CLIMATE DAMAGE CAUSED BY RUSSIA'S WAR IN UKRAINE

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

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

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LICENCE

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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. The war has also led to significant environmental damage with the destruction of the Nova Kakhovka dam in June 2023 as one of the most devastating events for both people and nature.

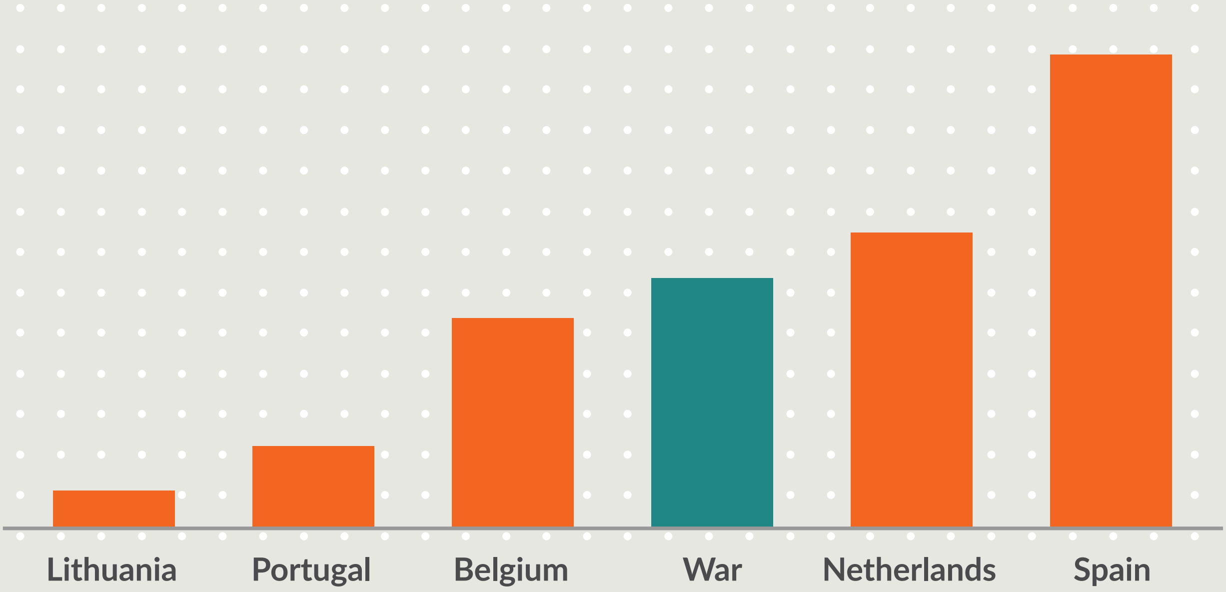
This war impacts the global climate due to the release of significant amounts of carbon dioxide and other greenhouse gases (GHG) into the atmosphere. This third interim assessment concludes that GHG emissions, attributable to 18 months or 555 days of the war, total to 150 million tCO_2e. This is more than the annual GHG emissions from a highly industrialized country like Belgium.

We believe the Russian Federation should be held accountable for these emissions and the resulting damage to the global climate. Russia should be held accountable because, without its act of aggression, these greenhouse gas emissions would not have happened. Applying the average Shadow carbon price of 64 USD/tCO_2e over the years 2022–2023, the total climate damage that the Russian Federation has caused and shall compensate is USD 9.6 billion.

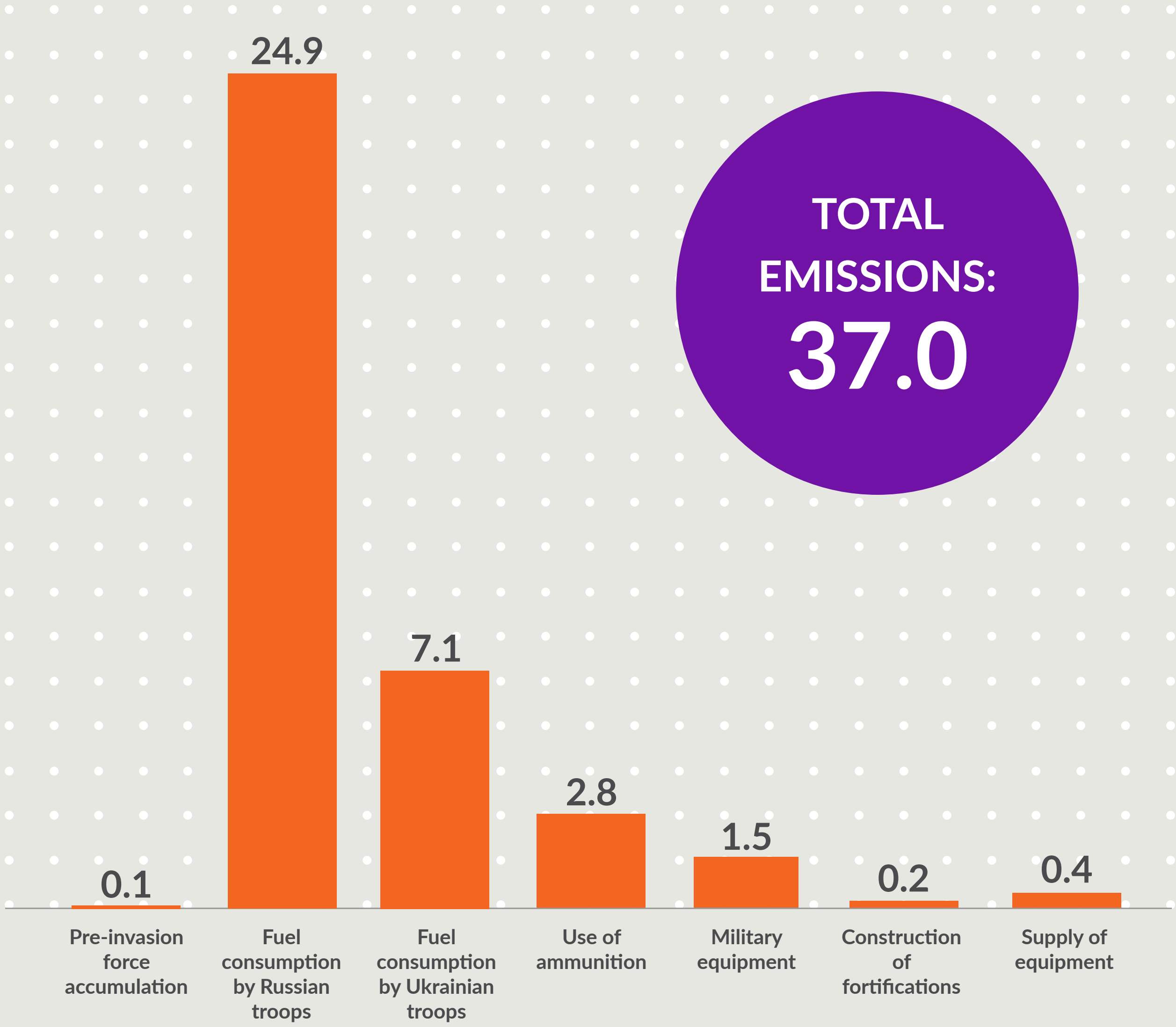
As the first step in holding Russia accountable, we recommend that these damages be included in the Registry of Damage for Ukraine, which is currently being set-up in the Hague under the auspices of the Council of Europe. For more detail, see Chapter 2.

Ukraine can use the compensation to mitigate the climate damage Russia has caused by reversing most of the war emissions to the benefit of the world community. The most obvious way to undo the damage is to channel funds to the reafforestation of destroyed forests and other nature-based solutions that remove emissions from the atmosphere. Future construction emissions, in particular those resulting from the usage of cement and steel, can be avoided by 30% to even 50% through introducing right incentives for a low-carbon reconstruction. Better insulation of buildings and an accelerated roll-out of renewable energy is a third way to undo the damage. For more detail, see Chapter 3.

GHG emissions of the war compared to annual emissions of selected European countries

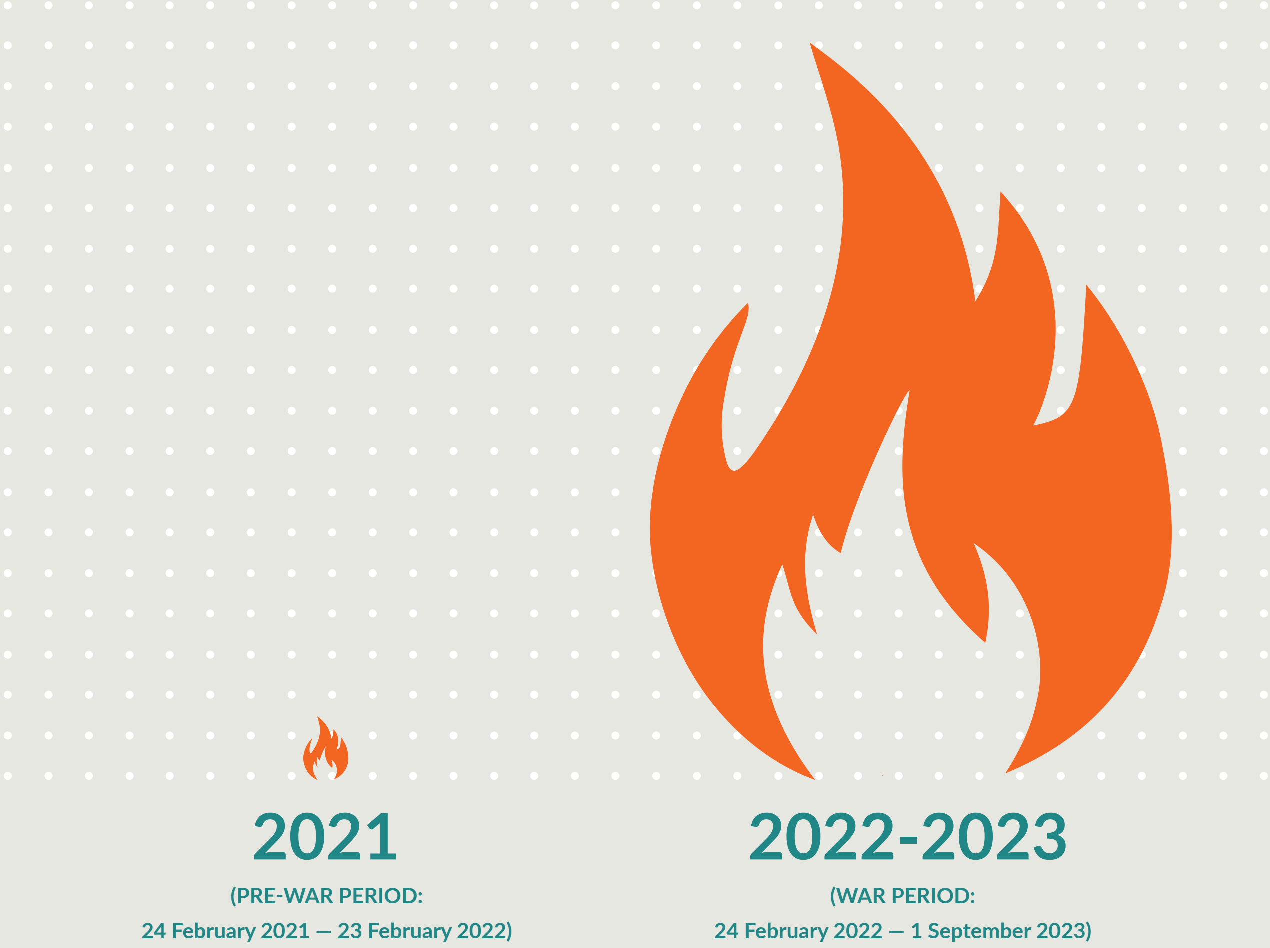


GHG emissions from warfare ($MtCO_2e$)



The number of fires larger than one hectare has increased 36-fold during the first year of the war compared to the pre-war period of 12 months and remained a significant source of GHG emissions. These fires are primarily observed in close proximity to the front line, with many leading to the destruction of forested areas. While fires subsided during the winter of 2022/2023, fires intensified again during the warmer spring and summer weather. **Total emissions: 22.2 million tCO_2e.**

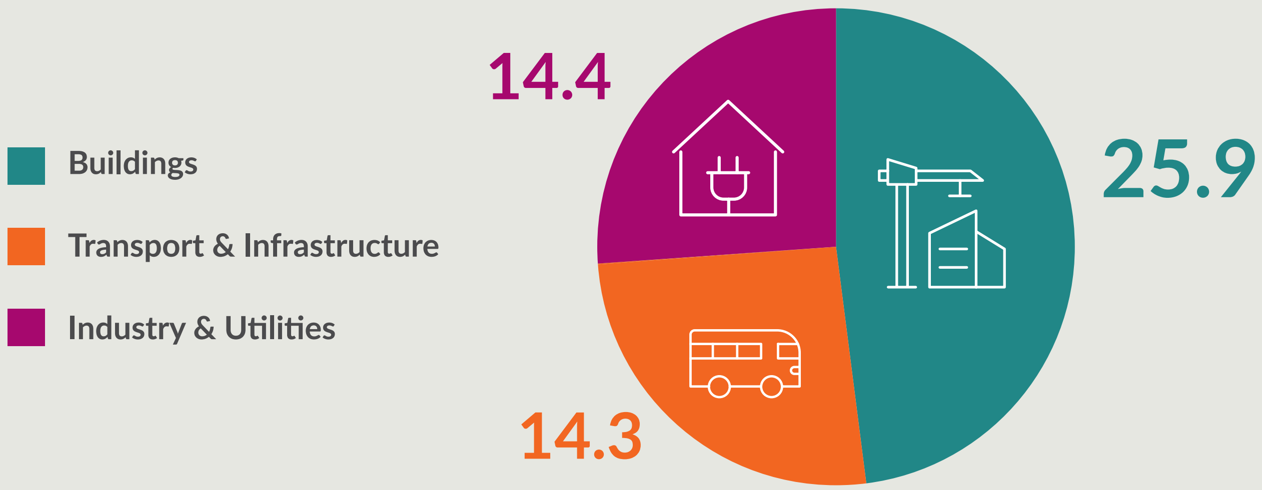
GHG emissions from fires ($MtCO_2e$)



The closure of the Siberian airspace by Russia to many carriers and the closure of Ukraine's airspace to commercial traffic have cut important east-west air routes between Europe and Asia for many Western carriers. Carriers have been 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. **Total emissions: 18 million tCO_2e.**

The post-war reconstruction of damaged and destroyed civilian infrastructure constitutes the largest source of emissions. As noted in our previous assessments, the reconstruction of buildings and other infrastructure is highly carbon-intensive. The destruction of the Nova Kakhovka dam, the resulting flood downstream, and the emptying of the reservoir constituted the most important single event and, although the frontline has remained relatively static in the past 12 months, the total damage to buildings continues increasing. **Total emissions: 54.7 million tCO_2e.**

GHG emissions of post-war reconstructure ($MtCO_2e$)



The share of each sector is visualized in the pie chart below, while the absolute numbers are listed in the table. The emissions from the sabotage of the Nord Stream 1 & 2 pipelines[1] on 26 September 2022 are included as well. It is unclear at this stage whether the damage to the Balticconnector pipeline[2] on 8 October 2023 can be attributed to the war and no data is yet available on the amount of natural gas that leaked into the atmosphere. Emissions might be included in a next interim assessment.

