraine-military-aid-weapons-us.html

190. Pentagon: 'Roughly 8 to 10 Flights a Day' Full of Aid for Ukraine Pouring into Europe, https://www.airandspaceforces.com/pentagon-8-to-10-flights-day-full-of-aid-for-ukraine-pouring-into-europe/

191. Inside the multinational logistics cell coordinating military aid for Ukraine, https://www.defensenews.com/global/europe/2022/07/21/inside-the-multinational-logistics-cell-coordinating-military-aid-for-ukraine/

For the purpose of current assessment, the reported total mass of arms deliveries has been adjusted based on the growth of military aid in financial terms and distributed between different countries based on the reported monetary value of military aid provided by each country. Simplified assumptions were used to distribute cargo deliveries by mode of transportation for different countries (e.g. equal shares between air and sea transport for transatlantic routes, reliance on train transportation for deliveries within Europe with 20% air transport use for the deliveries from Southern European and Northern European countries). Emission factors provided by DEFRA for freighting goods were used for different methods of cargo transportation (i.e. freight train, general cargo ship and terminal ship, and long-haul freight flights).[192]

For instance, the US has provided USD 46.3 billion of military aid or more than 40% of reported military aid. We assume that a proportional share by weight has been supplied from the US and half of that volume has been supplied by air. This corresponds to about 46,000 tonnes of equipment and materials supplied by airplanes from the eastern coast of the US to the east of Poland and generating about 363,000 tonnes of CO_2e of GHG emissions. Approximately 42,000 tonnes were generated from air transportation from other countries, while only about 10,000 tonnes of CO_2e were generated by sea and railway transport.

Based on preliminary estimation, GHG emissions associated with military aid supply amount to approximately **0.42 million tCO_2e**, with about 97% coming from air transportation due to its high carbon intensity, long distances of transatlantic flights, and large volumes of supply.

There were almost no changes compared to the previous assessment because of the lower amount of additional military aid provided and adjustment of some figures due to the use of different sources of information.

Russia has also reportedly been supplied by military equipment from other countries, including Belarus, Iran, Syria, and more recently North Korea.[193] These equipment supplies, as well as equipment relocation within Russia, rely heavily on railway transportation but also use air and sea transport. For instance, North Korea has reportedly provided around 5,000 containers of weapons to Russia as of the end of December 2023. The logistics includes short-distance sea transportation from North Korea to Russia, truck transportation from port to railway, then long-distance railway transportation over more than 9,000 km to the Rostov region of Russia, and finally truck transportation to distributed storage sites near the battlefield.[194] Still, information on air transport use for military equipment transportation was also reported, in particular, with respect to relocation of air-defence equipment from Kaliningrad (sixfold increase in weekly flights frequency was observed).[195]

Low reliance on air transportation and use of electrified railway system in Russia limits associated GHG emissions. However, even assuming low additional input (e.g. 10% from the estimated impact of equipment supply to Ukraine), this would bring total GHG emissions associated with the long-distance supply of military equipment to about **0.5 million tCO_2e**.

192. Greenhouse gas reporting: conversion factors 2023, https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023

193. North Korea Shipped Arms to Russia for Use in Ukraine, U.S. Says, https://www.nytimes.com/2023/10/13/us/politics/north-korea-weapons-russia-ukraine.html

194. Mapping North Korea's discreet artillery ammo route to Russia, https://frontelligence.substack.com/p/mapping-north-koreas-discreet-artillery

195. As Cargo Flights Leave Kaliningrad, Air Defence Systems Disappear, https://www.bellingcat.com/news/2023/11/13/as-cargo-flights-leave-kaliningrad-air-defence-systems-disappear/

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)[196]. 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 (consists of nitrocellulose, nitro-glycerine, and nitroguanidine); • 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 being in the range of 5.06 to 12.9 kg CO_2e per kg of material. Global warming impact of key energetic materials[197]: • 5.06 kg CO_2e for TNT, • 6.53 kg CO_2e for nitrocellulose, • 5.85 kg CO_2e for nitro-glycerine, • 32.1 kg CO_2e for nitroguanidine, • 8.59 kg CO_2e for RDX. For composition B explosive, which is typically used in artillery projectiles and other ammunition (standard composition includes 59.5% RDX and 39.4% TNT phlegmatised with 1% paraffin wax), the weighted average global warming impact would be 7.1 kg CO_2e per kg of material. The carbon footprint would be lower if TNT was only used in a projectile. There is no information on propellant composition, but if we assume the average global warming impact of nitrocellulose and nitro-glycerine, the value would be 6.19 kg CO_2e per kg.
Emissions from artillery shell manufacturing	Thus, the carbon footprint of materials used for the manufacturing of the warhead of a 155 mm projectile would be 136 kg CO_2e (approximately 3 kg CO_2e per kg of warhead) and would consist of: • 60.35 kg CO_2e for the manufacturing of composition B explosive; • 75.62 kg CO_2e for the manufacturing of steel casing.[198] The carbon footprint does not take into account the manufacturing of a fuse and containers for transportation of projectiles. The assumed carbon footprint of materials used for propellant manufacturing would be 59 kg CO_2e (using the emission factor of 6.19 kg CO_2e per kg) though the amount of propellant used per projectile would depend on specific combat conditions. The estimates used in the study are very conservative as they do not account for all components and materials used for the artillery shell manufacturing (e.g. PETN and copper used for the warhead manufacturing), some materials and components used for propellant production (black powder, lead, B/KNO3), as well as do not account for the carbon footprint of fuse manufacturing, which despite having a small weight include the use of carbon intensive materials and components (e.g. aluminium, brass, RDX, electronic component). Besides, the estimates of global warming impact made during the LCA studies do not account for energy consumption (e.g. electricity, heat) for the assembly of the 155mm ammunition due to lack of information. Thus, the actual carbon footprint could be materially higher and further research on carbon emissions associated with ammunition manufacturing is required.
Emissions at point of firing	Carbon dioxide emissions at the point of firing (associated with the generic 155 mm ammunition) are 2.74 kg CO_2e (CO_2 only). If indirect global warming potential of CO is taken into account, the emissions would be 10.02 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 28. Specific emission factors related to ammunition

196. Explosive weapon effects – final report, GICHD, Geneva, February 2017, http://characterisationexplosiveweapons.org/studies/annex-b-152-155-artillery-version/
197. 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
198. Assuming the 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. See https://circularecology.com/embodied-carbon-footprint-database.html

Number of artillery shells used

The number of artillery shells used has varied during the different stages of the war and depends on combat intensity and shells availability for both parties. Assumptions for different periods of the war 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
THIRD INTERIM ASSESSMENT (6 months period from March 2023 till August 2023)			
Assumed use of shells by Russia	15,000	450,000	2,700,000
Assumed use of shells by Ukraine	7,000	210,000	1,260,000
Total	22,000	660,000	3,960,000
FOURTH INTERIM ASSESSMENT (6 months period from September 2023 till February 2024)			
Assumed use of shells by Russia	8,000	240,000	1,440,000
Assumed use of shells by Ukraine	4,000	120,000	720,000
Total	12,000	360,000	2,160,000
TOTAL NUMBER OF SHELLS DURING THE ASSESSMENT PERIOD (24 February 2022 — 28 February 2024)			
Assumed use of shells by Russia			13,140,000
Assumed use of shells by Ukraine			4,770,000
Total			17,910,000

Table 29. Estimated artillery ammunition use

The estimated figures are generally aligned with other available data on stocks, production capacity, and supply volumes.

In particular, over half of the assumed volume for Ukraine could be tracked via information about the assistance provided by various partners, with supplies from the US exceeding 2.1 million shells,[199] about 0.5 million shells supplied by the EU during 2023[200], and at least 0.1 million supplied by other countries[201]. 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.[202] 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.[203]

According to some estimates, before the war, Russia had about 17 million units of ammunition, of which about 10 million have been reportedly used during the first 9 months of the war.[204] Since most of the pre-war stocks of artillery shells were manufactured decades ago, their age and unsatisfactory storage conditions led to propellant deterioration and made the older stocks unusable.[205] Different estimates put increased production and/or recovery volumes during the war in the range between 1 and 2 million shells per year, which was not sufficient to cover the demand and resulted in reliance on additional supplies from the stocks in Belarus, North Korea, and Iran.[206] However, there are also higher estimates of artillery ammunition production capacity of 3.5 million shells per year by the end of 2023 and potential further growth to 4.5 million per year in 2024.[207] These figures demonstrate the feasibility of using 13.1 million of shells during the two years of the war.

Considering future demand, artillery ammunition manufacturing is expected to increase drastically. Companies in Europe and the US are already significantly increasing production capacity to be able to match Ukraine's demand (at minimum 2.4 million per year) and restore reserves with doubling monthly production capacity rates throughout 2023 and further growth expected during the next two years.[208] The EU countries are expected to reach 1.4 million shells capacity and the US — 1.2 million shells capacity by the end of 2024.[209]

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199. According to the Fact Sheet on U.S. Security Assistance to Ukraine (https://media.defense.gov/2023/Sep/21/2003306164/-1/-1/0/Ukraine-Fact-Sheet.PDF), the US alone has provided over 2,000,000 155 mm artillery shells, as well as over 7,000 precision-guided 155 mm artillery shells, more than 200,00 152 mm artillery shells, and 40,000 122 mm artillery shells.
200. Can Europe arm Ukraine—or even itself?, https://www.economist.com/europe/2024/01/14/can-europe-arm-ukraine-or-even-itself
201. 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 the Czech Republic, https://www.czdefence.com/article/czech-republic-donates-artillery-ammunition-worth-czk-366-million-to-ukraine; and thousands of rounds from Estonia https://www.eurointegration.com.ua/eng/news/2023/01/23/7154651/; and other countries https://www.kyivpost.com/post/11042
202. 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
203. 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/
204. Grosberg: Venemaal jätkub ründevõimet veel kauaks, https://www.err.ee/1608815563/grosberg-venemaal-jatkub-runde-voimet-veel-kauaks
205. Комбриг 45-ої бригади Олег Файдюк: Нам однозначно треба більше гармат, https://www.pravda.com.ua/articles/2023/02/7/7388192/
206. Russia ramps up artillery production but still falling short, Western official says, https://www.reuters.com/world/europe/russia-ramps-up-artillery-production-still-falling-short-western-official-says-2023-09-09/; Investigation: Belarus sent over 130,000 tons of munitions to Russia in first year of full-scale war, https://kyivindependent.com/investigation-belarus-sent-over-130-000-tons-of-munitions-to-russia-in-first-year-of-full-scale-war/; Вадим Скібіцький: У росіян є мотивація воювати за гроші, щодня до армії йде близько 1000-1100 осіб, https://www.rbc.ua/rus/news/vadim-skibitskiy-rosiyan-e-motivatsiya-voyuvati-1705266418.html
207. Setting Transatlantic Defence up for Success: A Military Strategy for Ukraine's Victory and Russia's Defeat, https://kaitseministeerium.ee/en/setting-transatlantic-defence-success-military-strategy-ukraines-victory-and-russias-defeat
208. Setting Transatlantic Defence up for Success: A Military Strategy for Ukraine's Victory and Russia's Defeat, https://kaitseministeerium.ee/en/setting-transatlantic-defence-success-military-strategy-ukraines-victory-and-russias-defeat
209. Visual analysis: Ukraine's war of survival enters third year, https://www.ft.com/content/39656a7f-fcf8-4ceb-b162-041863dc7a55