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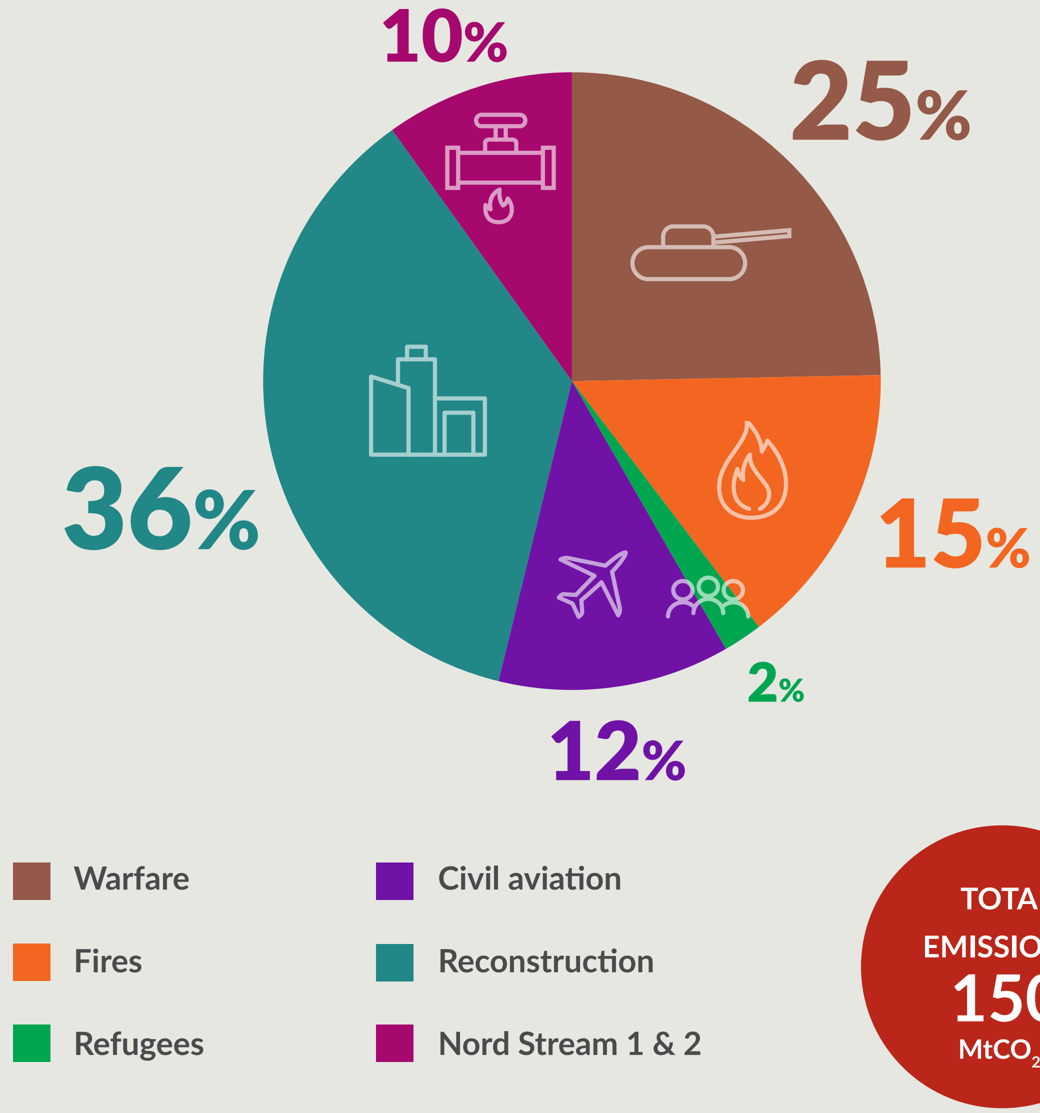
1. The possible climate effect of the gas leaks from the Nord Stream 1 and Nord Stream 2 pipelines, Danish Energy Agency, https://ens.dk/en/press/possible-climate-effect-gas-leaks-nord-stream-1-and-nord-stream-2-pipelines
2. Suspicion of a leak in the Balticconnector gas pipeline between Finland and Estonia, Gasgrid Finland: https://gasgrid.fi/en/2023/10/08/suspicion-of-a-leak-in-the-balticconnector-gas-pipeline-between-finland-and-estonia/

Total GHG emissions



TOTAL EMISSIONS:
150
MtCO$_2$e

SECTOR	EMISSIONS 18 MONTHS (MtCO$_2$e)	PERCENTAGE, %
Warfare	37.0	25
Fires	22.2	15
Refugees	3.0	2
Civil aviation	18.0	12
Reconstruction	54.7	36
Nord Stream 1 & 2	14.6	10
TOTAL	**150**	**100**

Table 1: Distribution of GHG emissions over the various sectors

1. Introduction

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

Many initiatives are keeping track of 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 civilians, who can report damages. The Conflict and Environment Observatory and the Zoï Environment Network release regular briefings to assess different environmental types of damages like radiation risk, water pollution, or industry[4]. Data on local pollution incidents is collected by civilians and processed by the Center for Environmental Initiatives Ecoaction together with Greenpeace using an interactive map[5].

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

In this report, we want to create awareness that Russia's act of aggression is not only impacting Ukrainian citizens and the Ukrainian environment, but is affecting the rest of the world through enhancing emissions and making the efforts to halt global heating more difficult. Secondly, GHG emissions related to the military and conflicts have often been overlooked, omitted, or underreported by both the military and the climate change community. This war puts the limelight on this overlooked issue and recently, many publications have appeared in the public domain[6].

The first assessment of climate damage[7] was presented at the Climate Conference COP27

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[3] https://ecozagroza.gov.ua/en

[4] Conflict and Environment Observatory (http://www.ceobs.org/publications/) and Zoï 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] For example: Low-carbon warfare: climate change, net zero and military operations, https://academic.oup.com/ia/article/99/2/667/7024982

[7] Climate Damage caused by Russia's war in Ukraine, first interim 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

in Sharm-el-Sheik, Egypt on 9 November 2022[8], 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 recons-truction of damaged and destroyed buildings, roads, and factories.

The second assessment of climate damage[9] updated these four emission causes, 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[10]. New sectors included the European energy sector, the rerouting of flights due to airspace closures, and the country-wide impact on Ukraine.

This third assessment covers 555 days since the full-scale invasion, namely, from 24 February 2022 to 1 September 2023. All sectors have been updated to reflect the full 555 days of war.

In the previous assessment we stated that Russia should be held accountable for the damage it has caused to the climate. In this report, we present a methodology of how the war emissions can be reflected in monetary terms, i.e. the damage it has caused to society. Furthermore, we give an overview of the possible legal pathways to litigate this damage.

Different solutions are presented on how Ukraine can use Russia's compensation to undo much of the additional GHG emissions, either by replanting forests or through a green recovery. In a detailed study several solutions are provided how the emissions from construction activities can be minimized.

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

In preparing the analysis, we have relied on open source information, including social media, scientific studies and open-source intelligence (OSINT) analysts, interviews with experts, industry reports, government publications, peer-reviewed articles, and other available sources of information. Acknowledging uncertainty of the estimates, we have relied on conservative assumptions, multiple sources of information, and comparing results from several alternative approaches where possible. Mapping carbon emissions of a major conflict has never been done before, let alone of an ongoing conflict, and a methodology is emerging as we are working. We are grateful to all experts, who have participated

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[8] The recording of the side-event: https://www.youtube.com/watch?v=ynQbzwxTnBw

[9] Climate Damage caused by Russia's war in Ukraine, second interim 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

[10] The recording of the side-event: https://www.youtube.com/watch?app=desktop&v=6yW1hWQmgpc

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.

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

2. Holding Russia accountable

Climate change-related losses and damage or, shorter, climate damage is a broad term used in different circumstances. In a general context, loss and damage refer to the negative consequences of climate change for human societies and the natural environment. The UNFCCC has defined loss and damage to include harms resulting from sudden-onset events (climate disasters, such as cyclones) as well as slow-onset processes (such as sea level rise)[11]. As climate change is caused by anthropogenic emissions of greenhouse gasses, any additional emissions intensify the effects of climate change and increase the associated risks. Since the full-scale invasion, an additional amount of 150 million tCO_2e were emitted and without doubt, this comes at a cost to the climate and therefore to society. Estimating the climate damage caused by Russia's war requires to put a price tag for each tCO_2e emitted.

One approach is to look at average market prices of cap-and-trade schemes like the EU Emissions Trading Scheme (EU ETS). EU ETS prices are currently fluctuating between EUR 80 and 100 per tCO_2e. Alternatively, one can look at carbon taxes levied by governments, which range from USD 156 per tCO_2e in Uruguay to only USD 0.08 per tCO_2e in Poland.[12] However, these prices result from market dynamics (EU ETS) or policy decisions (carbon tax) rather than reflect the cost to society for each tCO_2e emitted.

A more valid approach is applying the so-called social cost of carbon (SCC), which represents an estimate of the potential monetised impacts on society of an additional metric ton of carbon dioxide emitted to the atmosphere. This measure includes the economic costs of climate change that could be felt in such 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.[13]

To this effect, many international organisations have introduced the shadow carbon price (SCP) to estimate the social costs of GHG emissions[14]. The European Investment Bank (EIB) for example, applies the SCP in the appraisal of projects. The values the bank uses are given in the table below, where the SCP starts at 80 EUR/tCO_2e in 2020 increasing to 800 EUR/tCO_2e by 2050.

	2020	2025	2030	2035	2040	2045	2050
Value (€/tCO_2e)	80	165	250	390	525	660	800

Table 2: Recommended aligned EIB shadow costs of carbon (€2016/tCO_2e) for the period of 2020–2050[15]

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[11] https://en.wikipedia.org/wiki/Loss_and_damage

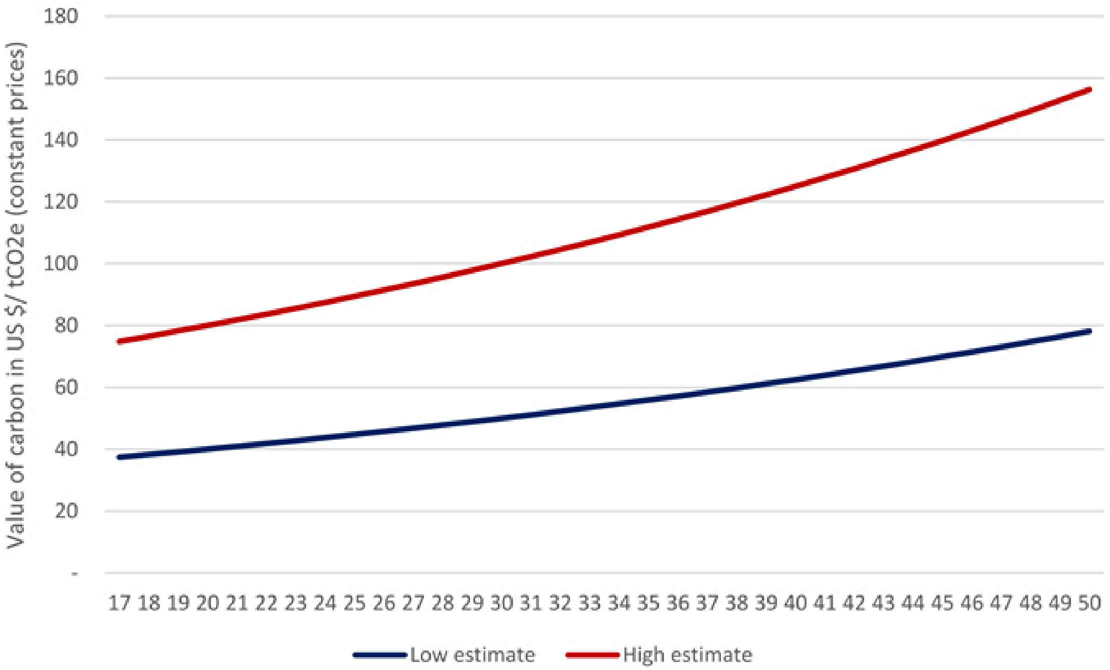
[12] https://www.statista.com/statistics/483590/prices-of-implemented-carbon-pricing-instruments-worldwide-by-select-country/#:~:text=As%20of%20March%2031%2C%202023,less%20than%20one%20USD%2FtCO₂e

[13] https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter16.pdf

[14] https://www.ebrd.com/news/2019/what-is-shadow-carbon-pricing.html

[15] EIB Group Climate Bank Roadmap 2021-2025, November 2020, Table A6. https://www.eib.org/attachments/thematic/eib_group_

The most authoritative and widely used pricing scheme is the shadow carbon price based on a study by the High-Level Commission on Carbon Prices, led by Joseph Stiglitz and Nicholas Stern in 2017[16]. The price estimates are based on the goals of the Paris Agreement to keep global warming well below 2°C. The metric leads to recommendations for a high and a low estimate of carbon prices, starting at USD 40/80 in 2020 and increasing to USD 50/100 by 2030. The shadow price has a high estimate and a low estimate due to the many uncertainties that surround such estimations. Nevertheless, there is a broad application of this metric and several reputable international financial institutions, like the World Bank and the European Bank of Reconstruction and Development (EBRD), are applying these shadow prices in their financial project appraisals[17].



Year	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Low	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	55	56	57	58	60	61	63	64	65	67	68	70	71	73	75	76	78
High	75	77	78	80	82	84	86	87	89	91	94	96	98	100	102	105	107	109	112	114	117	120	122	125	128	131	134	137	140	143	146	149	153	156

Fig. 1: Recommended shadow price of carbon (USD), World Bank: Shadow Price of Carbon, 2017

Given the authoritative character and wide application of the shadow price set by the High-Level Commission on Carbon Prices, we have applied this shadow carbon price to the war emissions. This third interim assessment covers emissions in the years of 2022 and 2023, while the average carbon price of 2022–2023 is taken resulting from a higher shadow price of USD 85 and a lower shadow price of USD 42.5, with an average of USD 64 per tCO_2e. This average is taken as the shadow carbon price of the war emissions caused by Russia's act of aggression.

With a total of 150 million tCO_2e in war-related emissions until 1 September 2023, Russia shall be liable for the total climate damage related to GHG emissions in the amount of 9.6 billion USD.

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climate_bank_roadmap_en.pdf

16. https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices

17. https://pubdocs.worldbank.org/en/911381516303509498/2017-Shadow-Price-of-Carbon-Guidance-Note-FINAL-CLEARED.pdf

In the following section, we explore the different pathways to hold the Russian Federation as a state (or its individuals to that matter) accountable from a legal perspective. How the proceeds can be used to mitigate the war emissions will be considered in the next chapter.

Study: Legal perspectives to holding Russia accountable for climate damage resulting from its act of aggression against Ukraine

State responsibility and climate change in public international law: the state of play

Holding states accountable for contributing to climate change and related damage remains one of the most difficult issues in public international law and is subject to legal debate worldwide. Bringing the issues of the use of force, aggression, and international humanitarian law into it makes it even more complicated.

State responsibility is a rather well-developed concept of public international law both in legal doctrine and case law, particularly supported by the work of the International Law Commission and the International Court of Justice (ICJ) respectively.[18]

The general approach and principle provided by Article 1 of the Draft Articles on the Responsibility of States for Internationally Wrongful Acts is that every internationally wrongful act of a state entails the international responsibility of that state. In turn, there is an internationally wrongful act of a state when conduct consisting of an action or omission: (a) is attributable to the state under international law; and (b) constitutes a breach of an international obligation of the state (Article 2 of the Draft articles). Legal consequences include the obligation of the responsible state to make full reparation for the injury caused by the internationally wrongful act (Article 31 of the Draft articles).

However, in relation to environmental damage the liability rules are still evolving and in need of further development[19]. In particular, the state responsibility regime leaves unclear the extent to which states are responsible towards the community of states in general/ the international community as a whole or a group of states based on multilateral treaty regimes[20]. Climate change clearly falls under both categories as a common concern of humankind. In particular, the global nature of climate change raises difficulties in establishing the causation (the extent to which actions of a state contributed or led to the problem and actual injury/damage to the affected state), as well as the very existence and content of respective international obligation of the state claimed to be responsible[21],

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[18] See Materials on the responsibility of states for internationally wrongful acts, 2nd edition, ST/LEG/SER.B/25/Rev.1, United Nations, New York (2023), submitted by the Secretariat of the United Nations within ICJ advisory opinion proceedings 'Obligations of States in respect of Climate Change', https://www.icj-cij.org/sites/default/files/case-related/187/187-20230630-req-06-01-en.pdf.

[19] Philippe Sands, Principles of International Environmental Law, 2nd edition, Cambridge University Press (2003). P.869.

[20] Malgosia Fitzmaurice, International Responsibility and Liability, in The Oxford Handbook of International Law, edited by D.Bodansky, J.Brunnée and E.Hey, Oxford University Press, 2008.P.1011.

[21] The fact that the UN General Assembly requested an advisory opinion of the International Court of Justice on the obligations of states in respect of climate change suggests there is much legal ambiguity as to the scope of such obligations in international law, see ICJ advisory proceedings, "Obligations of States in respect of Climate Change", https://www.icj-cij.org/case/187

including erga omnes obligations,[22] in relation to climate change mitigation.

Notwithstanding the many uncertainties, there are indications that climate change litigation should not per se fail.[23] In fact, climate change litigation is increasingly being pursued before various international, regional, and domestic fora.[24]

This is one of the reasons why the so-called climate litigation at some point took a "rights-based" approach (linking human rights regimes and climate change). It has also been largely pursued at the national level, including through tort law and investment arbitration.[25] As the "rights turn" in climate litigation has taken hold, actors undertaking, supporting, or encouraging it have proliferated apace (ranging from environmental and human rights NGOs to UN special rapporteurs and human rights bodies).[26] Yet, there is no precedent of actual interstate litigation in public international law to hold any state accountable for contributing to climate change or the damage caused by it to a particular state.

The United Nations General Assembly has recently recognized that the environmental consequences of armed conflicts may be severe and have the potential to exacerbate global environmental challenges, such as climate change and biodiversity loss.[27] There is also a consensus that the international climate change regime should not be limited to peacetime and should remain in force during armed conflicts due to humanitarian and environmental reasons.[28] However, there is a clear gap in international doctrine and practice regarding the responsibility of states for climate change damage caused by armed conflicts.

Therefore, the section below is not focused on traditional strategies of and approaches to state responsibility in relation to climate change damage. The reasons for this are rather practical: any strategy or theoretical line of legal argumentation to hold Russia accountable for the climate change-related damage resulting from its aggression against Ukraine must be closely linked to a particular legal framework, such as a court or special body, to present and defend them. Given the uncertainties related to traditional climate change litigation strategies and a rather narrow range of frameworks (jurisdictions) for them, we do not attempt to apply such traditional strategies to the present subject (aggression by Russia against Ukraine). Instead, we took a broad understanding of the issue (including the very

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[22] Erga omnes are obligations towards the international community as a whole (as distinguished from obligations towards a specific state). According to ICJ, obligations erga omnes "derive, for example, in contemporary international law, from the outlawing of acts of aggression, and of genocide, as also from the principles and rules concerning the basic rights of the human person, including protection from slavery and racial discrimination," see Supra Note 8.

[23] Faure, Michael & Nollkaemper, Andre. (2008). International Liability as an Instrument to Prevent and Compensate for Climate Change. Stanford journal of international law. 43.

[24] See IPCC AR6, in Chapter 13, page 1375, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter13.pdf and Chapter 14, Section 14.5.1.2 and Section 14.5.3, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter14.pdf

[25] See Michael Burger & Maria Antonia Tigre, Global Climate Litigation Report: 2023 Status Review (Sabin Center for Climate Change Law, Columbia Law School & United Nations Environment Programme, 2023). https://scholarship.law.columbia.edu/sabin_climate_change/202

[26] See Litigating the Climate Emergency: how human rights, courts, and legal mobilization can bolster climate action, edited by César Rodríguez-Garavito, Cambridge University Press (2023).

[27] Principles on protection of the environment in relation to armed conflicts, recital 3, Preamble, https://www.icj-cij.org/sites/default/files/case-related/187/187-20230630-req-06-04-en.pdf.

[28] Pezzot, R. (2023). IHL in the era of climate change: The application of the UN climate change regime to belligerent occupations. International Review of the Red Cross, 105(923), 1071-1091. doi:10.1017/S1816383123000188. https://www.cambridge.org/core/journals/international-review-of-the-red-cross/article/abs/ihl-in-the-era-of-climate-change-the-application-of-the-un-climate-change-regime-to-belligerent-occupations/C8A1AF9508602E5E91DAE65F6C284D68

concept of climate change damage) and focused on the main existing efforts to bring Russia to account for its aggression against Ukraine to understand how climate change issues can be integrated into such efforts. It should also be stressed that climate science should provide the key source of evidence for any such legal strategies or approaches.[29]

Climate Reparations

Ukraine and its partners are discussing ways to make Russia pay for the damages related to the aggression against Ukraine (reparations). While the vast majority of such damages will include those suffered by Ukraine, the overall reparations mechanism will certainly include ways to seek compensation for losses incurred by other states, foreigners, private companies, and even international organisations. While it is highly unlikely the reparations mechanism will include losses sustained by the international community as a whole (where climate change-related damage would primarily fall), there are ways to include damage related to climate change.

The official position of the Ukrainian government is that compensation for war losses to Ukraine should be carried out through an international compensation mechanism.[30] Currently, a political and diplomatic consensus has been formed around this idea, except for the issue of financing compensation within the framework of such a mechanism.

It is assumed that the compensation mechanism will be established under the auspices of the Council of Europe, and in May 2023, the Enlarged Partial Agreement[31] was signed, which created the International Register of Damages. Markiyan Klyuchkovskyi, the Executive Director of the Register, stated in July that the operation of the Register should start by the end of the year.[32]

The issue of compensation for environmental damage has not been widely discussed so far in light of the creation and functioning of the international compensation mechanism for Ukraine. However, the PACE Resolution No. 2506(2023)[33] of 22 June 2023 clearly states that the destruction of the Kakhovka Dam "constitutes a war crime and ecocide" (para. 1) and supports the principle stating that "the Russian Federation, as a State, provide full compensation to Ukraine once the war is over" (para. 12).

Currently, not much is known about the practical steps for collecting evidence, assessment, and compensation mechanisms for environmental damages inflicted by the Russian aggression against Ukraine within the framework of the international compensation mechanism. Iryna Mudra, Ukrainian Deputy Minister of Justice, at the conference "Special

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[29] Rupert F Stuart-Smith, Friederike EL Otto & Thom Wetzer, Liability for Climate Change Impacts: the Role of Climate Attribution Science, in Elbert R De Jong et al (eds), Corporate Responsibility and Liability in Relation to Climate Change (Intersentia 2022), https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4226257

[30] https://minjust.gov.ua/news/ministry/irina-mudra-zaproponovaniy-ukrainoyu-mijnarodniy-kompensatsiyniy-mehanizm-bezpretsedentniy-u-mijnarodnomu-pravi

[31] https://search.coe.int/cm/Pages/result_details.aspx?ObjectId=0900001680ab2595&fbclid=IwAR0mtsVTR7TPayLGAH-gMSuuk9LeZA7PLDbvgZv4RdmnW8DeXiTc7uU6xu98

[32] https://hromadske.radio/publications/10-faktiv-pro-stvorennia-reiestru-zbytkiv-zavdanykh-ahresiieiu-rf-proty-ukrainy

[33] https://pace.coe.int/en/files/32994

Tribunal For The Crime Of Aggression Against Ukraine. Justice To Be Served" on 21 August in Kyiv, stated that a draft of the categories of damages to be recorded in the Register had already been developed, without clarifying whether it was also about environmental damages.[34] As it emerges from Riga principles that were adopted during the second meeting of the Conference of Participants in the Ukrainian Damage Register in September 2023, environmental claims will be included within the purview of the Register as "other claims", together with damage to property, infrastructure, and cultural heritage[35].

Since the international compensation mechanism for Ukraine will probably be institutionally similar to the model of the UN Compensation Commission and given the scale of the environmental losses, it can be assumed that this type of damages will be allocated to a separate category that will be subject to compensation. The question of the sequence of compensation of these damages next to other categories, and the method of determining the amount of compensation (fixed or individual) currently remains unknown.

It is important to ensure at the stage of creating the reparations mechanism that climate change-related damages are not excluded from consideration. This may be achieved by including certain categories of claims by states and international organisations addressing additional GHG emissions directly related to the war, the negative impact on the capacity of some countries to meet their climate change goals, the costs to assess the climate change impact of the war, etc.

Financing the payment of compensation for environmental damage is a more urgent issue. Currently, the option of voluntary compensation from the Russian Federation looks unrealistic, and the confiscation of frozen Russian assets faces doubts of the EU and the G7 states to violate the fundamental principles of state immunity, property protection and the international economic relations based on them. Regarding environmental damages, it is worth considering more flexible forms of financing, in particular through taxing Russian hydrocarbons consumption or activities of Russian companies whose activities/operations affect the environment.

Bringing criminals to justice: war crimes

Ukraine's official position, confirmed by President Volodymyr Zelenskyy in the "Peace Formula"[36] and supported in the PACE Resolution, is to define the actions of the Russian Federation, either specific ones (such as the destruction of the Kakhovka Dam) or the overall environmental damage from aggression, as ecocide. At the same time, it is currently difficult to say whether the actions of the Russian Federation will be qualified at the national level precisely as ecocide and whether grounds will be created at the international level for bringing guilty persons to justice for ecocide. Likewise, the issue of the Russian Federation's responsibility for climate change is not currently being discussed.

[34] https://trforrus-dot-yamm-track.appspot.com/24qvCYO--6F3-qEjHBpLdtSmouMcBobmY37skJ8-0XU6K1nIjigEo7fhH_OJn6zKoek-En7_yHhzls48pa2CHYvfAJXdg8KxY_HeO08Elb7l_z4cYh-Wg0jBqclnohpkoAVyuCA5X9NFU6nBu2ZZre8Y5HLO_cN2Q2C2r_L_vSNzBzO_M

[35] https://rm.coe.int/moj-declaration-riga-principles-final-en/1680ac8728

[36] https://www.pravda.com.ua/eng/news/2022/11/15/7376378/

The classification of Russian environmental crimes as ecocide, climate change, or war crimes is, in fact, of secondary importance in the context of compensation. Liability in the form of compensation for environmental damages will arise regardless of these details. At the same time, the investigation and qualification of crimes against the environment can contribute to the establishment of facts and assessment of damages.

One of the options to prosecute those guilty of environmental crimes and get compensation for committing them is considering such actions as war crimes. According to the Rome Statute, war crimes include acts that cause "widespread, long-term and severe damage to the natural environment which would be excessive in relation to the concrete and direct overall military advantage anticipated" (Art. 8(2)(b)(iv))[37]. Since Ukraine has recognized the jurisdiction of the International Criminal Court over these crimes, it is obvious that the ICC can consider it.

Yet, the application of Article 8(2)(b)(iv)) of the Rome Statute to climate change effects of the Russian aggression does not seem promising: the burden of proof is extremely high ("widespread," "excessive," "long-term," and "severe" damage) in the context of the global nature of climate change and the contribution of this war to it.

Any ICC case will face the above-mentioned problem of financing compensation, since the accused individuals will probably not have sufficient resources to pay compensation to the victims. At the same time, within the ICC there is a Trust Fund for Victims (TFV) mechanism, from which the awarded compensations are paid and which can be funded both from the property of the accused and from other sources. In the future, confiscated assets of the Russian Federation may be transferred to this TFV for compensation payments, including for the damage caused by crimes against the environment.

Ecocide

Ecocide as a criminal offence is provided for in Art. 441 of the Criminal Code of Ukraine[38] as "a mass destruction of flora and fauna, poisoning of the atmosphere or water resources, as well as committing other actions that may cause an ecological disaster." The punishment is established in the form of imprisonment for a term of eight to fifteen years and does not directly provide for the payment of compensation.

A similar situation exists with other articles of the Criminal Code, under which the damage to the environment during Russian aggression can be classified (e.g. Article 258 "Terrorist act," Article 438 "Violation of laws and customs of war," etc.). In such cases, the criminal legislation of Ukraine envisions two ways of obtaining compensation for damages caused as a result of criminal offences:

- through the filing of a civil lawsuit against the suspect as a way of applying for compensation in criminal proceedings in accordance with Art. 128 of the Criminal

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37. https://www.icc-cpi.int/sites/default/files/RS-Eng.pdf

38. https://zakon.rada.gov.ua/laws/show/2341-14?lang=en

Procedure Code of Ukraine[39];

- in the order of compensation by the state for damages inflicted as a result of criminal offences, on the basis of Art. 127 (3) of the Criminal Procedure Code of Ukraine[40].

The civil action in criminal proceedings mechanism envisages that the victims may file a civil action against the accused in a criminal offence for compensation for the damage caused. In the event of a guilty verdict, the court may satisfy these claims in whole or in part. However, there are several circumstances that make it difficult to use this mechanism. In particular, common obstacles include the need for a civil claim to be filed before the start of a criminal trial while the claim can only address the compensation for direct property damage from the crime (not moral damage) and the need for the guilty verdict (which acknowledges the fact of guilt of committing crimes and, accordingly, the cause-and-effect relationship between the actions of the accused and the damage caused). Additionally, in the case of proceedings in absentia (which is allowed in Ukraine) it will be difficult to enforce the court decision in this part and force the guilty individual(s) to pay compensation. Lastly, the property status of persons found guilty may not be sufficient to pay compensation in the awarded amount.

The last problem is typical for the practice of compensation for damages inflicted during armed conflicts by individuals found guilty. For example, the International Criminal Court in the Prosecutor v. Bosco Ntaganda decision found that the accused "was found indigent for the purposes of the proceedings instituted against him,"[41] i.e. to make reparations.

Regarding compensation by the state for damages caused as a result of criminal offences, the corresponding guarantees are provided in Art. 127(3) of the Criminal Procedure Code of Ukraine[42]. However, according to these regulations, such compensation is possible only in the manner determined by the laws of Ukraine. The provision regarding the "procedure determined by law" in practice means that such compensation can be made only if such a special procedure is established by the Parliament or the Cabinet of Ministers.

In cases when there is no such a special procedure, courts refer to the absence of a special procedure for the compensation of damage, and the compensation by the state in accordance with Part 3 of Art. 127 (3) of the Criminal Procedure Code of Ukraine[43] cannot be implemented on the basis of general rules.

Ukraine, however, insists that an international tribunal should be set up and does not wish such an international tribunal to apply Ukraine's laws[44].

The question of bringing the top political leadership of the Russian Federation to responsibility for aggression within the framework of the Special Tribunal on Russian Aggression is also being discussed. While current international legal discourse is well developed on

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39. https://rm.coe.int/16802f6016
40. Ibid.
41. https://www.icc-cpi.int/court-record/icc-01/04-02/06-2659
42. https://rm.coe.int/16802f6016
43. https://rm.coe.int/16802f6016
44. https://www.eurointegration.com.ua/articles/2023/08/22/7167998/

ecocide[45] and often includes climate change damage, it is unlikely that any special tribunal, if established, will include the crime of ecocide. Therefore, the mandate of this tribunal will likely be limited only to the crime of aggression against Ukraine, and thus it is unclear whether it will deal with the issue of compensation for damages and whether it will be possible to consider crimes against the environment as a component of the crime of aggression.

Thus, if one wishes to bring the aggressor to justice for climate change damage within such an international tribunal, this should start with including ecocide into the mandate of such tribunal. Yet, bringing the climate change effects of the war within the scope of ecocide will be a difficult challenge in practice, for both political and legal reasons.

Can private companies use legal action against the Russian Federation to get compensation for climate change-related damages?

Private companies, including those established outside Ukraine, can be directly affected by Russian aggression for various reasons. The most obvious and widespread damage is damage to their property located on the territory of Ukraine, including loss of property, seizure of property, and halt in operation.

It would be hard, if possible, to argue a traditional climate change-related damage suffered by foreign companies in or outside Ukraine (i.e. damage related to effects of climate change, such as sea rise or extreme weather conditions). The well-known causation problem[46] is more than complicated by the tiny, in terms of total global emissions, share of GHG emissions resulting from the Russian aggression and by difficulties in attributing related emissions. This does not mean, however, that there has been no other damage related to climate change.

By taking a broader understanding of the climate change-related damage, we can think of some types of damage to private companies, which may, for the sake of this discussion, be relevant to or qualified as climate change-related damages. These may include direct financial costs of any extra GHG emissions due to the operational changes inflicted by the Russian aggression (including transportation) or financial losses related to the comeback of coal power plants in the electricity sector.[47] In any case, such financial damage needs to be assessed in country-specific and company context.

While traditional climate change litigation is aimed at bringing companies to account for climate change damage, several legal actions by private companies against states have

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45. See, e.g. A Greene, The campaign to make ecocide an international crime: Quixotic quest or moral imperative, Fordham Envtl. L. Rev., 2019, Vol.30, No.3, https://ir.lawnet.fordham.edu/cgi/viewcontent.cgi?article=1814&context=elr

46. See Stuart-Smith, R.F., Otto, F.E.L., Saad, A.I. et al. Filling the evidentiary gap in climate litigation. Nat. Clim. Chang. 11, 651–655 (2021). https://doi.org/10.1038/s41558-021-01086-7; Rupert F Stuart-Smith, Friederike EL Otto & Thom Wetzer, op.cit.