Other ammunition and explosives

Mines

About 30% of Ukraine's territory (174 000 km^2) has been exposed to intense combat operations and requires survey and clearance from the vast amounts of explosive ordnance.[210] Ukraine became the most mined country in the world with anti-tank and anti-personnel mines used extensively during the two years of the war. Contamination with unexploded ordnance put human lives at risk, resulting in large number of injuries and deaths, and took the land out of productive economic activities; it will take decades to make some territories safe again.[211]

Only at the northern borders of Ukraine, since June 2022 till the end of 2023, there were more than 500,000 anti-tank mines installed by Ukraine to protect its borders from new attacks.[212] There is no specific information, but it could be assumed that a similar number of mines have been installed by both parties on the south and east of Ukraine.[213] For the purpose of assessment, it was assumed that about 1 million of anti-tank mines have been used by both Ukraine and Russia.

Drones

Drones of various types are actively used by both sides. All classes of Unmanned Aerial Vehicles (UAVs) have a limited life expectancy and require continuous replacements, which increase manufacturing demand and associated GHG emissions.

The Ukrainian army uses different models of UAVs, including FPV drones, reconnaissance and long-distance attack drones, and even maritime drones. During 2023, Ukraine has scaled up drone procurement and manufacturing, while the Ukrainian army reportedly received 100,000 drones of various types. At the beginning of 2024, the President of Ukraine created a separate branch of the Ukrainian Armed Forces — the Unmanned Systems Forces.[214]

Similarly, the Russian army also used different types of drones (Shahed-136/131 attack UAVs, Lancet drones, Orlan, FPVs, and other drones), reportedly at an even larger scale.

Using drones allowed partially mitigating ongoing artillery ammunition shortages, although artillery systems can deliver much more powerful strikes than loitering munitions and drone-dropped munitions.[215]

FPV drones

FPV drones (FPV – First Person View) are used to hit and destroy targets at the depth of up to 7-15 km and in some cases up to 20-22 km. They are typically carrying 1-2 kg of explosives and can be used against vehicles, positions, infantry, and other targets. They started to be applied in 2022 but the use at scale began in the second half of 2023 with a growing trend in use intensity, which is expected to continue throughout 2024.

210. GLOBSEC. Walking on Fire: Demining in Ukraine, https://www.globsec.org/sites/default/files/2023-04/Demining%20in%20Ukraine%20report%20ver5%20web.pdf
211. Ukraine is now the most mined country. It will take decades to make safe, https://www.washingtonpost.com/world/2023/07/22/ukraine-is-now-most-mined-country-it-will-take-decades-make-safe/
212. На Півночі України проти ворога встановлено понад 500 тисяч протитанкових мін? https://armyinform.com.ua/2023/10/20/na-pivnochi-ukrayiny-proty-voroga-vstanovleno-ponad-500-tysyach-protytankovyh-min/
213. See the example demonstrating the density of mine fields and diversity of mines types used, https://twitter.com/Tatarigami_UA/status/1690076614342680576
214. На шляху до мільйона дронів. Результати виробництва БПЛА, технологічні виклики і нові завдання на 2024 рік, https://www.pravda.com.ua/articles/2024/02/21/7442817/
215. ISW, Russian Offensive Campaign Assessment, April 10, 2024, https://www.understandingwar.org/backgrounder/russian-offensive-campaign-assessment-april-10-2024

OSINT analysts estimated that between August 2023 and February 2024, visual and geolocated evidence was collected on the use of 5,502 FPV drones by Russia and 7,280 by Ukraine, with Ukrainian Forces maintaining advantage in this area. The collected data demonstrate a constantly growing trend of FPV use by both sides (30-50% growth rate per month), but the rate of growth could potentially reach limits related to drones availability, challenging weather conditions, or exigencies of the frontline situation.[216] As of February 2024, visually confirmed FPV use intensity reached 88 drones per day for Ukraine and 76 drones for Russia.

Though the total number of recorded and geolocated FPV drone strikes is significant, it is likely representing only a fraction of actually used drones.[217] In particular, analysts note a significant level of FPV use against fortifications and defensive positions of Ukrainian forces with video not widely spread online, which would increase the numbers for recorded Russia's FPV use.[218] Moreover, based on various comments of FPV users, only about 30% to 50% of drones hit the target due to technical failures, electronic warfare countermeasures, user errors, and other factors. Thus, the actual number is likely to be significantly higher and only a fraction of FPV drones use cases are recorded by OSINT analysts (assumed to be around 25%).

Based on available data, the number of only visually confirmed FPV drones use cases exceeded 12,782 as of the end of the two years of the war with the most intensive use of FPV drones concentrated on the sections of frontline with the most intensive fighting.[219] Taking into account both the reported success rates and limitations of visual confirmation (including lack of relevant data for the period before August 2023), we assume that the total number of FPV drones used is close to 50,000 units for both sides with a larger share for Ukraine and intensity expected to grow further. As of February 2024, the number of visually confirmed FPV drones use cases was approaching 5,000 per month, which could indicate the total use rate of 20,000 units per month.

According to Ukrainian authorities, production of FPV drones is planned to be increased to 1 million per year in 2024[220] though these numbers are still to be confirmed.

Drone drops

Dropping grenades and other explosives from drones was actively used by both parties throughout the war. Though there are no specific total use figures, the scale is similar or, taking into account earlier adoption, even higher than the use of FPV drones.[221]

Attack drones

Russian forces use different types of attack drones with Shahed drones as the most typical long-range attack drones and Lancets as the most common short-range drones. Based on the information collected from the updates of the Ukrainian Air Force, during the two years of the war Ukraine was attacked by 4,628 Shahed-136/131 drones. Lancet drone use intensity

216. Update on FPV drone warfare (27-01-2024), https://tochnyi.info/2024/01/update-on-fpv-drone-warfare-27-01-2024-2/; and updated data as of early March 2024 https://twitter.com/HartreeFock/status/1763619401960476979

217. By the end of the second year of the war, only at one section of the frontline with intensive fighting on the south of Ukraine the reported FPV use by Russia was in the range of 20-40 per day with more than 3,263 drones identified during the five month period (05.10.2023-29.02.2024) and a growing intensity use trend (about 30-35 drones per day used on average in February 2024 on this section of the frontline). See reports at https://www.facebook.com/Brovdi.Art

218. Andrew Perpetua, https://twitter.com/AndrewPerpetua/status/1742907402788250097

219. Update on FPV drone warfare (27-01-2024), https://tochnyi.info/2024/01/update-on-fpv-drone-warfare-27-01-2024-2/

220. БПЛА на фронті: чи зможемо наступного року забезпечити військо українськими дронами, https://espreso.tv/bpla-na-fronti-chi-zmozhemo-nastupnogo-roku-zabezpechiti-viysko-ukrainskimi-dronami

221. See the comparison of FPV drones use and drones drops in late 2023 – early 2024, https://twitter.com/NHunter007/status/1774884307409977644

is about 20 units per day based on the comments of the Ukrainian Armed Forces representatives, which would result in 14,600 units during the two years of the war.

Ukraine uses various types of attack drones and actively develops new capabilities in this area though the information on the use intensity is limited. According to publicly reported data, there were 1,369 drone strikes or drone interceptions on the territory of Russia during the two years of the war with limited events recorded during 2022 and a significant increase in strikes' intensity in 2023. In addition, there were 119 strikes recorded in Crimea, which, however, also includes missile strikes.[222]

Missiles

Missiles typically use synthetic hydrocarbon fuels (e.g. JP-10 based on tetrahydrodicyclopentadiene ($C_{10}H_{16}$) hydrocarbon), which have higher energy density compared to standard jet fuels and are obtained by chemical synthesis of specific hydrocarbons of very high purity using various catalysts. Though there are no assessments of the carbon footprint of missiles, their manufacturing and use are still assumed to be carbon intensive.

During the two years of the war, Ukraine was attacked by approximately 8,000 missiles of various types launched from air, sea, and ground-based systems. Approximately one third of that (about 2,700 units) are C300/C400 missiles, 1,513 — X-101/555/55 missiles, about 1,000 — Iskander missiles, and 843 — Kalibr missiles.[223] The total weight of missiles is about 18,000 tonne.

Ukraine also uses missiles but at a very small scale and there is limited information available. Due to information sensitivity, the lists of military aid often include the type of ammunition supplied and in some cases, the number of launching systems but not the number of ammunition or missiles. Some reports estimate the total number of SCALP / Storm Shadow missiles supplied to be around 200.