47. For example, in 2022 in Germany, generation from lignite increased by 5.4% and generation from hard coal increased by 21.4%. This is due to the fact that Germany allowed coal-fired power plants to return to the electricity market to be less dependent on natural gas amid strained relations with Russia. Source: https://www.enerdata.net/publications/daily-energy-news/germanys-power-consumption-falls-2022-generation-renewables-rises.html

been pursued in recent years (described as “anti-climate” or “backlash” cases[48]). In particular, such legal actions have been initiated as investor-state disputes; at least 14 such cases were identified between 2010 and 2022.[49] Despite being “anti-climate” these cases may well be considered as suggesting a promising legal procedure, a forum where private companies may seek compensation of climate change-related damages caused by the Russian aggression. The strengths of such a strategy include well-established legal frameworks for bringing the claim against the Russian state and high prospects of enforcing any decision by an international arbitration court in national jurisdictions. There are already precedents for such cases against Russia, including by the Naftogaz company in relation to the seizure of its assets in Crimea[50].

Another important framework for private companies to seek compensation is the future compensation (reparations) mechanism. Similarly to the UN Compensation Commission, which allowed private entities to claim damages, future compensation or reparations mechanism, when established, should allow private companies outside Ukraine to claim their damages either directly or by their respective states. It would be then up to the companies to consider raising allegations of climate change-related damages or classifying them as being so.

Conclusions: Strategies to hold Russia accountable for climate change-related damage due to its aggression against Ukraine

Neither the international climate change regime nor the international humanitarian law offers a clear pathway to bring Russia accountable for climate change damages resulting from the war against Ukraine.

Traditional climate change litigation, as understood in the legal and public discourse, is unlikely to provide feasible strategies or opportunities to hold Russia or its officials accountable for the damages caused to climate as a result of its war against Ukraine. This is supported by the difficulties such litigation already faces, particularly in international public law.

It is also unlikely that using traditional climate litigation strategies will get necessary political support from key Ukraine’s partner countries, which will not support creating a precedent for establishing state responsibility for climate change. The potential ramifications of litigation involving state responsibility, if successful, might extend beyond the legal realm and might encompass significant political and diplomatic implications. Setting any precedent in this regard, be it positive or negative, requires careful strategic planning and evaluation of broader consequences.

The strategies to hold Russia accountable for climate change-related damages flowing from its aggression against Ukraine should be based on a broad understanding of such damages and focus on using existing efforts to bring Russia to justice. Such broad understanding

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[48] Michael Burger & Maria Antonia Tigre, op.cit, p.14.

[49] Ibid.

[50] https://www.naftogaz.com/en/news/naftogaz-us-legal-action-against-russia

means it should not be limited to damages caused by climate change to individual countries, while such damages should not be excluded. In principle, it should encompass any negative consequences to the climate system itself, including any increase in GHG emissions, any resulting or associated loss, damage or injury to foreign governments, nationals, corporations, or the international community as a whole, as a result of Russia's unlawful invasion and occupation of Ukraine. They may also include the costs of the measures to offset emissions inevitably released during the post-war reconstruction measures.

Holding Russia accountable will encompass political and legal strategies. Climate change-related legal actions may involve holding either states (state responsibility), individuals (criminal responsibility), or legal entities (corporate responsibility) accountable. Climate change-related reparations/compensations, in contrast, will primarily require a diplomatic and political approach. Both play unique roles in addressing climate-related damages and require distinct approaches and different mechanisms. Both will necessarily complement each other.

The primary political strategy should encompass efforts to include climate change-related damages in the reparation mechanism to be established in relation to the aggression and/or use of force by Russia as an internationally wrongful act. The mechanism, in particular its founding legal act/framework, should provide a possibility to claim reparations for the damage to the environment and climate change by states, private companies, and individuals (no matter what form such act will have, i.e. a decision by an international organisation, a special international treaty, etc.). This does not mean the wording should be detailed or specific as various details will necessarily be set by further decisions implementing the mechanism. This also does not mean claiming climate change damages would be easy: known challenges of attribution, causation, and assessment will continue to apply. What is important is to ensure that there is a political and legal framework enabling such considerations within the reparation mechanism.

Expected international (or hybrid) criminal proceedings may also include opportunities to hold Russian officials accountable. Current limitations of the Rome Statute will most likely exclude climate change-related charges as part of the war crimes investigated and prosecuted. However, in case a new or special tribunal is established, its jurisdiction may include ecocide or a broader understanding of environmental crime(-s) if key international partners agree.

Private companies outside Ukraine have likely sustained damages that may be qualified as "climate change related," including costs of any additional GHG emissions they incurred. Such companies may use existing arbitration frameworks, in particular those available for investment disputes, to claim such damages. Alternatively, the reparations mechanism may include legal grounds (either for them directly or for their respective states of registration to act on their behalf) to raise claims in relation to climate change damages they sustained, if any.

Lastly, there will be no opportunities created, or those created will fail, to bring Russia to account for climate change damages unless sufficient and robust studies are available.

Research studies are crucial already at this stage to make sure climate change damage from Russia’s war is identified, assessed, and made public. Such studies will enhance public discourse, generate political support, and lay the factual foundation for any legal action against Russia or its officials.

3. Repairing the damage

In this chapter, we want to show different ways how the climate damage of the war can be repaired, i.e. by absorbing carbon dioxide, accelerated climate mitigation action, or avoiding future emissions.

In theory, the Russian Federation could be ordered to reverse the war emissions. The Russian Federation, as the aggressor country, has shown no consideration for the damage it causes and portrays this “special military operation” as a provoked war. Neither does it take any responsibility for the damage it is causing; therefore, it is unlikely that Russia will take any responsibility for the climate damage. Other than that, the Russian Federation has a bad track record when it comes to acting on climate change, in particular, in reducing emissions. In the recent assessment of the Russian Climate Strategy, it was concluded that “Russia’s climate plans are largely falling flat. In effect, climate laws, regulations and strategies are adopted in order to dilute any effective carbon-reduction policies that may threaten the rents for the elites.”[51] The energy think tank Ember Climate had similar observations observing that “Russia still has near-zero wind and solar generation. This leaves Russia very much a global outlier – there is no other G20 country that has yet to plan wind or solar at scale.”[52]

Most of the war-related emissions happen or will happen in the future on the territory of Ukraine. There is a significant damage to civilian infrastructure and nature and recovering, reconstructing, or reinstating to the pre-war situation can be done in a low carbon way through the build back better principle. Hence, it is more than logical for Ukraine to take upon this role to undo the damage and use the territory of Ukraine to mitigate these emissions, assuming that Russia will pay.

There are many ways how Ukraine could reverse the damage. The most obvious one is to undo the emissions resulting from wildfires in forests. Forest fires are a normal phenomenon and can have both natural causes, like lightning, and human causes, like cigarettes. In a sustainably managed forest, the forest would recover from a wild fire and grow back. By growing back, it will absorb a similar amount of carbon dioxide it released during the fire though this will require significant time. The damage to forests caused by war activities on the other hand, is much more severe and can be irreversible. In our calculations, we have assumed that many forests will die in due time and all that biomaterial will degrade. This means that forest will not naturally recover and would need an active intervention to do so. Here, climate damage compensation by the Russian Federation can help, by a fast reafforestation of the affected area and implementing other nature-based solutions to speed up sequestration.

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51. Climate Strategies 2023, Russian Climate Strategy: Imitating Leadership, https://climatestrategies.org/publication/russian-climate-strategy-imitating-leadership/

52. Ember Climate, Russia’s electricity transition has yet to begin, accessed 9 October 2023. https://ember-climate.org/countries-and-regions/countries/russia/

Another obvious way of mitigating war emissions is through an expedited roll-out of renewable energy in Ukraine. Renewable energy, like wind and solar, is already a competitive way of generating electricity, but additional funds, including investment in decentralized power generation capacities, grid modernization, and energy storage, could help to even quicker replace fossil fuel generation.

A third way is through a low-carbon reconstruction of damaged buildings and infrastructure. Although emissions from the reconstruction cannot be reduced to zero, construction emissions can be minimized. In this report, we will take a closer look into the origin of construction emissions and how such low-carbon reconstruction could look like.

Study: Low-carbon reconstruction and reducing embodied carbon

Our three consecutive assessments have demonstrated that the largest part of emissions that are attributable to the war, will result from post-war reconstruction (see chapter 4.5 Reconstruction). The assessments have assumed that all damaged and destroyed infrastructure are rebuild using traditional construction materials and techniques, but there is a significant potential to minimize emissions in case of application of sustainable and low-carbon technologies and materials for reconstruction works.

In this study, we will first explain the difference between embodied carbon (construction materials) and operational carbon (energy use). Then we look how embodied carbon is being regulated in Europe and how embodied carbon can be reduced at different stages of a construction project. We apply these general concepts to the post-war reconstruction of Ukraine and quantify to what extent these construction emissions can be avoided or minimized. Last we describe ways to be incentivize the construction industry to reduce emissions and what would be the next steps to make this happen.

In this case study, we will mainly look into the category Buildings and Industry, which constitute 50% of reconstruction emissions. The other 50% of reconstruction emissions are related to Utilities and Infrastructure category and hold similar emission reduction opportunities.

Whole life carbon of buildings: Operational vs. embodied carbon

The emissions of a building are determined by the entire life cycle of a building. The whole life cycle of a building according to EN-15978, is shown in the table below with different

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 3: Life cycle stages of buildings

stages of a building's life, starting from the supply of raw materials for the production of construction materials to the disposal of a building at the end of life.

Each stage creates emissions adding up to the 'whole life carbon' of a building, which is split into operational carbon and embodied carbon: Operational energy use (B6) and operational water use (B7) make up for operational carbon, while all the other stages (A, B1-5 and C) add up to so-called embodied carbon. In this study we will only address embodied carbon and not operational carbon.

In older buildings, by far the largest source of emissions is operational carbon during the life time of a building, in particular buildings built during the Soviet era in Ukraine. Older buildings are often badly insulated and therefore consume a lot of energy. The focus of the construction industry so far has been to reduce energy demand by better insulating buildings, while governmental regulation has become more restrictive through updated building codes. As buildings become increasingly energy efficient and energy supply decar-

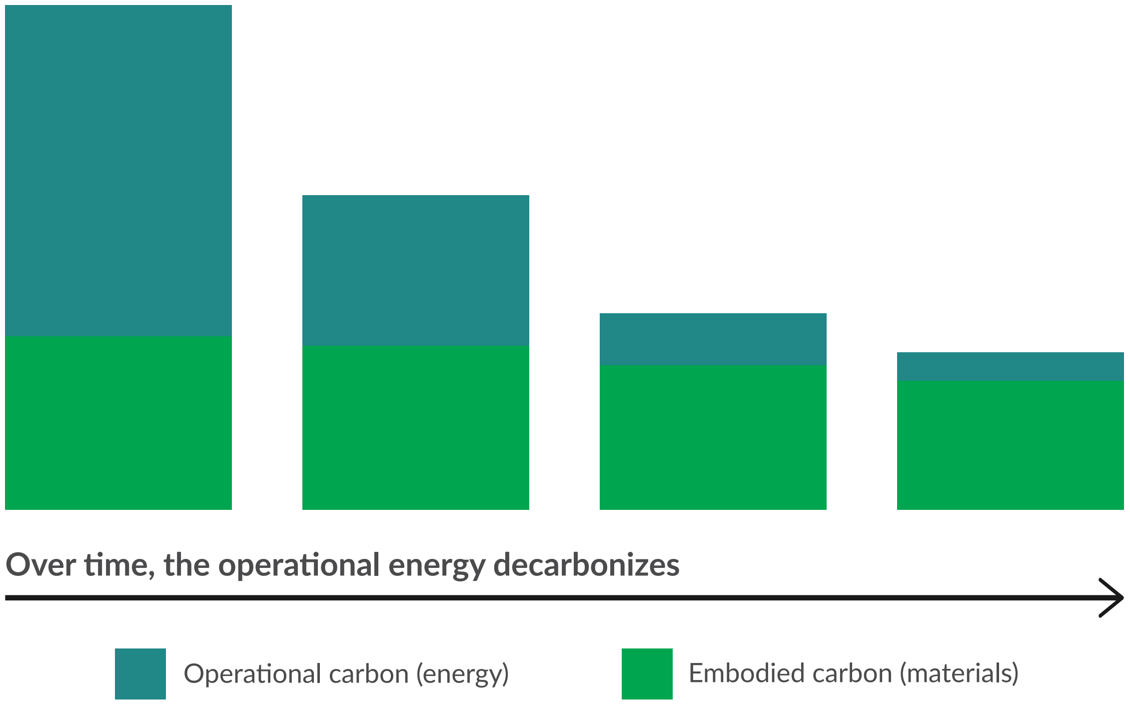

Fig. 2: The importance of embodied carbon flows as the energy demand is reduced and energy sources are decarbonized.

bonizes, operational carbon is reduced and embodied carbon will become the dominant source of carbon.

As long as manufacturing of construction materials, like cement and steel, relies on fossil fuels and emissions intensive chemical processes apply, embodied carbon will continue unabated. The impact associated with embodied carbon occurs at the time of construction and renovation and cannot be reduced afterwards, which underlines the importance of design choices at the early stages.

Emerging regulation in Europe

Recognizing the need to address embodied carbon, several European countries are developing regulations to bring down these emissions. In the table below, an overview of selected European countries implementing embodied carbon regulations is given. As one can see, these regulations are fairly recent or will only come into force in the future. A common feature of most regulations is that embodied carbon is expressed in $kgCO_2e/m^2$. [53]

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[53] This specific emission factor is usually calculated by dividing the embodied carbon of a building over the full life time by the gross floor area of the building.

Country	Methodology	In Force	Reference Unit	Compliance Type
Denmark	Bygningsreglement	2023	Impact/m^2/y	Limit value
Finland	Finnish method / Rakl.	"2024 Expected"	"kgCO$_2$e/n-m^2/a & kgCO$_2$e/site-m^2/a"	Limit value
France	RE2020	2022	kgCO$_2$e/m^2	Limit value
Netherlands	MPG	2013	€/m^2/a	Limit value
Norway	NS 3720 / TEK 17	2022	kgCO$_2$e/m^2/a	Declaration
Sweden	Klimatdeklaration av byggnader	2022	kgCO$_2$e/m^2	Declaration
UK	London Plan / Part Z	"In force / Proposed"	kgCO^{2}e & kgCO^{2}e/m^2"	Declaration
EU	Level(s)	"2027/2030 Proposed"	kgCO^{2}e	Declaration

Table 4: Regulatory frameworks for embodied carbon in Europe[54]

The French regulation is the most advanced one, with the maximum permitted embodied carbon for private residences reducing over time as presented in the table below.

Building type	Maximum value (in kgCO$_2$e/m^2)			
	2022 – 2024	2025 – 2027	2028 – 2030	from 2031
Individual or attached housing	640	530	475	415
Collective housing	740	650	580	490

Table 5: Embodied carbon limits for private housing in France[55]**.**

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54. Construction carbon regulations in Europe, October 2022, One-click LCA. https://www.oneclicklca.com/construction-carbon-regulations-in-europe/

55. https://www.legifrance.gouv.fr/download/pdf?id=Y9LyRJ3tkBWsZEVIQZBXMJOztP5gCXMNFUg5VvtB7GA

There is no embodied carbon regulation at the EU level yet. But as is often the case, novel regulation is first developed by member states and later harmonized at the EU level, and it is expected this will happen regarding embodied or whole life carbon as well. However, the EU taxonomy (see box below) has already incorporated embodied carbon as a potential green project category.

Reducing embodied carbon in practise

Reducing embodied carbon is not easy. It is not easy because the construction sector is conservative and heavily regulated, and throughout the project development stages many actors are involved. While the greatest potential to reduce embodied carbon is at the planning and designing stage of a project, at these early stages embodied carbon is normally not taken into consideration. When embodied carbon is taken into account at all, it often only happens during construction or operation & maintenance, but then it is very difficult to reduce embodied carbon. This is visually shown in the graph below. Once a building is built, there is hardly any potential to reduce embodied carbon.

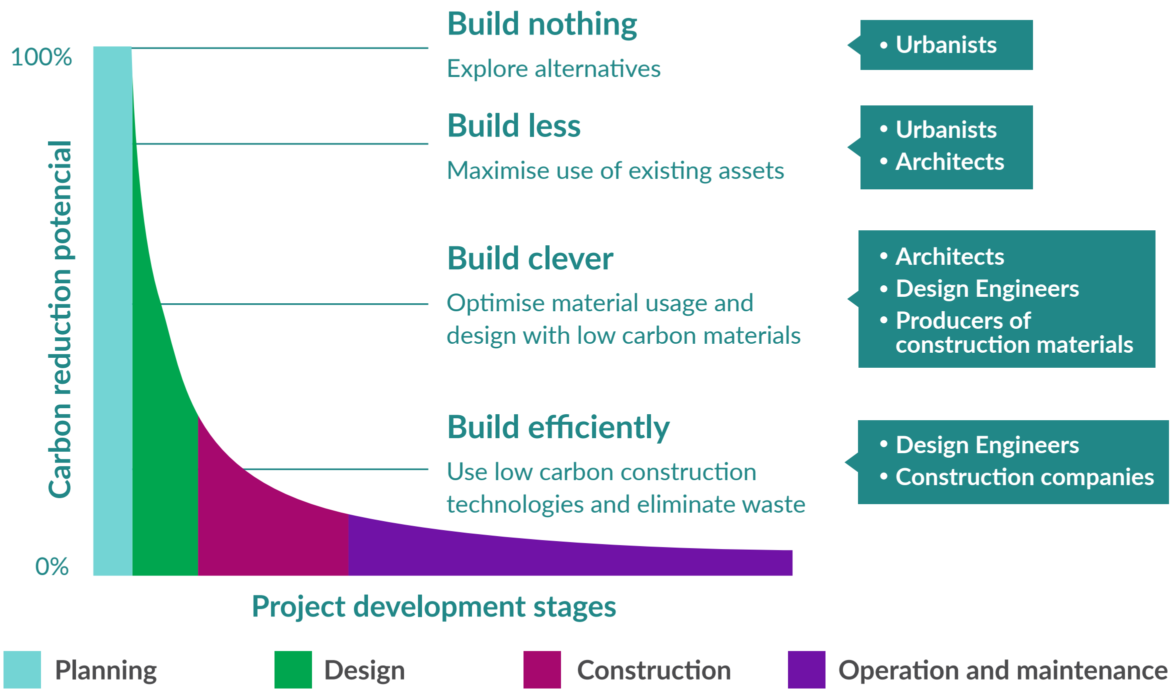

Fig. 3: Potential to reduce embodied carbon and actors involved at different project development stages.

A recent study commissioned by the World Business Council for Sustainable Development lists over 50 measures for investors and project developers regarding how they can reduce embodied carbon at different stages of a project[56]. This clearly shows the many different opportunities to reduce emissions but at the same time the complexity of embodied carbon mitigation. This is one of the reasons why governmental regulators are resorting to setting

[56] Decarbonizing construction, Guidance for investors and developers to reduce embodied carbon. https://www.wbcsd.org/Programs/Cities-and-Mobility/Sustainable-Cities/Transforming-the-Built-Environment/Decarbonization/Resources/Decarbonizing-construction-Guidance-for-investors-and-developers-to-reduce-embodied-carbon

an upper limit in emissions (in $kgCO_2e/m^2$ over the lifetime[57]) and leave it to the market how to achieve this target.

How does this translate into the Ukrainian context?

First of all, Ukraine will see a steep decrease of operational carbon due to improving insulation of buildings. Under normal circumstances, this would have been a gradual decrease, but now, with an enormous reconstruction effort ahead and increased pressure to improve energy security, the reduction of energy demand will only accelerate and hence the reduction of operational carbon of buildings. Similarly to other European countries, energy (electricity) supply will decarbonize as well. Hence, the focus on construction emissions only becomes more important.

Our current assessment concluded that reconstruction emissions will be 54.7 million tCO_2e, of which 32.3 million tCO_2e will be from the reconstruction of the Buildings and Industry category (see chapter 4.5). There is no breakdown of the emissions for construction emissions of a typical building in Ukraine, but at the European level some insights are available, which is shown below. This overview is the result of a sample of one thousand European buildings from the Carbon Heroes Benchmark Program.

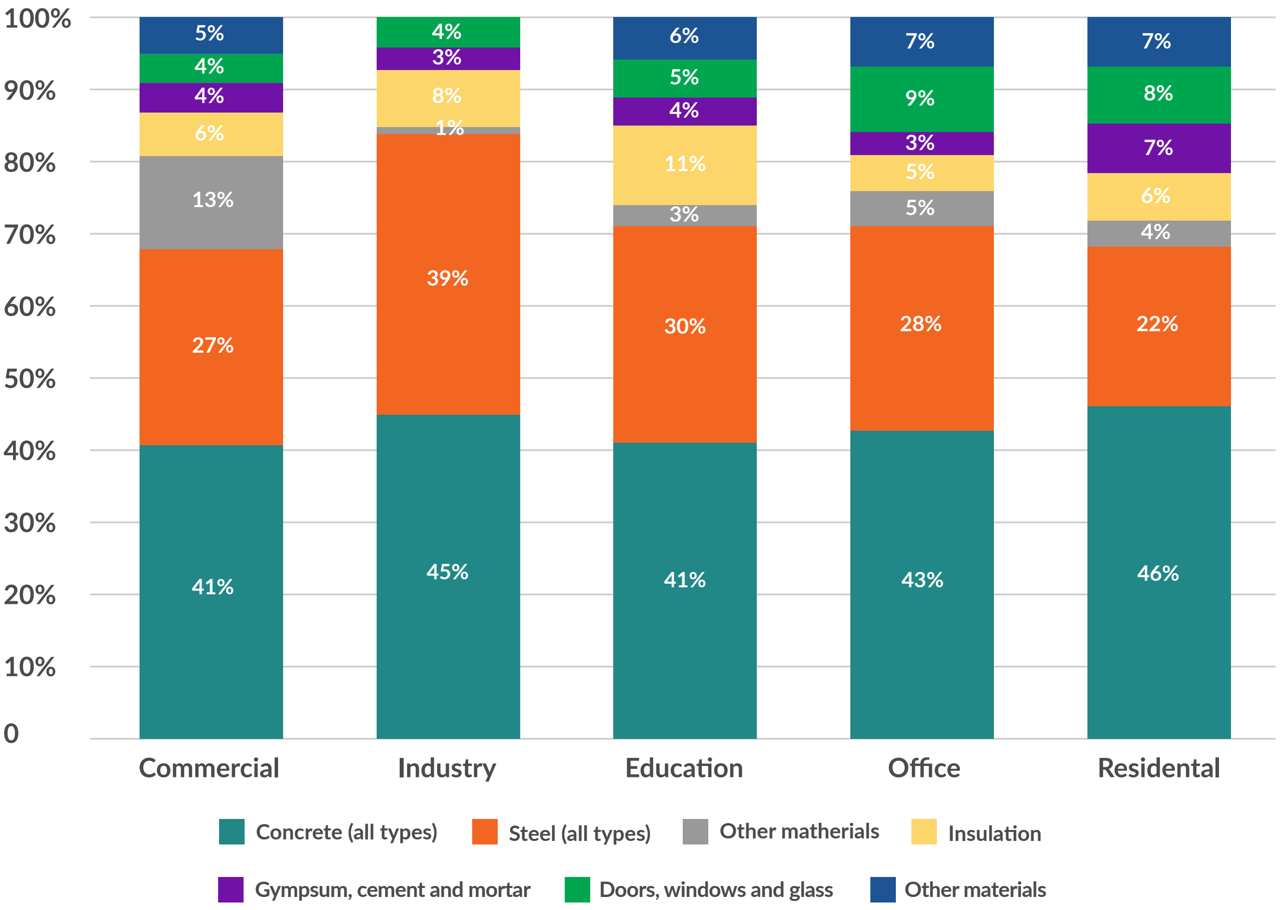

Fig. 4: Embodied carbon breakdown by material type for key building types.[58]

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57. Other ways to express embodied carbon include $kgCO_2e/m^2$, which represents carbon per square meter per year in Finland, Norway, and Denmark, or €/m^2 in the Netherlands, where carbon and other emissions are converted to monetary costs to the environment.

58. One Click LCA Ldt. Carbon Heroes Benchmark. https://www.oneclicklca.com/construction/carbonheroes/

On average, the two largest sources of emissions are concrete (43%) and steel (30%), which combined are responsible for three quarters of all embodied carbon. These are frequently used building materials and are very carbon-intensive in production.

The main contributor to concrete emissions is cement, which contains clinker. To produce clinker, much energy is needed to start the so-called calcination process, which is a chemical process that produces large quantities of CO_2 as well. It goes beyond the scope of this study to describe the different carbon sources of cement production in detail, but basically the main direction to reduce carbon intensity of concrete and cement is to replace clinker with supplementary cementitious materials (SCMs), which are often the by-products of other industries.[59] Examples of SCMs include Ground Granulated Blast Furnace Slag, a by-product of the iron industry, Pulverised Fuel Ash, a by-product of coal combustion, and calcined clay. In Ukraine, both by-products are available in large quantities. How this can affect the carbon intensity of cement is demonstrated in the table below.

Guideline values for geenhouse gas emissions from concrete						
Designation	C 20/25	C 25/30	C 30/37	C 35/45	C 45/55	C 50/60
	Greenhouse gas emissions (kg CO_2 equivalent/m^3 concrete)					
Concrete current average	178	197	219	244	286	300
Concrete with CEM I (CSC benchmark)	213	237	261	286	312	325
Concrete 20% below average (e.g. CEM III/A or CEM II/C)	142	158	175	195	229	240
Concrete 30% below average (e.g. CEM VI)	142	138	153	171	200	210

Table 6: Guideline values for greenhouse gas emissions from concrete

As can be seen from the table above, provided there is sufficient supply of SCMs, with the right incentives Ukraine has the potential to reduce carbon emissions by 30%.

The other large component is steel. Similarly to cement, steel production is energy intensive and during the process, chemical reactions generate CO_2 emissions. The Ukrainian iron and steel production is known to be less efficient compared to the world average and about 20% more carbon intensive. So, modernization of the Ukrainian steel industry will already lead to significant reductions. But the greatest reduction potential regards the recycling of steel. Steel is a product that can easily be recycled without much degradation of its strength (contrary to concrete) and it is common practise to recycle steel. Typically, the main constraint to recycling is the availability of scrap metal, but due to the war damage, much debris is available containing many steel elements, like beams and reinforcement steel in concrete. Recovering and recycling this available steel will lead to significant carbon reductions[60].

59. For a detailed description see Embodied Carbon Concrete: https://www.istructe.org/IStructE/media/Public/Resources/ARUP-Embodied-carbon-concrete_1.pdf

60. For a detailed description see Embodied Carbon Steel: https://www.istructe.org/IStructE/media/Public/Resources/ARUP-Embodied-carbon-steel_1.pdf

Combining all the measures indicated above, we estimate that in the Buildings and Industry category some **10 million tCO_2e** can be avoided representing a **30% avoidance** of reconstruction emissions.

An even greater reduction potential regards the use of alternative bio-based building materials, first of all, products from trees, like wooden-frame houses insulated with cellulose (made from used paper) or cross laminated timber (CTL). Another promising category is building or insulation materials made from straw or hemp, like hempcrete[61]. A recent study commissioned under the New European Bauhaus gives an excellent overview of the available options and their application so far in Ukraine.[62] All these bio-based construction materials have one huge advantage: they store the carbon absorbed by plants or trees when they were growing. Their embodied carbon is therefore negative and they minimize the use of carbon-intensive cement and steel. In some cases bio-based construction materials can even fully compensate the carbon emissions of cement and steel that could not be avoided, e.g. for foundations. In such cases, the building becomes even carbon neutral.[63]

There are also other types of mineral-based construction materials with lower embodied carbon content, such autoclaved aerated concrete (AAC) or various structural elements with the addition of recycled plastic, which could contribute to the decarbonisation of buildings sector. There could be also various innovations, which reduce the number of cement and concrete used for the construction via applying different additives and mixtures or structural solutions that ensure the reliability and strength of buildings while reducing climate impact.

Using alternative construction materials can reduce embodied even beyond a 30% reduction but, as there is limited experience with and availability of these materials, more time is needed to find broad application in Ukraine.

Last, but certainly not least, the best way to reduce embodied carbon is by designing a building in such a way that less building materials are needed. This is the easiest and cost-effective way to reduce embodied carbon: simply using less. The recent IPCC 6th Assessment Report highlights the importance of sufficiency interventions in buildings, which include optimisation of buildings use, repurposing unused existing buildings, prioritising multi-family homes over single-family buildings, and adjusting the size of buildings. This does require a rather smart design and a deep understanding of how design decisions impact the total embodied carbon of a building. In recent years, significant progress has been made in this regard and several software packages have entered the market to provide this insight AND offer low-carbon alternatives.

61. There are examples of Ukrainian companies producing hempcrete. See, https://www.hempire.com.ua

62. https://new-european-bauhaus.europa.eu/system/files/2023-02/221207_NEB_circular_housing.pdf

63. See as example a holiday resort in Hungary where bio-based construction materials offset cement and steel emissions: https://www.irotaecolodge.com/en/pdf/PDF_LCA_EN.pdf

How can the construction sector be incentivised to reduce emissions?

As mentioned previously, regulators in the EU set upper emissions limits (usually in tCO_2e/m^2 over the lifetime) and leave it up to the market how to achieve this target. In Ukraine, we believe it would be too early to mandate an upper limit, given that the understanding of embodied carbon by regulators and the construction sector is at an early stage. Instead, we recommend to provide an incentive for investors and project developers to remain below a certain benchmark.

This incentive would work as follows. First, a benchmark is established for different project categories like residential, educational, office, commercial, and industrial buildings. This embodied benchmark is expressed in tCO_2e/m^2.

Second, new buildings designs have their embodied carbon calculated and ranked against this benchmark. The resulting outcome can be a binary decision (below=green or above=not green) or with a certain ranking from A (deep green) to G (red). This kind of ranking has already been proposed as part of the so-called Carbon Heroes Benchmark Programme developed by One-click LCA.[64]

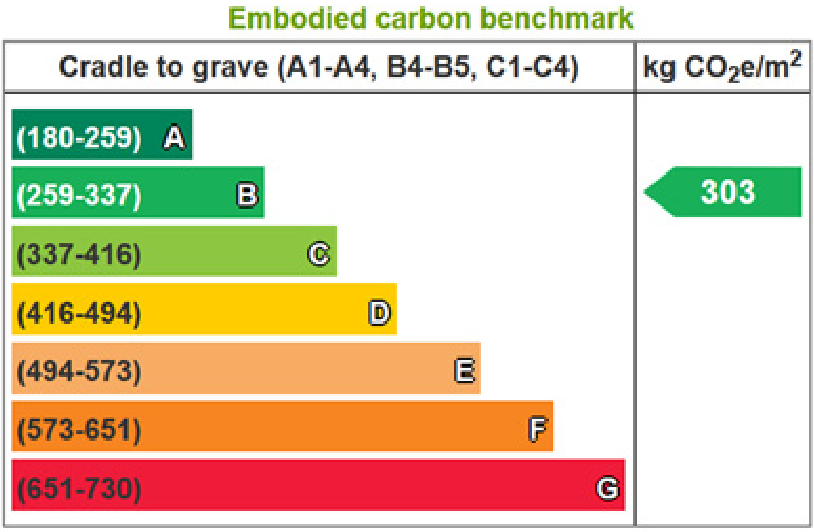

Fig. 5: Ranking of a building design against a benchmark

This ranking system is in fact a taxonomy of construction projects, tailored to the specific needs of the reconstruction of Ukraine but based on the same principles as the EU Taxonomy (see box below). Similarly to the EU Taxonomy, this suggested "UA Construction Taxonomy" helps define which reconstruction efforts are truly green and which are considered to be regular or standard designs.

Many of the recovery efforts will be financed with money provided by European and other Western donors or channelled to Ukraine through international financial institutions (IFIs) like the EBRD or the World Bank. Decarbonisation is increasingly becoming an urgent priority for these donors and IFIs, and they would like to channel as much money as possible to green projects.