Aerial bombs

Aerial bombs have been actively used by Russia throughout the war. During the first year of the war, aviation bombs were used to bombard Mariupol, Kharkiv, Chernihiv, and other Ukrainian cities. There were examples of using FAB-250, FAB-500, FAB-1500, and even FAB-3000 bombs, where the number corresponds to the mass of the bomb, reported.[224]

During the second year of the war, the intensity increased significantly, as Russia started to use aerial bombs with special gliding kits (i.e. conventional free-falling aerial bombs equipped with the so-called UMPK kits — unified gliding and correction modules). The Russian forces use such kits for aerial bombs FAB-250, FAB-500, and FAB-1500.[225]

222. Visual analysis: Ukraine's war of survival enters third year, https://www.ft.com/content/39656a7f-fcf8-4ceb-b162-041863dc7a55

223. See reports at https://www.ukrinform.ua/rubric-ato/3830593-rosia-vid-pocatku-povnomasstabnoi-vijni-vipustila-po-ukraini-ponad-8-tisac-raket-ignat.html, https://hromadske.radio/news/2023/12/21/7400-raket-zapustyly-okupanty-po-ukraini-vid-pochatku-povnomasshtabnoho-vtorhnennia-ihnat

224. See, for instance, Друга після тактичних ядерних зарядів: фугасна авіабомба ФАБ-3000, характеристики, радіус дії, https://fakty.com.ua/ua/ukraine/20220418-druga-pislya-taktychnyh-yadernyh-zaryadiv-fugasna-aviabomba-fab-3000-harakterystyky-radius-diyi/; Можна "скласти" багатоповерховий будинок: чим фашисти бомблять українські міста, фото, https://apostrophe.ua/ua/news/society/2022-03-04/mojno-slojit-mnogoetajnyiy-dom-chem-fashistyi-bombyat-ukrainskie-goroda-foto/261426; Бомби вагою 500 кг: яку зброю ніс збитий над Черніговом Су-34 та які пошкодження завдав при падінні, https://suspilne.media/214106-bombi-vagou-500-kg-aku-zbrou-nis-zbitij-nad-cernigovom-su-34-ta-aki-poskodzenna-nanis-pri-padinni/;

225. 1.5-Ton FAB-1500 Became a Guided Glide Bomb with UMPK Kit, russian Sources Claim, https://en.defence-ua.com/news/15_ton_fab_1500_became_a_guided_glide_bomb_with_umpk_kit_russian_sources_claim-7851.html

Intensity of aerial bombs use sometimes exceeds 100 units per day and more often ranges between 20 and 40 bombs per day[226]. During the period of most intensive fighting, only in Avdiivka city 60-80 bombs were used daily, including 75 bombs weighing 500 kg each used in a single day.[227],[228] As of mid-March 2024, it was reported that 3,500 bombs were used in 2024 alone (about 45 bombs per day), while only several hundreds were used during the same period in 2023.[229]

The total number of bombs could exceed 12,000 units during the two years of the war (i.e. assuming 30 bombs per day on average during the second year of the war and additional 1,000 for the first year of the war). Taking into account the different mass of the bombs and prevailing use of FAB-500 bombs, this indicates that more than 5,000 tonnes of aerial bombs could have been used during the two years.

Ukraine uses aerial bombs at a very small scale and there is limited information available.

Mortar rounds

The most common mortar systems include 60 mm, 80 mm, and 120 mm mortars. Only during the first year of the war, one Ukrainian company supplied 100,000 60 mm grenades to the armed forces[230], while more recently, the production capacity of mortar rounds was reported at 20,000 units per month.[231] Besides, the US supplied more than 400,000 mortar rounds[232] to Ukraine and only one aid package from Germany included about 100,000 mortar rounds.[233] For the purpose of assessment, it was assumed that the use rate is about 1 million units per year by each side.

Small arms rounds

The use of small arms rounds is impossible to track due to immense volumes, but the overall quantity is estimated in hundreds of millions if not billions units of different calibres. Only the US supplied more than 400 million rounds of small arms ammunition and grenades to Ukraine.[234] For the purpose of assessment, it was assumed that the use rate is about 1.5 billion units during the two years of the war by each side.

226. In April 2023, the intensity was reported at 20 bombs per day, https://www.slovoidilo.ua/2023/04/05/stattja/bezpeka/kerovani-bomby-rosijskyx-terorystiv-ce-take-chym-nymy-borotysya; In October 2023, 1,065 aerial bombs were reportedly used (almost 40 per day on average) and on 6 November, the intensity reached 106 bombs, https://apostrophe.ua/ua/news/society/2023-11-13/rossiyane-massovo-byut-fabami-po-vsey-linii-fronta-voennyiy-rasskazal-o-situatsii-pod-bahmutom/308412

227. Ukraine Withdraws From Besieged City as Russia Advances, https://www.wsj.com/world/europe/ukraine-withdraws-from-besieged-city-as-russia-advances-554644c0

228. Характер дій РФ з гучною назвою "наступи" передбачає затяжну війну, і це противник намагається нам нав'язати, жертвуючи величезною кількістю своїх людей - заступник начальника ГУР МО, https://interfax.com.ua/news/interview/968704.html

229. This year, Russia dropped more than 3,500 bombs on Ukrainian positions – Ministry of Defense, https://mil.in.ua/en/news/this-year-russia-dropped-more-than-3-500-bombs-on-ukrainian-positions-ministry-of-defense/

230. https://politics.pika.net.ua/v-ukrayini-pochalos-masove-vyrobnycztvo-60-mm-min-dlya-potreb-zsu

231. Secretive Ukrainian arms production a 'threat' for Russia, says manufacturer, https://abcnews.go.com/International/secretive-ukrainian-arms-production-threat-russia-manufacturer/story?id=106707984

232. U.S. Security Cooperation with Ukraine, FACT SHEET, https://www.state.gov/u-s-security-cooperation-with-ukraine/

233. Скільки сьогодні може коштувати 120-мм міна і як довго чекати, якщо це поставки з-за кордону, https://defence-ua.com/news/skilki_sogodni_mozhe_koshtuvati_120_mm_mina_i_jak_dovgo_chekati_jakscho_tse_postavki_z_za_kordonu-13423.html

234. U.S. Security Cooperation with Ukraine, FACT SHEET, https://www.state.gov/u-s-security-cooperation-with-ukraine/

Type of munition and explosives	Number of units	Average unit weight, kg	Total weight, t
Assumed values for Russian forces			
Artillery	13,140,000	40	525,600
Aerial bombs	12,000	438	5,250
Missiles - X-101/555/55	1,513	2,400	3,631
Missiles - Kalibr	843	1,770	1,492
Missiles Iskander	1,000	3,800	3,800
Missiles - C300 / C400	2,700	1,600	4,320
Other missiles	2,000	2,400	4,800
FPV drones	20,000	2	30
Drone drops	20,000	1	20
Shahed drones	4,628	200	926
Lancet drones	14,600	12	175
Mortar rounds	2,000,000	8	16,100
Rounds of small arms ammunition	1,500,000,000	0.012	18,000
Anti-tank mines	1,000,000	10	10,000
Sub-total	**-**	**-**	**594,144**
Assumed values for Ukrainian forces			
Artillery	4,230,000	40	169,200
Aerial bombs	500	250	125
Missiles	200	1,300	260
FPV drones	30,000	2	60
Drone drops	30,000	1	30
Long-distance attack drones	1,488	200	298
Mortar rounds	2,000,000	8	16,100
Rounds of small arms ammunition	1,500,000,000	0	18,000
Anti-tank mines	1,000,000	10	10,000
Sub-total	**-**	**-**	**214,073**
Total	**-**	**-**	**808,217**
Total for artillery shells	17,370,000	40	694,800
Ratio between the total and artillery shells	-	-	1.16

Table 30. : Information on other ammunition and explosives

Emissions from construction of fortifications

Trenches

As of August 2023, based on the analysis of satellite images (Sentinel-2 L2A), the total length of fortification structures identified was 3,309 km. The analysis was carried out using the images made during the periods of clear weather and absence of clouds and precipitation, which allows identifying trenches with the minimum trench width of 150 cm.

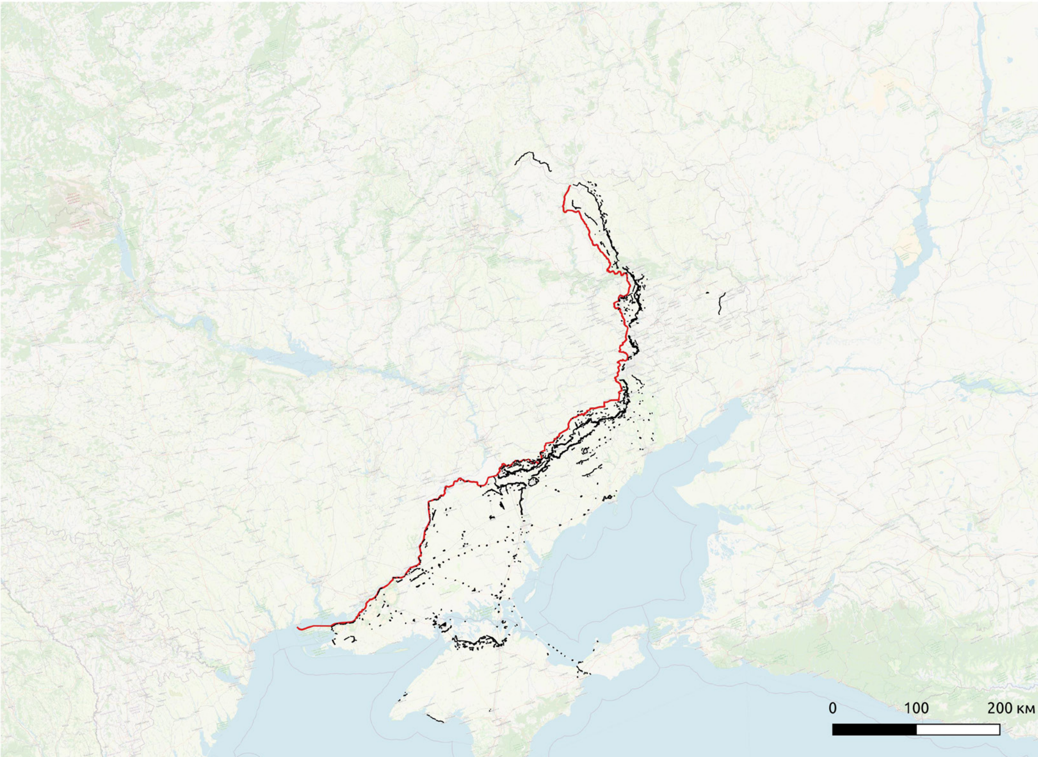


Figure 25.Location of fortifications on the occupied territory of Ukraine and in Russia

There is a special military trenching machine (BTM-3) used by motorised 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.[235] The speed of digging and fuel consumption depend on soil characteristics. Assuming the average capacity of 400 m per hour, digging of 1,000 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. A similar level of fuel consumption could be expected for dismantling and restoration works.

Dragon's teeth lines

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

235. 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

4 m per element, assuming the distance of approximately 2 m between the elements). Assuming that typically at least two rows are installed, approximately 50,000-75,000 elements would be required for the construction of 100 km of protective lines (for two and three rows lines respectively).

For the purpose of carbon footprint estimation, it is assumed that 1,200 km of "dragon's teeth" lines were installed and 900,000 concrete units were manufactured for these purposes (three rows of concrete pyramids). The assumption seems reasonable and conservative taking into account reported initial plans, confirmed sites of installation, and production volumes. Thus, at least 1,080,000 tonnes of concrete have been used for the construction of dragon's teeth structures.

This estimate is based on partial data as there are additional "dragon's teeth" lines that were visually confirmed and reported at locations further away from the frontline, including in Crimea, along the international border between Ukraine and Russia, near Berdiansk airport, and in other locations.

Figure 26. 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)

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.[236] 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 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

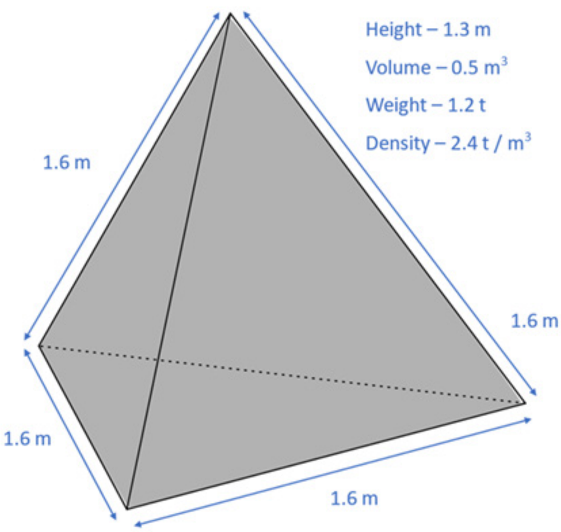


Figure 27. Parameters of concrete tetrahedrons used as "dragon's teeth" obstacles

236. Протитанкові «зуби дракона» на сході Криму продовжують до Чорного моря (фото), https://ua.krymr.com/a/news-zuby-drakona-krym/32347585.html

defensive lines with concrete pyramids were installed along the North Crimea Canal, in particular near Maslove and Novoivanivka villages.[237] Fortifications are built in several echelons — to the south of Armiansk, between Armiansk and Krasnoperekopsk towns, additional dragon's teeth line could be observed on satellite images.[238] 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,[239] to the north of Mykhailivka town,[240] 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).[241]

Journalist investigation revealed that concrete pyramid-shaped structures used for the construction of the 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.[242] Manufacturing of such obstacles was also reportedly started in Crimea with the capacity of 5,000 units per month.[243] Concrete pyramids were also manufactured on other occupied territories of Ukraine. 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.[244] Thus, dozen thousands of concrete pyramids were manufactured each month starting from the end of 2022 and used for the construction of fortifications.

237. A web of trenches shows Russia fears losing Crimea, https://www.washingtonpost.com/world/interactive/2023/ukraine-russia-crimea-battle-trenches/

238. Brady Africk, https://twitter.com/bradyafr/status/1645754948297138176/photo/1

239. 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

240. See https://twitter.com/Tatarigami_UA/status/1645651237415575553

241. 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

242. 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-granicz u-v-bryanskoj-oblasti-rf/

243. Production of anti-tank barriers launched in occupied Crimea, https://www.pravda.com.ua/eng/news/2022/11/29/7378476/

244. "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.

Equipment	Indicative weight, t	Indicative embodied carbon, t	Number of destroyed equipment	Number of damaged equipment	Indicative mass of destroyed equipment, t	Indicative mass of damaged equipment, t	Emissions, tCO_2e
Tanks	40	240	1,922	156	76,880	6,240	568,512
Armoured fighting vehicles	8	48	885	35	7,080	280	51,648
Infantry fighting vehicles	14	84	2,695	141	37,730	1,974	276,394
Armoured personnel carriers	11	66	283	18	3,113	198	22,889
Infantry mobility vehicles	6	36	172	14	1,032	84	7,632
Self-propelled artillery	27	162	560	41	15,120	1,107	111,521
Multiple rocket launchers	14	84	278	33	3,892	462	29,131
Trucks, vehicles and jeeps	8	48	2,497	84	19,976	672	145,440
Aircrafts	12	72	99	8	1,188	96	8,784
Helicopters	11	66	103	30	1,133	330	8,950
Naval ships	-	-	16	6	28,025	5,037	213,866
TOTAL	**-**	**-**	**9,510**	**566**	**195,169**	**16,480**	**1,444,766**

Table 31. Russian equipment losses and associated emissions[245]

245. Calculated based on the data reported at https://www.oryxspioenkop.com/2022/02/attack-on-europe-documenting-equipment.html. Values of the number and mass of destroyed and damaged equipment are indicated based on visually confirmed losses. Calculated emissions take into account that at least 20% of losses are not visually confirmed / not included in the lists

Ukrainian equipment losses

Equipment	Indicative weight, t	Indicative embodied carbon, t	Number of destroyed equipment	Number of damaged equipment	Indicative mass of destroyed equipment, t	Indicative mass of damaged equipment, t	Emissions, tCO_2e
Tanks	40	240	534	67	21,360	2,680	160,224
Armoured fighting vehicles	8	48	259	13	2,072	104	15,168
Infantry fighting vehicles	14	84	649	58	9,086	812	67,368
Armoured personnel carriers	11	66	277	29	3,047	319	22,704
Infantry mobility vehicles	6	36	265	38	1,590	228	11,995
Self-propelled artillery	27	162	223	70	6,021	1,890	47,887
Multiple rocket launchers	14	84	41	14	574	196	4,603
Trucks, vehicles and jeeps	8	48	639	23	5,112	184	37,248
Aircrafts	12	72	82	1	984	12	7,114
Helicopters	11	66	39	1	429	11	3,115
Naval ships	-	-	11	5	5,311	3,499	46,635
Total	**-**	**-**	**3,019**	**319**	**55,586**	**9,935**	**424,062**

Table 32. Information on Ukrainian equipment losses and associated emissions [246]

Emission factors

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.[247]

Some construction equipment manufacturers start to estimate both direct and indirect emissions of their key products. However, there are no Product Category Rules established for the construction equipment industry and carbon footprint reports prepared by manufacturers could be based on different methodology, system boundaries, and input data.[248]

246. Calculated based on the data reported at https://www.oryxspioenkop.com/2022/02/attack-on-europe-documenting-ukrainian.html. Values of the number and mass of destroyed and damaged equipment are indicated based on visually confirmed losses. Calculated emissions take into account that at least 20% of losses are not visually confirmed / not included in the lists

247. 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

248. Volvo CE carbon footprint principles, https://www.volvoce.com/-/media/volvoce/global/global-site/our-offer/brochures/environ-

Based on the information reported by Volvo CE, the average carbon footprint (cradle-to-gate) for selected types and models of construction equipment is 4.5 kg CO_2 per kg of equipment (based on minimal operating weight or net weight). Almost 99% of carbon footprint on average is associated with Scope 3 upstream emissions, while only about 1% with Scope 1 and Scope 2 emissions during the production process (downstream Scope 3 emissions from the use of equipment have not been taken into account).

Model	Carbon footprint			Minimal operating weight or net weight, kg	Carbon footprint per kg of equipment, kg CO_2
	Total	Scope 3 upstream	Scope 1 and 2		
Crawler Excavator EC220	87,740	86,800	940	20,470	4.3
Crawler Excavator EC480	180,940	177,700	3,240	45,500	4.0
Compact Excavator EW60	26,910	26,500	410	5,150	5.2
Wheeled Excavator EWR150	77,660	76,800	860	15,400	5.0
Articulated Hauler A60	164,660	1,660	163,000	43,750	3.8
Articulated Hauler A40	112,230	111,000	1,230	30,150	3.7
Wheel Loader L90	71,840	69,900	1,940	14,500	5.0
Wheel Loader L150	108,170	106,800	1,370	24,100	4.5
Wheel Loader L220	144,420	142,900	1,520	31,200	4.6
Wheel Loader L350	221,810	220,500	1,110	50,000	4.4
AVERAGE					**4.5**

Table 33. Data on the carbon footprint of some construction equipment[249]

A study on climate impact of Norwegian defence sector also used proxy from the closest civil type of equipment based on Ecoinvent database data to estimate the emission factors for the production of military equipment since corresponding values for military equipment are unavailable (even though development, production, and cost differ).[250] In particular, 6.8 kg CO_2e per kg of weight factor was used for light vehicles (i.e. a diesel passenger car; weight values of 1,200 and 2,000 kg were used). For other types of machinery, specific carbon emissions factor was lower, but there is also a significant difference between some types of military

mental-product-declarations/life-cycle-assessment-carbon-footprint-methodology-volvoce.pdf

249. Calculated based on the information reported by Volvo CE in carbon footprint declarations available at https://www.volvoce.com/global/en/products-and-services/environmental-declarations/ and equipment weight reported in relevant technical specifications

250. 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

vehicles and assumed civil proxies (e.g. 33.7 tCO_2e per unit of heavy vehicles was used based on data for a building machine and 24.4 tCO_2e per unit of medium vehicles based on data for a 16 metric tonne lorry). The data demonstrate wide variations in emission factors as well as limitations related to comparison of civilian equipment and military equipment types (e.g. 2,195 tCO_2e per unit was used for medium haul aircraft and 8.9 tCO_2e per unit for helicopters). Unit-based comparison does not take into account greater weight of military equipment and very different potential types and sizes of equipment in some categories.

Based on the information presented above and taking into account expected higher carbon intensity of military equipment compared to civil equipment, the value of **6 kg of CO_2e per kg** of machinery weight has been applied as an indicative carbon footprint of military equipment.

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.

A2. Landscape fires

Overview of landscape fires per region. The most significantly affected regions were Donetsk, Kherson, Zaporizhzhia, Luhansk, Kyiv, Mykolaiv, Kharkiv, and Odesa.