Ukraine has clearly stated that its recovery and reconstruction should be green, and

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[64] https://www.oneclicklca.com/carbon-heroes-benchmark-program-whole-building-embodied-carbon-profiling/

building-back-better is also used in this context. What exactly is meant under the green reconstruction, nevertheless, remains often unclear. Constructing buildings with good thermal insulation and double or triple glazing is already required by the Ukrainian building norms and makes economic sense. The same applies to the installation of solar panels on buildings, which, as such, is a good thing to do, but with increasing energy prices and the dropping costs of PV-systems, probably would not need much stimulation.

So, with the suggested “UA Construction Taxonomy,” these IFIs can select projects they want to fund and provide preferential financial terms for these investments. They could also decide to provide a bigger discount on interest rates the higher the project scores against the benchmark.

The compensation proceeds from Russia, mentioned in the previous chapter, can also provide an incentive to project investors. For example, one can take the difference between the carbon benchmark and the project’s embodied carbon and multiply this number by the shadow carbon price of 64 USD/tCO_2e.

Alternative sources of income could potentially be carbon markets, like a voluntary carbon market or projects under Article 6 of the Paris Agreement. However, these markets provide revenue streams rather than any upfront financing. Furthermore, Article 6 regulations are under development and need some time to get operational. No carbon trading regime so far accepts this Article 6 project as a compliance tool. Therefore, we would not advise focusing on these market mechanisms for now.

EU Taxonomy

The EU’s sustainable finance taxonomy is one of the most important upcoming regulations in the EU concerning decarbonisation of the construction industry, as it requires financial market participants to provide disclosures aligned with taxonomy by 2025. The disclosure requirements are incorporated through several elements and include, for example, financial market participants to evaluate the sustainability of their investments that have been aligned with taxonomy. According to the taxonomy, all building trade-related activities can potentially contribute greatly to climate change mitigation. New building construction, building renovation, individual renovation measures, and building acquisition and ownership are all included in the activities listed in the taxonomy. For non-financial companies, the disclosure must include the proportion of turnover, capital expenditure, and operating expenditure aligned with the taxonomy and requires new buildings of over 5,000 m2 to account for whole life carbon emissions to qualify. However, no limit values have been set yet. The implementation advisory body is expected to introduce embodied carbon thresholds by 2025.

4.1 Warfare

There are no reliable estimates on GHG emissions caused by the military around the world while initiatives to increase the transparency and assess data on the climate impact of armed forces have only started to gain attention.[65]

Nevertheless, modern armies are known to be large consumers of fossil fuel even during peace time due to the operation of high-tech equipment employed (planes, helicopters, ships, tanks, and armed vehicles) and various ancillary infrastructure (airstrips, roads, permanent bases, training grounds, and supply vehicles). Energy consumption of the military is high due to the prioritization of superior combat performance of equipment, the need for rapid movement of troops, overall high-tech militarization of the armed forces, and increasing their size rather than energy efficiency[66].

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

First of all, assuming the conservative 1% share of the military's operational emissions in national inventories, during peace time, Russia's military would likely be responsible for the emissions of about 20 million tCO_2e[67], while Ukrainian military – for approximately 3 million tCO_2e. According to some estimates, Russia has committed 80% of its ground forces to the war in Ukraine, while Ukraine has obviously committed all available and additionally mobilized resources to resist Russia's invasion. During the war, the level of emissions would certainly be significantly higher and most likely would be increased manyfold due to the mobilization of manpower, more intensive use of fuel, construction of fortifications, and extended supply chains.

Secondly, fuel consumption is the most significant single source of GHG emissions associated with the operation of the military and warfare. During peace time, fuel consumption could be responsible for up to one third of total emissions or for a considerably higher share if calculated including operational emissions only (i.e. without considering supply chain emissions). Consumption of fuels significantly increases during active military activities and warfare and the rate of increase depends on the share of forces committed to military action. The highest volume of fuel consumption is typically associated with jet fuel use for aviation, which could represent more than two thirds of total fuel consumption, and diesel

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65. 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

66. 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

67. This estimate would be in line with some scarce earlier data on annual fuel consumption by Russia's military in 2016 in the amount exceeding 2 million tonnes per year, of which approximately two thirds were used by aviation (see https://tass.ru/armiya-i-opk/4031315), assuming that fuel consumption is responsible for approximately one third of total emissions.

fuel, which could represent about 20% of total fuel consumption. The ratio between jet fuel and diesel fuel will depend on the types of operations the military is performing as well as aviation use intensity during the warfare, which could be relatively low in some cases.

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

Finally, due to the complexity of supply chains and secrecy of information, especially during an ongoing war, it is not possible to track all climate impacts and achieve 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 participants in military operations, is also relevant for the assessment of warfare-related GHG emissions. A step-by-step approach moving from the helicopter view of the key sources of warfare emissions (e.g. jet fuel in case of fuel consumption, artillery shells in case of ammunition, etc.) to the gradual extension of the depth and scope of accounting is the only way forward. Finding allies and building alliances 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 understanding the scale and structure of warfare emissions, gradual improvement of the accuracy and more robust justification of assumptions is possible.

Besides, the impact of Russian aggression falls far beyond the direct emissions from fuel and energy consumption or even emissions associated with the supply chain. Analysts use a concept of total, global, and hybrid war to describe hybrid warfare tactics, including cyber, economic, informational, and covert operations, which are considered as much a part of Russia’s approach to war as conventional warfare. Examples of such tactics include weaponisation of energy, blockades of grain and other food items from Ukraine through the Black Sea, and even weaponisation of environment to influence the public opinion of allies and the international community[68]. Impacts of such hybrid warfare practices should be also analysed as a part of other indirect GHG emissions linked to the military and warfare.

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

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

GHG emissions from fossil fuel combustion

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

The most visible equipment using fossil fuels include aircrafts and main battle tanks along with other armoured equipment, but the largest share of fuel consumption during the warfare is likely associated with the less obvious fuel consumers behind the frontlines. To deploy tanks and other armoured vehicles on the battlefield, a huge military machine operates on the background and requires even higher volumes of fuel and energy. This includes heavy vehicles transporting military equipment, cargo helicopters and planes, forward bases support activities, generators used at command posts and temporary bases, as well as other 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[69] 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.).

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.

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

Estimating fuel consumption by Russian forces

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

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

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.[70]

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

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

71. Calculated based on the data reported by Bloomberg: Russia Sends More Fuel to Army In Ukraine Amid Mobilization, https://www.bloomberg.com/news/articles/2022-10-12/russia-sends-more-fuel-to-army-in-ukraine-amid-mobilization

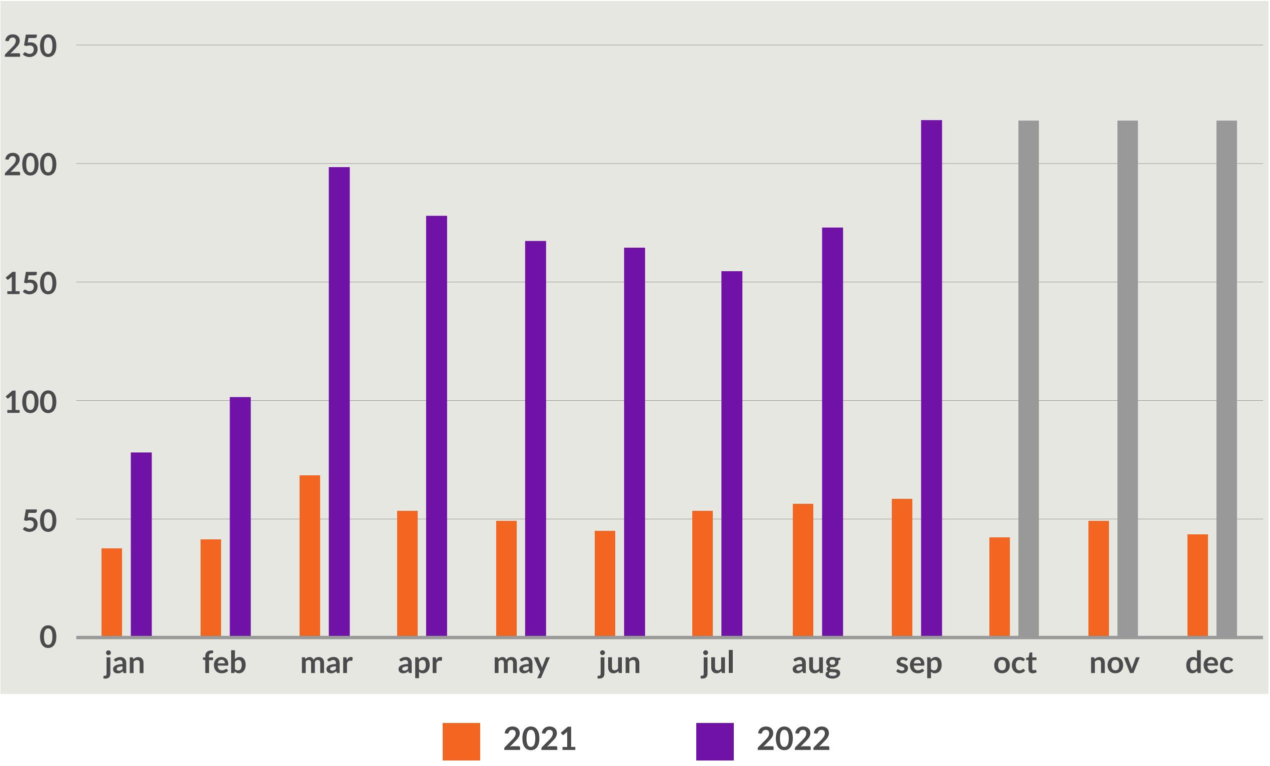

Fig. 6. Increase in fuel supply to the regions bordering Ukraine, by months, 1,000 t [72]

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	966
Estimated additional fuel supply by railway during 2022	1,483
Assumed fuel supply via other routes	30%
Estimated total fuel consumption due to the war in 2022	1,927
Estimated monthly average fuel consumption due to the war (Sep-Dec 2022)	220
Estimated total fuel consumption due to the war – up to Aug 2023	3,685

Table 7. 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.

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72. Supply in Q4, 2022 is assumed based on the data for September and marked grey; this is a conservative estimate taking into account mobilization of additional manpower and resources

The 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. Fuel consumption for the first year of the war using a supply-based approach is estimated at 3.7 million tonnes.

Fuel use based on manpower involved

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

Deloitte's study published in 2009 noted a constant increase in fuel consumption during military conflicts due to increasing mechanization of technologies used in wartime, expeditionary nature of conflict requiring mobility over long distances, rugged terrain, and irregular warfare nature of operations. The average fuel consumption as of 2007 was estimated at 22 gallons per soldier per day (equivalent to 83.3 litres per soldier per day) and was expected to grow further.[73] Other reports put estimated daily fuel consumption at 16[74] and 27.3[75] 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[76] and at the beginning of 2023 the number of soldiers involved in the occupation of Ukrainian territory was reported as 326,000-350,000, since additional personnel was involved after the mobilization announced in September 2022.[77] By September 2023, the number of personnel in occupational forces has increased to 420,000[78].

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 war and 326,000 soldiers for the second year have been applied. The value of 83.3 litres of fuel per soldier per day have been used. As of the end of August 2023, the estimated amount of fuel consumption using this approach is 9 million tonnes.

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73. Deloitte, Energy Security. America's Best Defense, https://legacy-assets.eenews.net/features/documents/2009/11/11/document_gw_02.pdf

74. The World's Biggest Fuel Consumer, https://www.forbes.com/2008/06/05/mileage-military-vehicles-tech-logistics08-cz_ph_0605fuel.html

75. U.S. military in Iraq feels gouge of fuel costs, https://www.nbcnews.com/id/wbna23922063

76. 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/

77. 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

78. В Україні перебуває понад 420 тисяч російських окупантів – ГУР, https://www.pravda.com.ua/news/2023/09/10/7419172/

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 6.3 million tonnes of fuel during 18 months of war (352 kt of fuel per month or an equivalent to 4.2 million tonnes of annual fuel consumption).

Data	Based on fuel supply estimates	Based on manpower estimates	Average
Fuel consumption, Mt	3.7	9	6.3

Table 8. Fuel consumption estimates

Most of the fuel is consumed by ground-based equipment, including the fighting "tooth" of the military and the supporting logistics "tail" of the armed forces (see the Annex for the indicative bottom-up assessment of fossil fuel consumption during the war). There are also cases of fuel storage facilities and fuel supply chain elements destruction, which contribute to the total figures with a single event potentially causing combustion of several kilotonnes of fuel (e.g. one or several storage tanks with the capacity of 5,000 tonnes or similar could be destroyed).

Ukraine's fuel consumption

As for Ukraine, there is also no data available on fuel consumption for military purposes, but it is very likely to be significantly lower compared to Russia's fuel consumption and significantly higher compared to previous years. Significantly lower fuel consumption by Ukraine is explained by the benefits of interior lines of defence for Ukraine and reliance on lighter equipment and vehicles, as well as longer supply-chain distances for the attacking country. This would also be in line with the difference in the numbers of visually confirmed main equipment losses during the war, where Russian losses are 2.7 times higher than Ukrainian ones.[79]

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.[80] 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.

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79. According to OSINT sources, as of the end of 8 October 2023, Russia has lost 12,405 units of equipment and Ukraine has lost 4,550 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

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

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

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.

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 ktonnes per month). This represents an almost tenfold increase compared to pre-war fuel consumption volumes as estimated based on reported emissions from military use of liquid fuels. For comparison, in 2022 Ukraine imported 7.3 million tonnes of oil products[81] (assumed fuel consumption represents 11-22% of oil products import). Overall fuel consumption during 18 months of war is estimated as 1.8 million tonnes. Ukrainian fuel consumption could be likely verified after the end of the war.

Emissions from fossil fuel consumption

Total estimated GHG emissions associated with fuel combustion are 32 million tCO_2e.

Data	Russian Forces	Ukrainian Forces	Total
Assumed fuel consumption, Mt	6.3	1.8	8.1
Direct GHG emissions from fuel combustion (estimated using default emission factor for diesel fuel), Mt CO_2e	20.2	5.7	25.9
Upstream GHG emissions associated with fuel combustion,[82] $MtCO_2e$	4.7	1.3	6.1
Total GHG emissions from fuel combustion, Mt CO_2e	**24.9**	**7.1**	**32.0**

Table 10. Total fuel consumption and GHG emissions

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

[82] Calculated based on the emission factor of 745.68 kg CO_2e per tonne of mineral diesel as reported by the UK Department for Environment Food & Rural Affairs – well-to-tank (i.e. upstream) emission factors for fuel in the "Conversion factors 2022: full set (for advanced users)" spreadsheet (on the "WTT- fuels" worksheet), available at https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022

GHG emissions from the use of ammunition

Artillery guns in both 152 mm (used by Russia and Ukraine) and 155 mm calibres (used by Ukraine) are able to deliver a projectile of approximately 40 kg to ranges of 17-40 km and are used during the war on a massive scale. While at the beginning of the war both sides used artillery shells of 152 mm calibre, later Ukraine switched mostly to 155 mm calibre artillery provided by Western partners. At the end of the first year of the war, the distribution of artillery shells used was reported to be 10 to 1 in favour of 155 calibre[83], while on average for 2022, some estimates reported relatively equal shares of both artillery ammunition types[84].

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

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

The use of artillery and other types of ammunition depends on the intensity of warfare at different parts of the front and varies significantly since the start of Russian invasion. During the first assessment, reviewed estimates of the number of shells shelled varied considerably in the range of 5,000-60,000 shells per day. It also varied over time depending on the intensity of shelling at different sections of the frontline. In May and June 2022, Russia's artillery fire intensity was especially significant.

During the first months of 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 shells per day. Russia relied on the quantity of shells to make up for a lack of precision strike capability[85].

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[86]. There was a large number of ammunition destroyed due to strikes at ammunition warehouses and storage sites, which caused detonation and explosion of ammunition (more than Russian 50 warehouses were destroyed).