Region	Coniferous forests	Deciduous forests	Croplands	Other vegetable lands	Urban	Wetlands	Total
Donetsk	2127.9	5274.3	130557.2	94843.0	1183.4	2828.2	236814.0
Kherson	13233.8	2901.4	159624.4	47025.6	1812.7	3003.1	227601.0
Zaporizhzhia	343.8	1308.5	100391.4	22082.1	328.1	1237.3	125691.3
Luhansk	10045.3	2779.3	40834.7	53986.1	2354.1	855.0	110854.5
Kyiv	11694.9	8513.2	15199.7	35873.3	283.9	1991.1	73556.0
Mykolaiv	2363.0	304.3	49480.5	15559.4	132.4	1180.5	69020.1
Kharkiv	10860.0	2621.1	30309.3	19150.6	139.8	2549.2	65630.0
Odesa	335.0	3882.6	30349.9	10747.3	29.2	9450.3	54794.4
Lviv	420.5	5524.0	6210.9	22932.3	57.0	801.7	35946.3
Dnipropetrovsk	131.9	763.6	22008.0	11066.6	214.0	834.1	35018.0
Zhytomyr	4993.3	4368.1	6983.0	14936.1	167.9	1568.8	33017.2
Rivne	1283.3	6077.5	8659.6	11033.3	23.8	5447.3	32524.7
Chernihiv	2623.1	2743.2	9164.2	12399.4	95.3	850.2	27875.3
Zakarpattia	26.8	3407.0	1245.9	8582.4	17.5	55.0	13334.5
Ivano-Frankivsk	69.1	1881.9	1247.0	8129.2	27.5	278.7	11633.5
Crimea	3.9	4.9	2880.1	5451.3	7.5	9.2	8357.0
Kirovograd	13.0	334.0	4066.6	2702.3	52.7	413.0	7581.6
Volyn	400.0	911.0	1402.0	3607.3	0.5	500.5	6821.3
Vinnytsia	15.5	329.7	2857.9	2149.1	0.5	104.7	5457.3
Poltava	1.8	134.2	2925.4	2002.3	0.1	153.3	5217.0
Khmelnytsk	5.9	261.1	2544.6	1763.9	0.0	103.7	4679.1
Sumy	317.0	102.2	1998.2	997.3	1.1	70.2	3486.1
Chernivtsi	2.2	245.4	782.3	2225.8	1.1	47.7	3304.4
Cherkasy	58.3	186.1	1120.9	1488.3	1.8	132.9	2988.4
Ternopil	2.2	113.5	875.1	691.5	1.3	16.4	1700.1
Total	**61371.5**	**54972.0**	**633718.8**	**411425.8**	**6933.1**	**34482.1**	**1202903.2**

Table 34. Distribution of the total area of landscape fires (in thousand ha) by land cover type within regions in 2022-2023

Age group	Fire severity level, dNBR	Component of forest biomass				
		Stem[251]	Bark	Crown	Under-growth[252]	Litter
Coniferous species						
Young (0-20 years)	Low	10	x	10	30	30
	Medium	20	x	30	50	50
	High	40	x	60	100	100
Young (21-40 years)	Low	x	x	10	30	30
	Medium	x	1	20	50	50
	High	x	2	40	95	95
Middle-aged and premature (41-80 years)	Low	x	x	x	30	30
	Medium	x	1	x	50	50
	High	x	2	5	90	90
Mature and overmature (81 years and older)	Low	x	x	x	30	30
	Medium	x	x	x	50	50
	High	x	1	5	90	90
Deciduous species						
Young (0-20 years)	Low	5	x	10	20	20
	Medium	10	x	20	30	30
	High	30	x	40	80	70
Young (21-40 years)	Low	x	x	x	20	20
	Medium	x	1	10	30	30
	High	x	x	30	70	70
Middle-aged and premature (41-100 years)	Low	x	x	x	20	20
	Medium	x	x	x	25	30
	High	x	1	x	65	70
Mature and overmature (101 years and older)	Low	x	x	x	15	20
	Medium	x	x	x	25	30
	High	x	x	x	65	70

Table 35. Average burnt factor coefficients of forest biomass losses as a result of forest fires, % [253]

251. Stem with bark

252. Undergrowth (living ground cover, young trees, and brushwood)

253. Zibtsev S., Pasternak V., Vasylyshyn R., Myroniuk V., Sydorenko S., Soshenskyi O. (2024). Assessment of carbon emissions due to landscape fires in Ukraine during war in 2022. Ukrainian Journal of Forest and Wood Science, 15(1), 126-139. https://doi.org/10.31548/forest/1.2024.126

Land cover	Area covered by fires, thousand ha	Biomass, thousand tC	Biomass, tC/ha
Wetlands	34.48	275.86	8.0
Other vegetation lands	411.43	1284.80	3.1
Deciduous forests	54.97	10698.03	194.6
Croplands	633.72	4550.81	7.2
Coniferous forests	61.37	8514.17	138.7
Total / average	**1195.97**	**25323.68**	**21.05**

Table 36.Biomass content by land cover type

Land cover	Area covered by fires, thousand ha	Loss of biomass, thousand tC	Loss of biomass, tC/ha
Wetlands	34.48	263.72	7.6
Other vegetation lands	411.43	1255.94	3.0
Deciduous forests	54.97	290.05	5.3
Croplands	633.72	3549.77	5.6
Coniferous forests	61.37	574.67	9.4
Total / average	**1195.97**	**5934.16**	**4.9**

Table 37. Biomass loss by land cover type

Land cover	Area covered by fires, thousand ha	Immediate GHG emissions, thousand tCO_2e	Immediate GHG emissions, tCO_2e/ha	Future GHG emissions, tCO_2e/ha
Wetlands	34.48	435.65	12.6	
Other vegetation lands	411.43	2074.77	5.0	
Deciduous forests	54.97	433.53	7.9	170.8
Croplands	633.72	5864.08	9.3	
Coniferous forests	61.37	897.96	14.6	145.5
Total / average	**1195.97**	**15196.99**	**12.6**	**15.2**

Table 38. GHG emission factors by land cover type

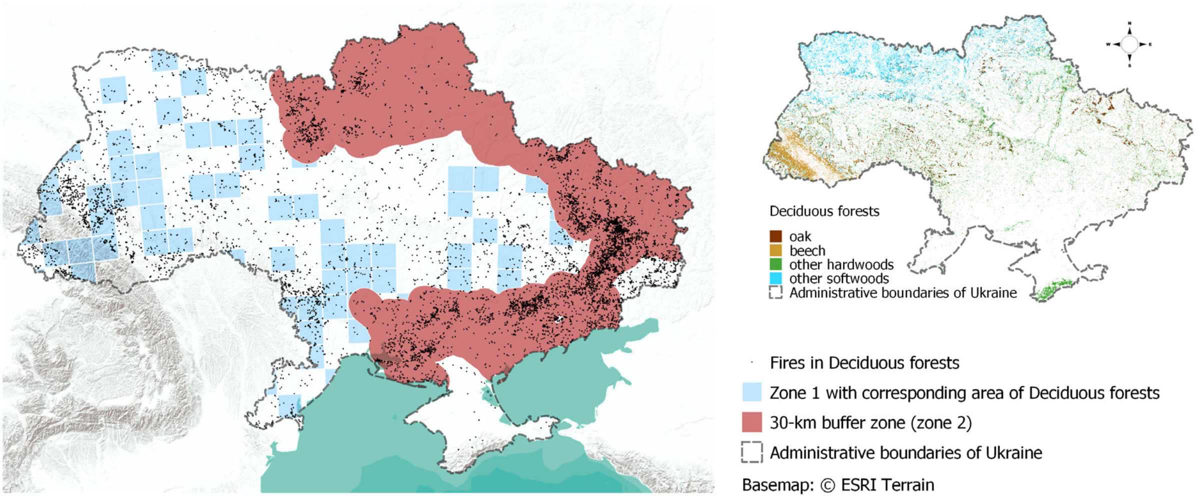


Figure 28. The estimated area of deciduous forests in Zone 1 (blue squares) compared to the 30-km buffer zone

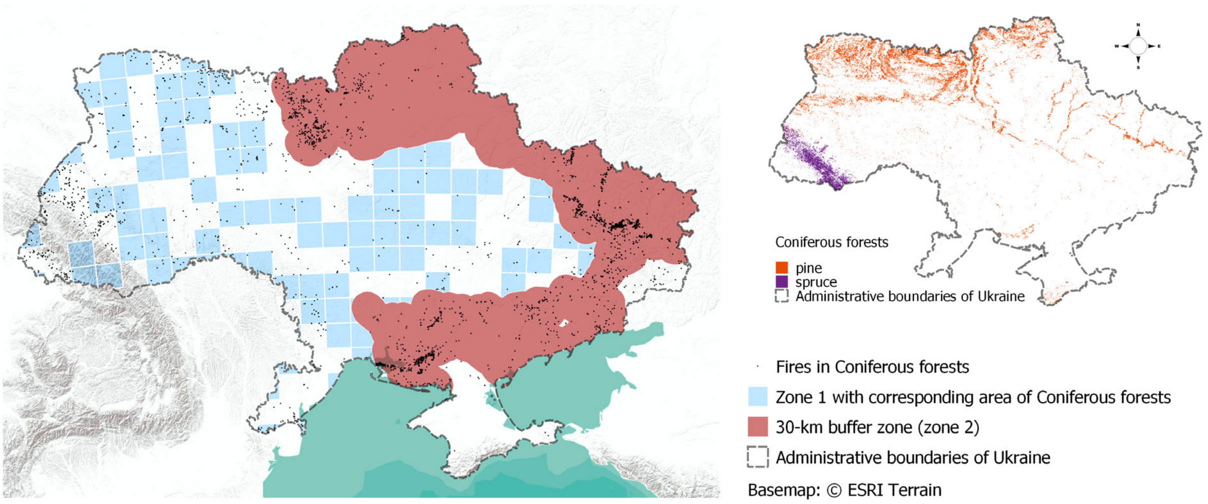


Figure 29. The estimated area of coniferous forests in Zone 1 (blue squares) compared to the 30-km buffer zone

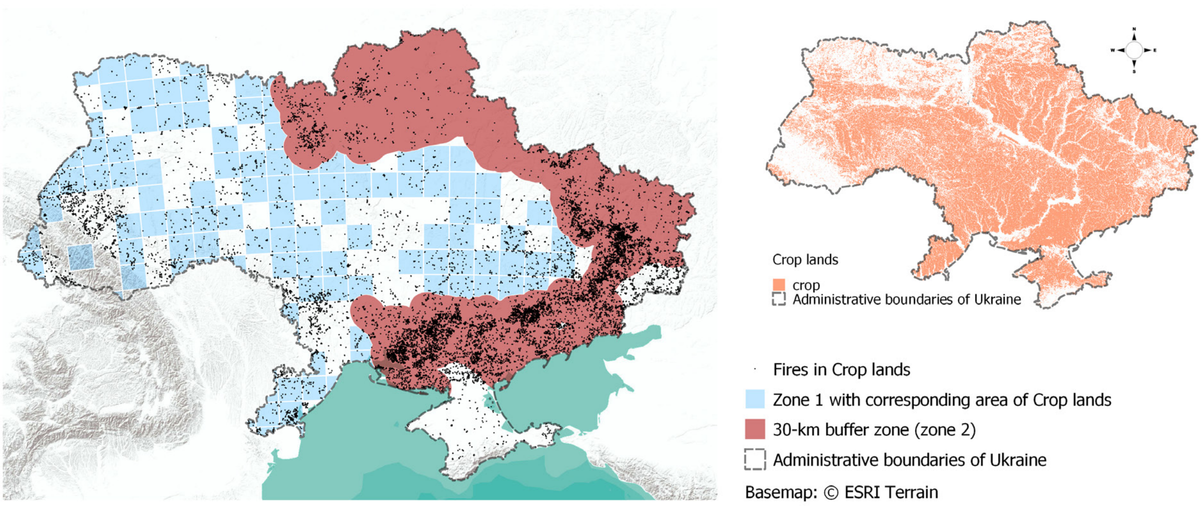


Figure 30. The estimated area of croplands in Zone 1 (blue squares) compared to the 30-km buffer zone

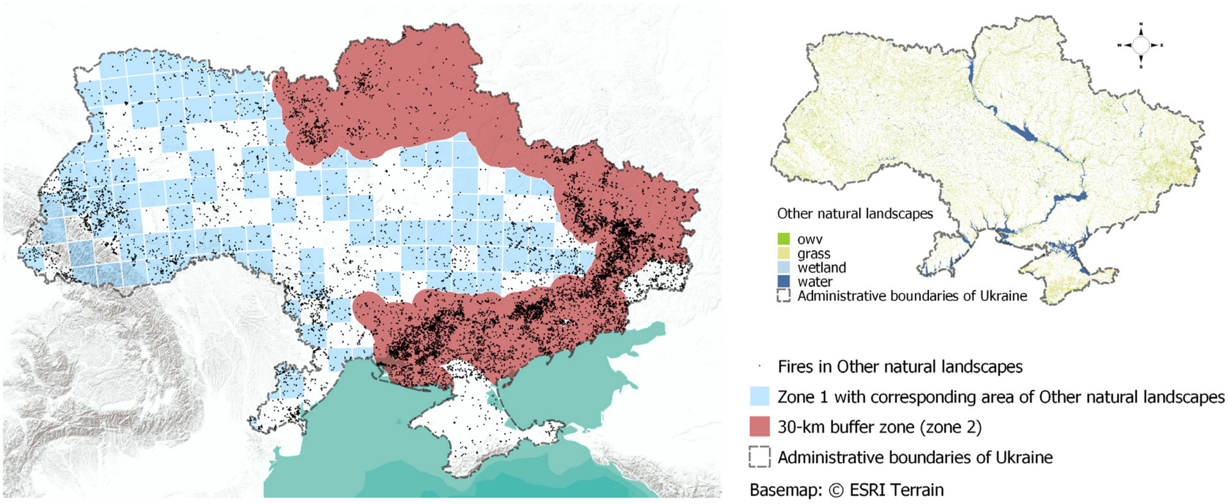
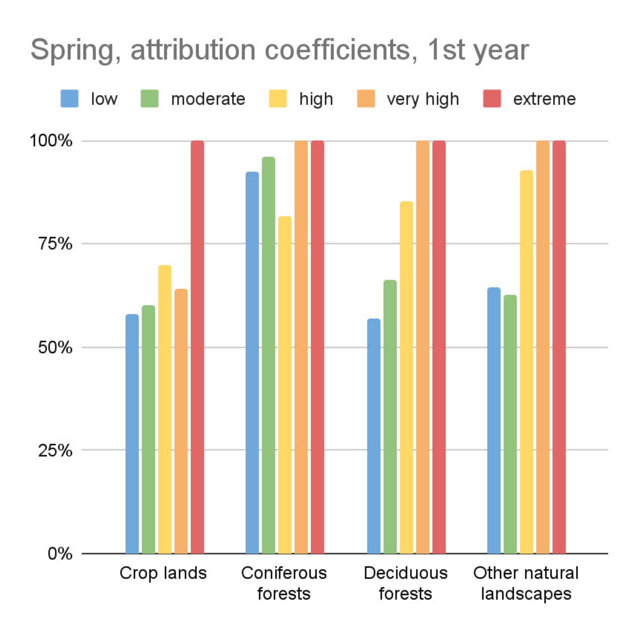
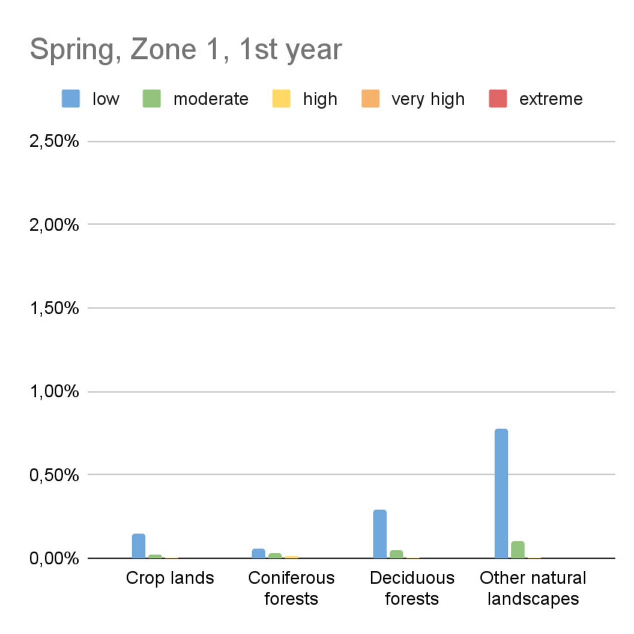
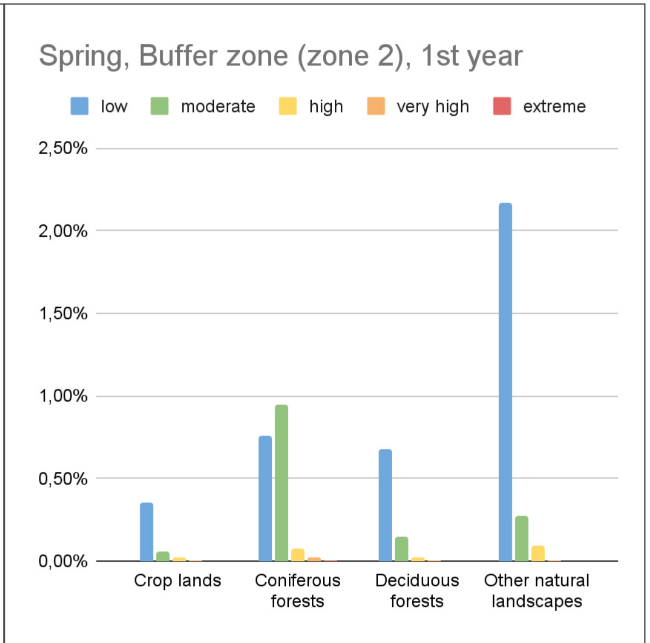


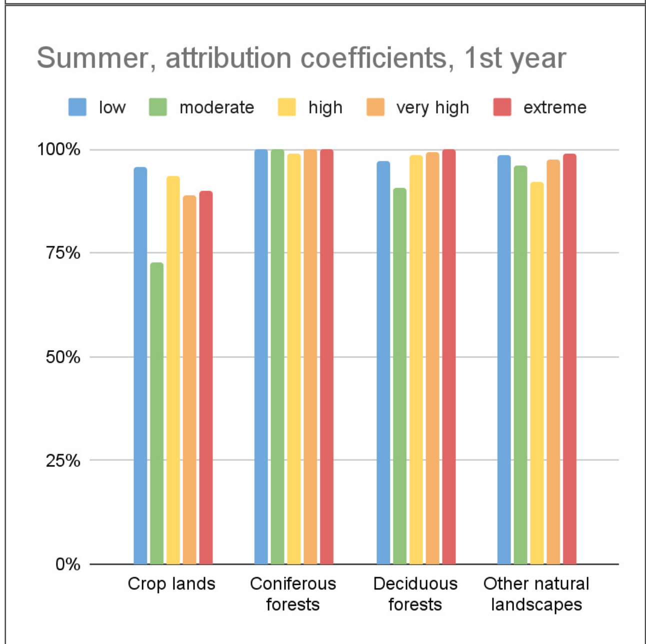
Figure 31. The estimated area of other natural landscapes in Zone 1 (blue squares) compared to the 30-km buffer zone

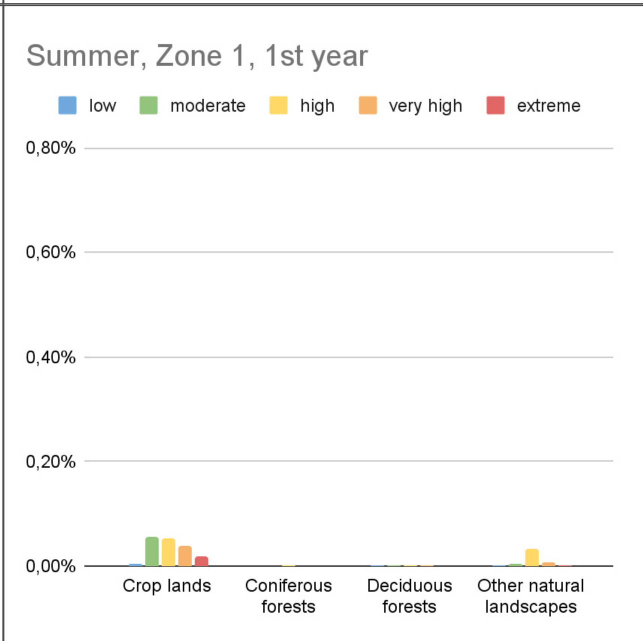
Attribution coefficients (%)	Land cover under fire in free Ukraine (%)	Land cover under fire in the buffer zone (%)