The assumed artillery use level for the initial interim assessment was 0.9 million of artillery shells per month (30,000 shells per day) for Russia and, additionally, 0.2 million shells per month for Ukraine (7,500 shells per day). The estimates could be considered conservative

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83. Комбриг 45-ої бригади Олег Файдюк: Нам однозначно треба більше гармат, https://www.pravda.com.ua/articles/2023/02/7/7388192/

84. 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/

85. 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

86. https://twitter.com/TrentTelenko/status/1605644712458670080

under the conditions of limited information available and high uncertainty levels, as well as use intensity estimates reported by various analysts[87].

Since then, there were growing reports of evolving artillery deficit for both Russian occupying forces[88] and the Ukrainian army. Though Russia might have huge stocks of artillery shells accumulated during Soviet times, their age and unsatisfactory storage conditions led to propellant deterioration and made the older stocks unusable[89].

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.[90]

Reports from February 2023 stated that Ukraine asked for an increased artillery shells supply in face of expected escalation and the average use level was about 5,000 shells per day[91]. 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.[92,93]

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.[94]

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

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[87] According to the Royal United Services Institute for Defence and Security Studies report, Russia was firing approximately 20,000 152-mm artillery shells per day compared to Ukraine's 6,000, with an even greater proportional disparity in multiple rocket launchers and missiles fired. Source: Ukraine at War Paving the Road from Survival to Victory, https://static.rusi.org/special-report-202207-ukraine-final-web_0.pdf. According to other analysts, the firing rate was 1-1.5 million rounds per month (30,000-50,000 per day) from May 2022 onwards, https://twitter.com/Volodymyr_D_/status/1560350883929620481. Representatives of the MoD of Ukraine reported the use of 40,000- 60,000 rounds per day by Russia during the period of intense fighting, https://telegraf.com.ua/ukr/ukraina/2022-09-06/5715744-godovoe-proizvodstvo-snaryadov-raskhoduetsya-za-mesyats-okkupanty-istoshchayut-svoi-arsenaly-pomozhet-li-kndr. There were estimates that during the six months of war Russia alone used 7 million artillery rounds, excluding losses due to the destruction of warehouses, https://theins.ru/politika/254514

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

[89] Комбриг 45-ої бригади Олег Файдюк: Нам однозначно треба більше гармат, https://www.pravda.com.ua/articles/2023/02/7/7388192/

[90] According to the US officials, the rate has dropped from 20,000 shells per day to around 5,000 per day on average, while Ukraine estimated that the rate has dropped from 60,000 to 20,000 per day. Ukraine also had to ration artillery use throughout the war and was on average firing around 3,000-7,000 artillery rounds per day. See: Russian artillery fire down nearly 75%, US officials say, in latest sign of struggles for Moscow, https://edition.cnn.com/2023/01/10/politics/russian-artillery-fire-down-75-percent-ukraine/index.html. See also https://twitter.com/konrad_muzyka/status/1635923958036922368

[91] Ukraine pleads for ammunition 'immediately' as Russia steps up attack, https://www.ft.com/content/817b7e61-9f09-494c-8f96-934810033b62

[92] Nato is in ammunition race against Russia in Ukraine, says Stoltenberg, https://www.ft.com/content/3d3c9102-b8ef-4b1c-a8dc-6c844de71981

[93] As of April 2023, Ukraine was reportedly using 7,700 artillery rounds per day, while Russia was firing three times more. See: Facing critical ammunition shortage, Ukrainian troops ration shells, https://www.washingtonpost.com/world/2023/04/08/ukraine-ammunition-shortage-shells-ration/

[94] 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

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.[95]

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

FIRST INTERIM ASSESSMENT (6 months period from 24 February till August 2022)			
Data	**Shells per day**	**Shells per month**	**Shells per 6 months**
Assumed use of shells by Russia	30,000	900,000	5,400,000
Assumed use of shells by Ukraine	7,500	225,000	1,350,000
Total	37,500	1,125,000	6,750,000
SECOND INTERIM ASSESSMENT (6 months period from September 2022 till February 2023)			
Assumed use of shells by Russia	20,000	600,000	3,600,000
Assumed use of shells by Ukraine	5,000	150,000	900,000
Total	25,000	750,000	4,500,000
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
TOTAL NUMBER OF SHELLS DURING THE ASSESSMENT PERIOD (24 February 2022 — 1 September 2023)			
Assumed use of shells by Russia			11,700,000
Assumed use of shells by Ukraine			3,510,000
Total			15,210,000

Table 11. Estimated artillery ammunition use

Total artillery shells used would be over 3.5 million shells for Ukraine and 11.7 million shells for Russia or over 15 million shells in total for the 18 months of war. Assuming 80 kg weight of the artillery shell with container, the total weight would be 1.2 million tonnes.

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[95] 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

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

In particular, over half of the assumed volume for Ukraine could be tracked via information about the assistance provided by various partners[96]. 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.[97] 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.[98]

According to some estimates, before the war, Russia had about 17 million units of ammunition, of which about 10 million have been reportedly used as of December 2022. Russia's artillery recovery capacity was about 1.7 million units per year before the war, and during the mobilization the capacity of the arms industry has also been increased and potentially doubled.[99] Some other analysis indicates that even likely overestimated production capacity is lower and was growing from 0.2 million shells in 2015 to 0.7 million shells in 2021[100] and potential production capacity after its increase during the war is between 1 and 2 million shells per year.[101] Besides, Russia also relied on the stocks from Belarus with 130,000 tonnes reportedly supplied during the first year of the war[102] and looks for the opportunities to import artillery shells from other countries.

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

- 2,069,000 tCO_2e due to manufacturing of ammunition (steel casing and explosives);

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96. 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 198 155 mm Howitzers and 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. Artillery shells were also supplied by other countries, including 50,000 152 mm shells provided by the UK and sourced from Pakistan https://euro-sd.com/2023/01/articles/29154/demand-and-supply-the-complexities-of-artillery-and-ammunition-supply-in-the-war-in-ukraine/; 27,000 155 mm rounds from Canada https://www.canada.ca/en/department-national-defence/campaigns/canadian-military-support-to-ukraine.html; 18,500 rounds from Germany https://www.oryxspioenkop.com/2022/09/fact-sheet-on-german-military-aid-to.html, over 4,000 rounds from Czech Republic, https://www.czdefence.com/article/czech-republic-donates-artillery-ammunition-worth-czk-366-million-to-ukraine; and thousands rounds from Estonia https://www.eurointegration.com.ua/eng/news/2023/01/23/7154651/; and other countries https://www.kyivpost.com/post/11042

97. 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

98. 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/

99. Grosberg: Venemaal jätkub ründevõimet veel kauaks, https://www.err.ee/1608815563/grosberg-venemaal-jatkub-runde-voimet-veel-kauaks

100. Russia Struggles to Maintain Munition Stocks (Part Two), https://jamestown.org/program/russia-struggles-to-maintain-munition-stocks-part-two/

101. 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

102. 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/

- 41,675 tCO_2e due to emissions at the point of firing;
- 2,890 tCO_2e due to emissions from detonation at the point of impact.

Total emissions from the use of ammunition would be approximately **2.1 million tCO_2e**.

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

Overall emissions associated with the use of ammunition and explosives would be at least **2.8 million tCO_2e**.

GHG emissions from construction of fortifications

After the liberation of a significant part of the Ukrainian territory in autumn 2022, Russia has started preparation in 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 has continued throughout 2023.

Numerous fortifications were constructed along the frontlines, which stretched over approximately 1,000 km on the east and south of the country.[103] The longest distance of fortified lines is represented by trenches of different depth and width.[104]

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 specialized 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.

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.[105] Also, trenches are typically not linear but follow octagonal or zigzag traces. Taking

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[103] See the following article for the visualization of fortification lines location and length: Follow the 600-mile front line between Ukrainian and Russian forces, https://www.washingtonpost.com/world/interactive/2023/russia-ukraine-front-line-map/

[104] See the following article for the description and visualization of the trenches and other elements of the fortification lines: Digging in. How Russia has heavily fortified swathes of Ukraine – a development that could complicate a spring counteroffensive, https://www.reuters.com/graphics/UKRAINE-CRISIS/COUNTEROFFENSIVE/mopakddwbpa/index.html

[105] 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

all this into account, the length of trench lines is significantly bigger than the length of the frontline, and based on the analysis of satellite images, it has been estimated at 3,309 km (based on the assessment as of 24 August 2023; see Fig 2 and the Annex for details on the approach).

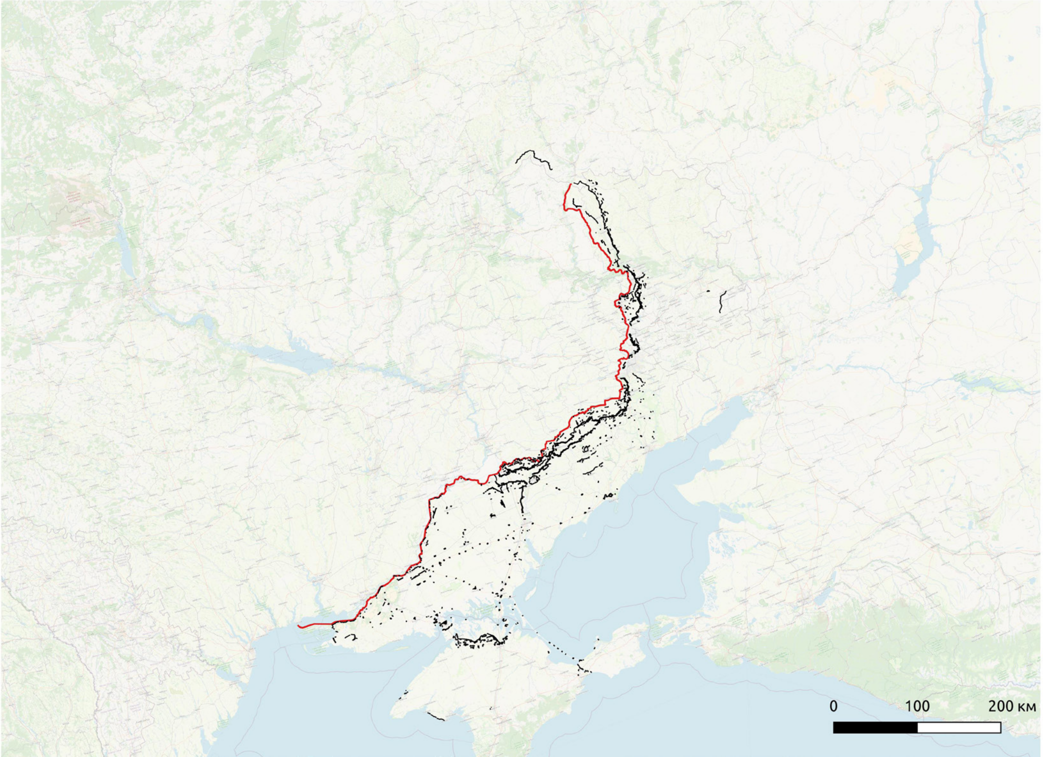

Fig. 7. Location of fortifications on the occupied territory of Ukraine and in Russia

However, as reports from the ground battles during the Ukrainian counter-offensive started to feed in media, it appeared that the scale of fortifications is even larger 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.

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.

There is a special military trenching machine (BTM-3) used by motorized and mechanized infantry units for the construction of trenches. The machine is able to dig trenches up to 1.5 m in depth (1.1 m wide at top and 0.5-0.6 m wide at bottom) with earth working capacity of 270-560 m/h (higher if the depth is lower). BTM-3 carries enough fuel for continuous digging for 10-12 hours and has fuel consumption of 75 kg per hour.[106] The speed of digging and fuel consumption depend on soil characteristics. Assuming the average

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106. 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

capacity of 400 m per hour, digging of 1000 km of trenches would require 2,500 hours and 187.5 tonnes of diesel fuel. Additional energy would be required for digging emplacements for shelters and machinery. Still, even though fuel consumption of a single trenching machine is significant, the overall consumption is not material compared to all fossil fuel use during the war and could be estimated as below 1,000 tonnes. A similar level of fuel consumption could be expected for dismantling and restoration works.

Construction of field fortifications requires significant amount of concrete, wood, and other construction materials.[107] 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.

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

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 the analysis of information collected by various OSINT analysts, the overall length of "dragon's teeth" lines within active combat zone along the frontlines was estimated as 419.3 km as of 1 September 2023.

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[107] See, for instance, a line of more than 75 trucks with construction materials for fortification lines near Svatove town, https://twitter.com/DefMon3/status/1596507887572234241

[108] See analysis of satellite images: Defenses Carved Into the Earth, https://www.nytimes.com/ interactive/2022/12/14/world/europe/russian-trench-fortifications-in-ukraine.html, First on CNN: Russian mercenary group constructs anti-tank fortification, satellite images show, https://edition.cnn.com/2022/10/22/europe/russia-anti-tank-fortification-intl/index.html; На шляху до моря, https://texty.org.ua/d/2023/way_to_sea/

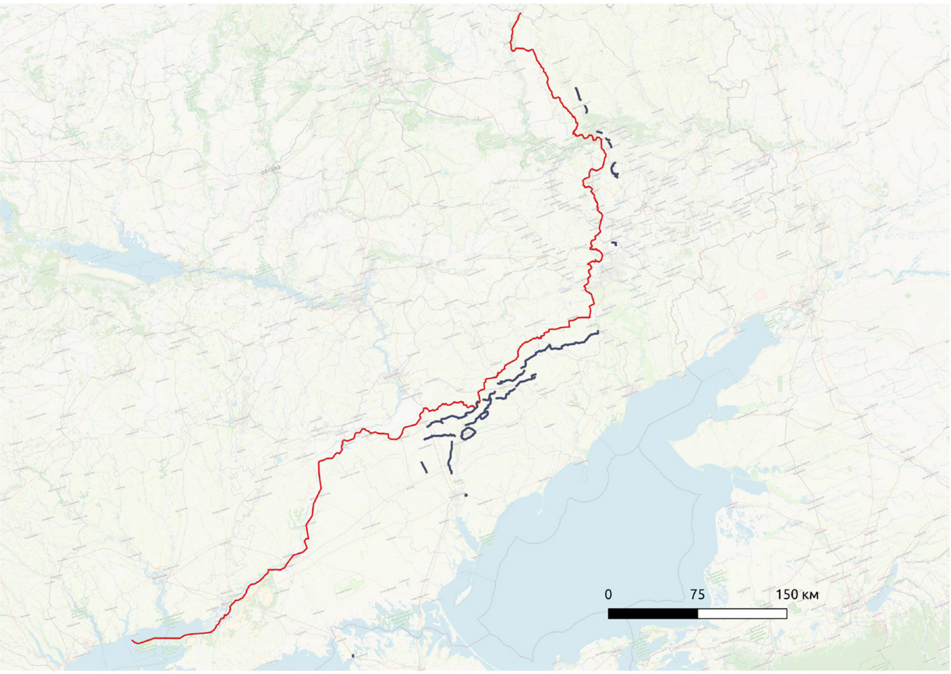

Fig. 8. Location of “dragon’s teeth” lines

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 (see the Annex for details).

For the purpose of carbon footprint estimation, it is assumed that at least 600 km of “dragon’s teeth” lines were installed and 450,000 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 540,000 t of concrete have been used for the construction of dragon’s teeth structures.

Approximately 125 “dragon’s teeth” in each row over the 460 m section of the field or about 27 units per 100 m in a single row

Fig. 9. Illustrative example of a dragon’s teeth line in Zaporizhzhia region

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

Still, this is only one type of concrete fortifications used at the battlefield. There were also numerous reports about the transportation and installation of precast concrete bunkers or pillboxes, in particular on the south of Ukraine.[109] For instance, the weight of a small firing position from concrete or machine-gun emplacement could be in the range of 1 to 2 tonnes. The weight of larger prefabricated or assembled from sections concrete pillboxes could be in the range of 10 to 30 tonnes. Large strongholds could require even higher volumes of concrete. 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[110].

For the purpose of assessment, it is assumed that at least 70,000 tonnes of concrete have been used for other fortification structures. The assumption requires further verification but is considered conservative taking into account the massive length of the fortification lines (i.e. this would correspond to the use of about 20 tonnes of concrete per km of trenches, which is an equivalent of one concrete pillbox or a small section of trenches with concrete cover per km).