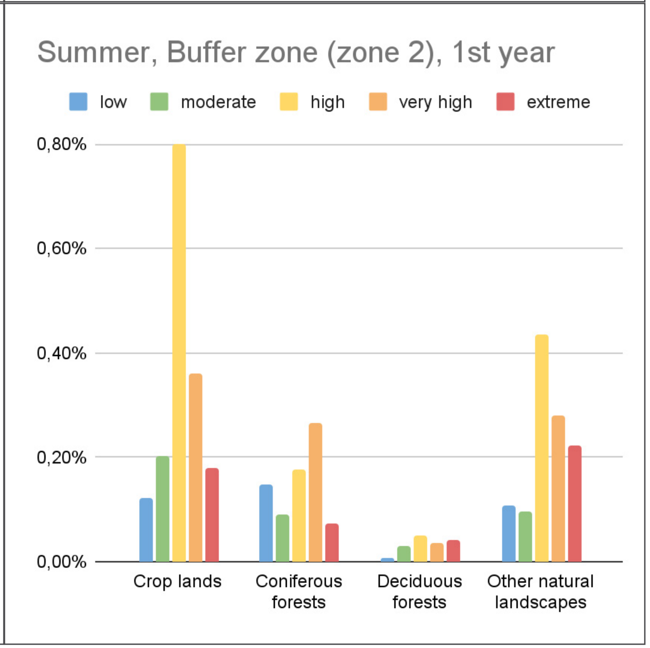
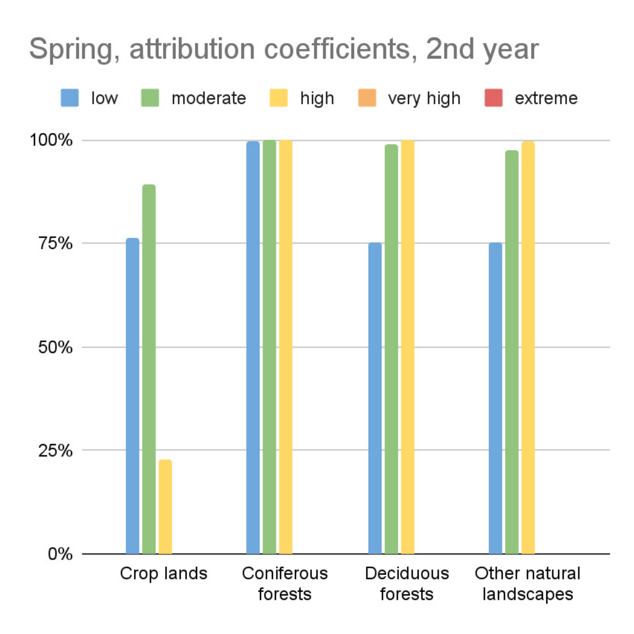
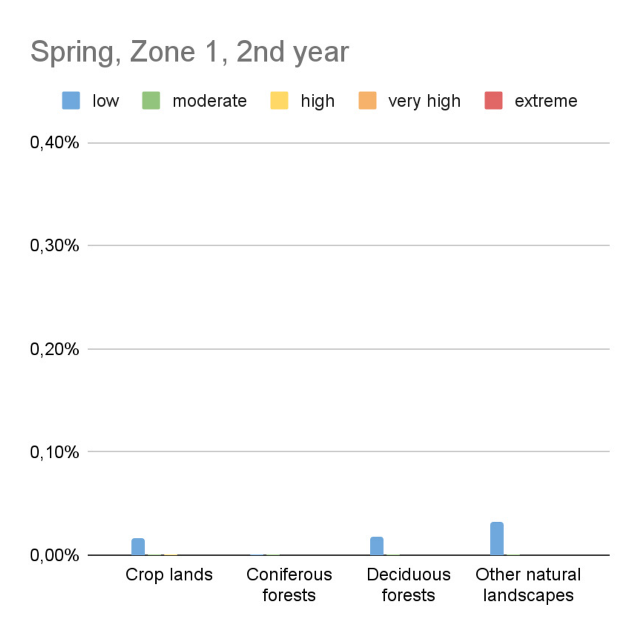
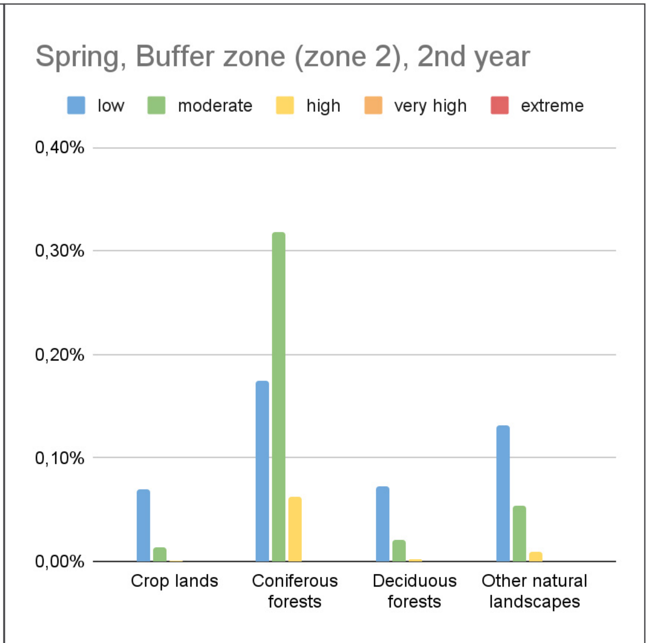


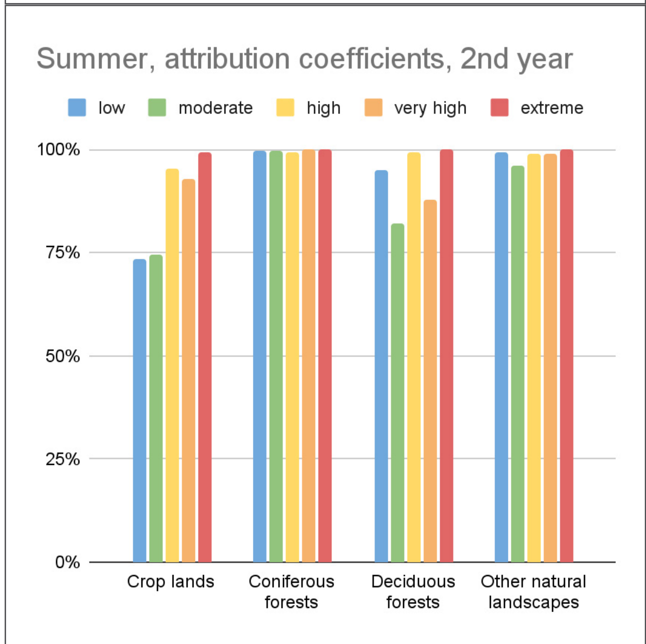
Figure 32.Attributed coefficients for the first year of the war (2022) for land cover classes and Fire Weather Index classes in %

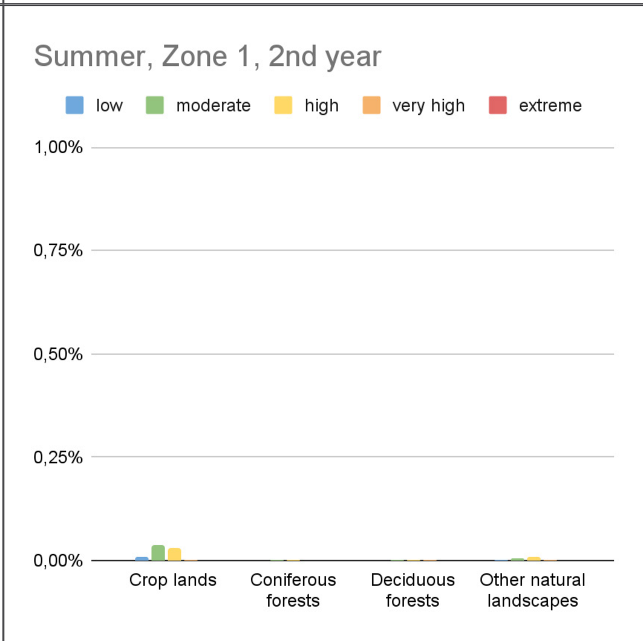
Attribution coefficients (%)	Land cover under fire in free Ukraine (%)	Land cover under fire in the buffer zone (%)

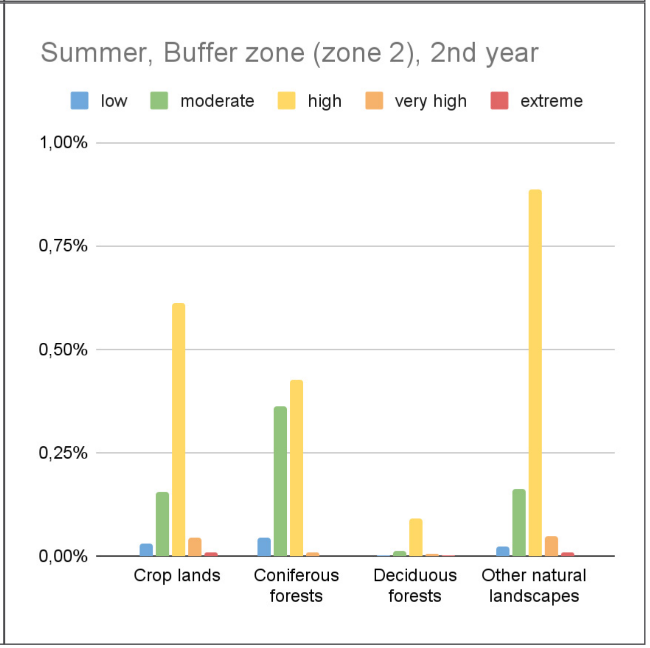












Attribution coefficients (%)	Land cover under fire in free Ukraine (%)	Land cover under fire in the buffer zone (%)

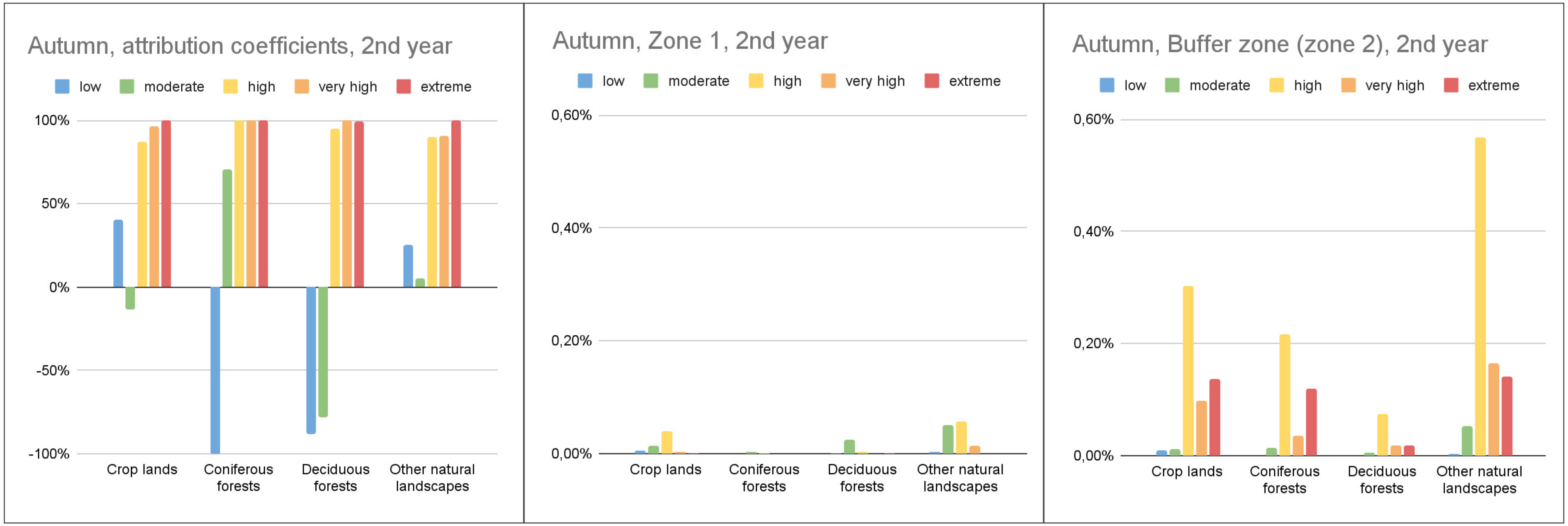


Figure 33. Attributed coefficients for the second year of the war (2023) for land cover classes and Fire Weather Index classes in %

A3. Energy Infrastructure

EVENT	IMPACT
01.04.2022 — fire at oil products storage facility in Belgorod	8 oil tanks with 2,000 m^3 of fuel each were reportedly affected
25.04.2022 — fire at oil products storage facility in the Fokino district of Bryansk city	More than one oil tank was affected. No information on the amount of fuel burnt
04.05.2022 — fire at oil products storage facility in Makiivka town	4 oil tanks with the capacity of 5,000 m^3 each were reportedly burnt
April-July 2022 — a series of fires at different oil depots in Donetsk city (29.04.2022, 07.07.2022, 26.07.2022)	No information on the amount of fuel burnt
27.10.2022 — fire at oil depot in Shakhtarsk town, Donetsk region. Additional fire in this location was reported on 02.12.2022	3 oil tanks were reportedly affected by the fire
03.05.2023 — fire at oil depot in Volna village in Krasnodar region	Total capacity of the reservoir fleet is more than 1 million tonnes. Reservoirs with the capacity of 20,000 m^3 are installed. No information on the amount of fuel burnt
03.05.2023 – fire at the fuel tanks yard of the Ilsky oil refinery, Krasnodar region	More than one oil tank was reportedly affected. No information on the amount of fuel burnt
05.07.2023 — fire at the oil products storage facility in Makiivka town, Donetsk region	More than 5 oil tanks were reportedly affected by the fire and there was also a leak of oil products
04.12.2023 — fire at oil depot in Luhansk city	No information on the number of tanks affected and the amount of fuel burnt
9.01.2024 — small-scale fire at oil products storage facility in Orel city	One reportedly empty reservoir was affected
19.01.2024 — fire at oil products storage facility in Bryansk region (Klintsy town). This storage facility was also attacked on 11.05.2023 with the reported damage to one reservoir and concrete base	4 fuel storage tanks with the capacity of 2,000 m^3 each were reportedly on fire. Total storage capacity of the facility is about 10,000 m^3

EVENT	IMPACT
January – March 2024 — a series of attacks on oil refinery plants in different regions of Russia were conducted with most of the impacts reportedly affecting technological equipment. At least 10 oil refinery plants were affected (21.01.2024 — Ust-Luga terminal in the Saint Petersburg region; 25.01.2024 — oil refinery in Tuapse in the Krasnodar region; 03.02.2024 — oil refinery in Volhohrad; 09.02.2024 — Ilsky oil refinery in the Krasnodar region; 12.03.2024 — fire at the oil refinery plant in Kstovo town in the Nizhny Novgorod region; 16.03.2024 — fire at the Ryazan oil refinery; 16.03.2024 — fires at three oil refinery plants, including in Syzran, Novokuybyshevsk, and Kuybyshevsk in the Samara region; 17.03.2024 — fire at and damage to the Slavyansk-ECO Oil Refinery in the Krasnodar Krai)	Technological equipment has been affected. Fires were reported during the incidents, but since the points of impacts were associated with technological equipment, GHG emissions were less intensive compared to the impact on oil / fuel storage tanks. No information on the volume of fuel burnt
15.02.2024 — fire at the Polevaya oil depot in the Kursk region with 3 tanks reportedly affected	3 tanks were on fire and some of them partly collapsed. The tanks affected have the capacity of 1,000 m^3 and 400 m^3
19.02.2024 — fire at the Makiivka oil depot	No information available
03.03.2024 — fire at a large oil depot in Feodosia. The Marine Oil Terminal in Feodosia is the largest in Crimea and has the overall storage capacity of about 250,000 tonnes of fuel. There are 14 tanks with the capacity of 10,000 m^3, 8 tanks with the capacity of 5,000 m^3, and smaller storage tanks	The information on the extent of damage is not available. At least one large storage tank was reportedly on fire and damaged. This oil depot was also attacked several times earlier, but no information on the damage is available (04.08.2023, 10.11.2023, 05.12.2023)
05.03.2024 — fire at an oil depot in Dolgoye village, Belgorod region	At least one small-scale fuel tank was destroyed and fuel burnt (1,000 m^3 or lower)
06.03.2024 — fire at an oil depot in the Kursk region on the territory of a mining and processing plant in Zheleznogorsk	At least one small-scale fuel tank was destroyed and fuel burnt (below 1,000 m^3)

EVENT	IMPACT
12.03.2024 — fires at an oil depot in Orel city	A tank with the capacity between 1,000-2,000 m^3 might have been destroyed by the fire
24.04.2024 — large-scale fires at an oil terminal in Yartsevo and Razdorovo, Smolensk region	Reservoirs with 26,000 m^3 of fuel were reportedly destroyed
27.04.2024 — attack on two oil refineries in the Krasnodarsk region (in Slavyansk-on-Kuban and Ilyinskoe)	Large-scale fires with the damage to both technological equipment and storage tanks were reported

Table 39. Events causing fires at oil depots and oil processing facilities

A4. Refugees and IDPs

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:

- Gasoline 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 the distance to Ukraine and the availability of a relevant transport mode. We have assumed that, in many cases, the first half of the journey was made by a gasoline car. For the second half of the journey, we have assumed as follows:

- For countries neighbouring Ukraine: gasoline 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.

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.[254] These factors may vary slightly depending on the country.

254. https://ourworldindata.org/grapher/co2-transport-mode

A5. Reconstruction

Estimating embodied carbon for different types of objects is the fundamental element of the methodology to determine reconstruction emissions. Under the embodied carbon approach, all emissions, both direct and indirect, are estimated over the whole life cycle of a facility, excluding operational emissions. For example, in case of a building, operational emissions include heating emissions, whereas for a vehicle they include gasoline, diesel, or electricity.

Buildings

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 40. Life-cycle stages of buildings

Embodied carbon includes stages A1-A3, A4-A5, B4-B5, and C1-C4. In this assessment, we only consider additional GHG emissions, 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 with demolition of a building, after which reconstruction stages A1-A3 and A4-A5 will happen. Operational carbon emissions from the Use stages B1-B3 and B6-B7 are excluded 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 (CEF) of buildings, a database of One Click LCA[255], 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	408
Cultural buildings	295
Educational buildings	419
Hotels and similar buildings	445
Industrial production buildings	398
Office buildings	379
Retail and wholesale buildings	401
Warehouses	305

Table 41. Specific Carbon Emission Factors per building types for life-cycle stages A1-A3, A4-A5, and C1-C4

The average size of each building was provided by the KSE (in m^2/unit) and then multiplied by relevant specific carbon emission factor (in tCO_2e/m^2) to obtain the embodied carbon of an object (tCO_2e/unit).

Transport & Infrastructure

In Transport & Infrastructure category, damaged roads represent a large share of the damage. A 2022 study estimated the life-cycle emissions of different types of roads.[256] 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 a road. The KSE has classified all roads as damaged, not destroyed, so only a third of the construction emission factor is used, similarly to buildings. This is probably a conservative estimation given the fact that months of combat operations cause significant damage to roads.

255. One Click LCA website: https://www.oneclicklca.com

256. 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-system	Dual-3 lane	Dual-2 lane	Single-1 lane
	tCO$_2$eq per functional unit		
Material production	1,711	1,433	591.5
Material transport	313	201.1	100.7
Construction	70	37.6	18.8
Road operation (lighting only) (40yrs.)	406.1	2,68.7	132.6
Maintenance (40yrs.)	158.8	73.5	36.6
Total emissions	**2,658.9**	**2,014.1**	**880.3**

Table 42. Embedded emissions estimated for the different sub-systems of asphalt pavement

For passenger vehicles, more research[257] 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.

Industry & Utilities

For the category of Industry & 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$_2$e/USD). As KSE considers damages as a replacement value, this approach is applicable to its data. Ideally, these spent-based factors should be determined at the country level, but these factors are not available for Ukraine. As a proxy, spend-based emission factors for the United Kingdom were used.[258] As a verification step, the spend-based approach was also applied in the category of Buildings and total emissions were comparable with those emissions resulting from the embodied carbon approach.

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

258. 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