Ukraine also constructs fortifications on the liberated territories and other territories along the border with Russia and Belarus. Fighting positions and shelters from reinforced concrete were installed in Kyiv,[111] Zhytomyr,[112] and Rivne,[113] regions. A concrete wall has been also constructed at some sections of the border between Ukraine and Belarus.[114] Field fortifications on the north of Ukraine include not only concrete fortifications but also shelters from special steel modules that are installed underground.[115] Concrete is also used for fortifications along the frontlines on the east and south of Ukraine (shelters, firing positions, strongholds, etc.). Besides, concrete shelters are installed in cities to protect civilians from shelling.[116] Smaller shelters and fortification structures could have a weight of about 20 tonnes while larger shelters weight around 70 tonnes. Apart from that, thousands of concrete blocks are used for the organisation of block-posts in cities and other locations.

There is no information available on the number of such structures installed; however, taking into account the announcements in the news and the length of the border, it is safe to assume that hundreds of shelters have been installed in cities and many hundreds of concrete structures were used for fortifications. For the purpose of this assessment,

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[109] See, for instance: https://twitter.com/TrentTelenko/status/1588626918651621377

[110] See, for instance, photos from the early stages of trench construction with concrete bunker visible on the background and later photos, where 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

[111] 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/

[112] Держкордон на Житомирщині укріплюють “ДОТами” та габіонами, https://mil.in.ua/uk/news/derzhkordon-na-zhytomyrshhyni-ukriplyuyut-dotamy-ta-gabionamy

[113] 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/

[114] 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

[115] Інженери готують позиції за допомогою підземних модулів, https://mil.in.ua/uk/news/inzhenery-gotuyut-pozytsiyi-za-dopomogoyu-pidzemnyh-moduliv/

[116] 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

the assumption was made that at least 100,000 tonnes of concrete have been used for fortification structures and shelters.

Concrete used for dragon's teeth manufacturing, t	540,000
Concrete used for other fortification structures by Russian forces, t	70,000
Concrete used for fortification structures and shelters by Ukraine, t	100,000
Total amount of concrete used for fortifications, t	710,000
Total amount of concrete used for fortifications, m^3	2.4
Assumed concrete density, t per m^3	296,000
Emission factor for concrete[117], t per m^3	0.5
GHGs emissions from concrete manufacturing, tCO_2e	**148,000**

Table 12. Assumptions used for the calculation of carbon footprint

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

To estimate the carbon footprint of fortifications and shelters in a more precise way, a detailed inventory of the types of fortifications employed and materials used for their construction would be required (e.g. data on the quantities of materials used by militaries for the construction of fortifications or detailed analysis of a sample of fortifications lines with the description of the number and characteristics of shelters, strongholds, and other parameters of fortifications with further extrapolation for the overall length of fortification lines). Since such elements of fortifications are usually covered with soil and other materials, it is hardly possible to evaluate their scale using remote techniques and such studies would likely be possible only after the end of the war.

The initial analysis demonstrates that potential carbon footprint of fortifications could be up to 0.2 million tCO_2e.

Embodied carbon in military equipment

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

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117. 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) used for fortifications 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.

The large-scale war caused by Russia's invasion of Ukraine resulted in an increased supply of military equipment and the need to increase investments in the manufacturing of new equipment. There are already reports demonstrating that military equipment manufacturing is increasing, and industrial plants are shifting to production of military-related products.[118] Thus, emissions associated with manufacturing of equipment are included in the estimation of climate damage.

The amount of embodied carbon is very specific to a particular equipment type and there is almost no data on life cycle emissions associated with manufacturing of military equipment, such as main battle tanks or other armoured vehicles. Producers of equipment are starting to report the carbon footprint but limit information to mainly Scope 1 and Scope 2 emissions and do not report on the key categories of Scope 3 emissions, such as emissions associated with the production of raw materials and other products used during manufacturing. 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.[119] Carbon intensity of military equipment manufacturing is likely higher than manufacturing of civil equipment and machinery.

The value of 6 kg CO_2e per kg of machinery has been applied as an indicative carbon footprint of military equipment (see the Annex for details).

As of the beginning of October 2023, the list of lost equipment based on open-source intelligence data included more than 12,400 visually confirmed losses for Russia and more than 4,500 losses for Ukraine. About three quarters of the entries represent destroyed and damaged equipment, while the remaining units were captured or abandoned.[120]

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

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

[120] 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

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

Only destroyed and damaged equipment was considered during the estimation of climate damage. For damaged equipment, only one third of the estimated embodied carbon has been taken into account in calculations. The eleven categories of equipment included in the assessment represent 88% of the visually confirmed destroyed and damaged equipment for Russia and 80% for Ukraine.

Though the accuracy of 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. 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	150,329	45,891	196,219
Indicative mass of damaged equipment (only one third accounted for in calculations), t	14,206	8,127	22,333
Total mass of equipment accounted in embodied carbon calculation (including assumed 20% not visually confirmed), t	186,077	58,320	244,396
Total embodied carbon, tCO_2e	**1,116,460**	**349,919**	**1,466,379**

Table 13. Total of GHG emissions from military equipment manufacturing

GHG emissions associated with manufacturing of the military equipment destroyed and damaged during the war was estimated at 1.5 million tCO_2e, including 1.1 million tCO_2e for Russian losses and 0.4 million tCO_2e for Ukrainian losses.

Emissions from arms deliveries

Western partners of Ukraine have delivered more than 150,000 tons 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, MLRS, artillery, etc.[121] Since that time, the monetary value of military aid provided to Ukraine increased by almost 30% and amounts to almost USD 96 billion as of September 2023.[122] Thus, the estimated arms delivery could have increased to about 190,000 tons. 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.[123] 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.[124]

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.[125] 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

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

[122] 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

[123] 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/

[124] 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/

[125] See 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/

option but they also incur the highest costs. The preference, whenever possible, is given to cargo ships as a less expensive option.[126] 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 were landing in Eastern Europe daily.[127] 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.[128]

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.

For the purpose of initial assessment, the reported total mass of arms deliveries has been distributed between different countries based on the reported monetary value of provided military aid.[129] 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).[130] Based on preliminary estimation, GHG emissions associated with military aid supply amount to approximately 0.4 million tCO_2e with almost 98% coming from air transportation due to its high carbon intensity, long distances of transatlantic flights, and large volumes of supply.

For instance, the US has provided USD 46.6 billion of military aid or almost half 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 368,000 tonnes of CO_2e of GHG emissions. Approximately 31,000 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.

Russia has also reportedly been supplied by military equipment from other countries, including Belarus, Iran, Syria, and more recently North Korea.[131] These equipment supplies

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[126] 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

[127] 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/

[128] 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/

[129] How Much Aid Has the U.S. Sent Ukraine? Here Are Six Charts., https://www.cfr.org/article/how-much-aid-has-us-sent-ukraine-here-are-six-charts

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

[131] 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

rely heavily on railway transportation but also use air and sea transport, though associated emissions have not been accounted for due to the lack of data.

Total warfare emissions

SOURCE OF EMISSIONS	$MtCO_2e$
Pre-invasion force accumulation [132]	0.1
Emissions from fuel consumption by Russian troops	24.9
Emissions from fuel consumption by Ukrainian troops	7.1
Emissions from the use of ammunition	2.8
Emissions from the construction of fortifications	0.2
Emissions associated with military equipment manufacturing	1.5
Emissions associated with long-distance transportation of military equipment	0.4
TOTAL	**37.0**

Table 14. Total of GHG emissions from warfare

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

4.2 Fires

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

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

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

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

Fires also affect the top layer of soil, soil microorganisms, plant communities, animals, and habitats, thus causing long-term negative impacts on biodiversity. Furthermore, forest fires reduce the sequestration ability, converting forests from a natural sink to a source of GHG emissions and further undermining climate mitigation efforts. For urban areas, emission volumes depend on the amount of combustible material on the affected areas and carbon content of materials (e.g. wood, plastic, etc.).

The area affected by fires has been estimated using remote monitoring tools based on satellites data. The use of ground-based observations to collect a more reliable information on the level of fires impact is not possible during the war period. Data on fires (number of fires, fire start and end time, coordinates of the boundaries of each fire, land categories for each fire) were obtained from open data fire monitoring information systems: the US-based Fire Information for Resource Management System (FIRMS)[133] and the European Forest Fire Information System (EFFIS).[134] The EFFIS system has begun to publish digital data on fires on the territory of Ukraine since 2020.

For the year 2022, on the request of the Ukrainian authorities, a special protocol was used by EFFIS to map fires in Ukraine. In particular, unlike other countries, all identified fires in Ukraine were mapped, including fires not only on natural areas but also on agricultural, urban, and industrial lands. Thus, 6,309 fires were mapped, resulting in a total burnt area of 498,711 ha.[135] Later, for the year 2023, the approach has been reversed, and a standard harmonized protocol of mapping only the burnt areas that affect the wildland territories was applied not only for new fires but also for the fires that occurred in 2022. This resulted in a significant reduction in the number of mapped fires and the area of affected land. In particular, the number of records for the first year of war has been reduced to 2,509, while the total area has been reduced by 45% to 272,684 ha. This change, however, limits the availability of data on fires on agricultural and urban land.[136] Thus, the assessment of GHG emissions from fires presented in this report could be underestimated as not all fires on agricultural and urban land were taken into account.

The assessment of the impact of the war was performed by comparing the areas of fires for pre-war and war periods:

- Pre-war period: 24 February 2021 to 23 February 2022;
- War period: 555 days period from 24 February 2022 to 1 September 2023[137].

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

To assess the impact of the war on fires, the territory of Ukraine has been divided into three zones:

Zone 1 – covers 55.9% of the territory of Ukraine, where ground military operations were not conducted – blue areas on the maps;

Zone 2 – zone of active hostilities (ground hostilities were conducted for more than 24 hours, frontlines from OSINT source[138]) covering 27.8% of the territory of Ukraine (12-mile zone on both sides of the changing front lines was applied) – yellow areas on the maps;

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[133] https://firms.modaps.eosdis.nasa.gov

[134] https://effis.jrc.ec.europa.eu

[135] Advance report on Forest Fires in Europe, Middle East and North Africa 2022, https://publications.jrc.ec.europa.eu/repository/handle/JRC133215

[136] For the purpose of current assessment, the same dataset as for the second interim update was used for the first 365 days of the war, which covered all detected fires, including fires on agricultural and urban land. For the most of 2023, the updated dataset from EFFIS was used. Thus, not all fires on agricultural and urban land are taken into account, which results in the underestimation of the impact.

[137] For the purpose of assessment, fires during the first year of the war (24 February 2022 to 23 February 2023) have been compared to the corresponding pre-war period (24 February 2021 to 23 February 2022), while fires during the further six months (24 February 2023 to 1 September 2023) have been compared to the relevant period in 2021 (24 February 2021 to 1 September 2021).

[138] https://liveuamap.com/uk

Zone 3 – occupied territories (12.3% of the territory of Ukraine), in which ground military operations were conducted for no more than 24 hours or did not take place at all – red areas on the maps.

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

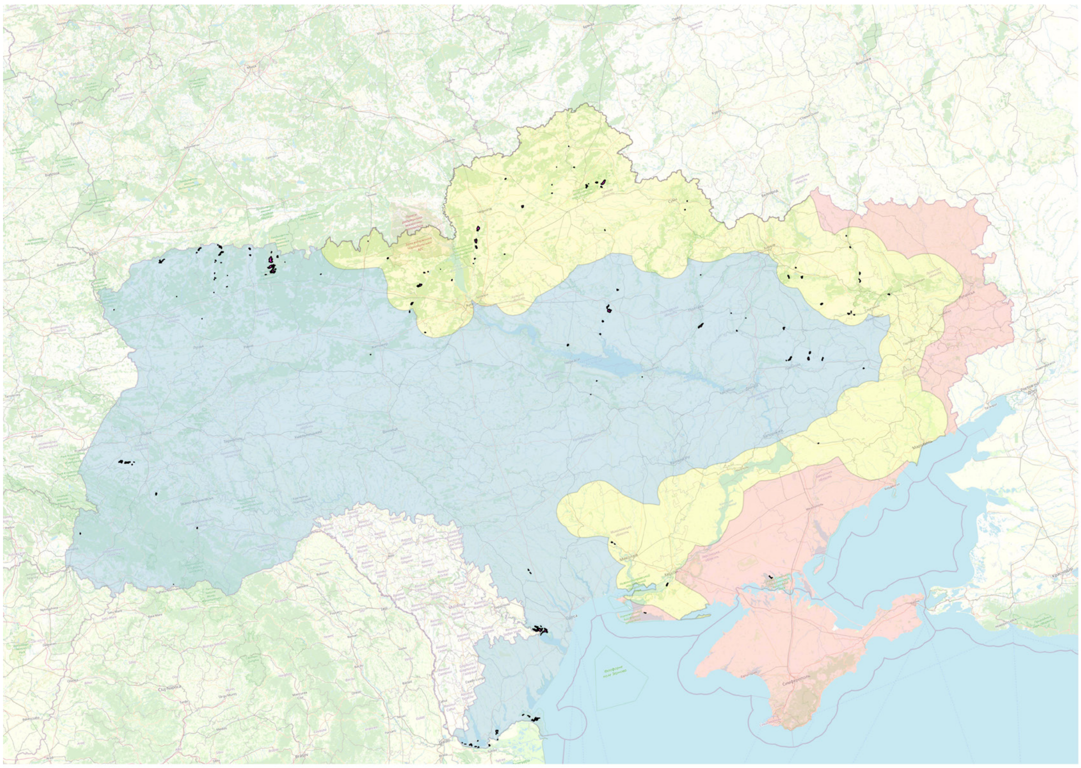

Fig. 10. Location of fires during the pre-war period (177 fires according to EFFIS)

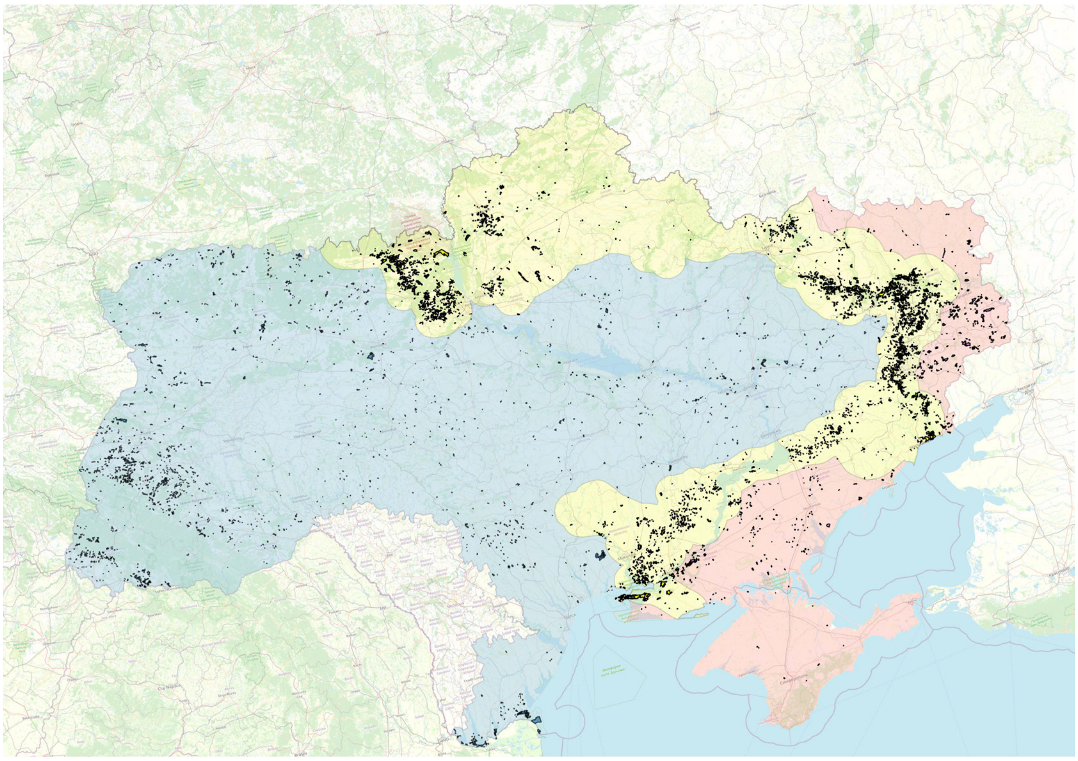

Fig. 11. Location of fires during the first year of the war (6,288 fires according to EFFIS)

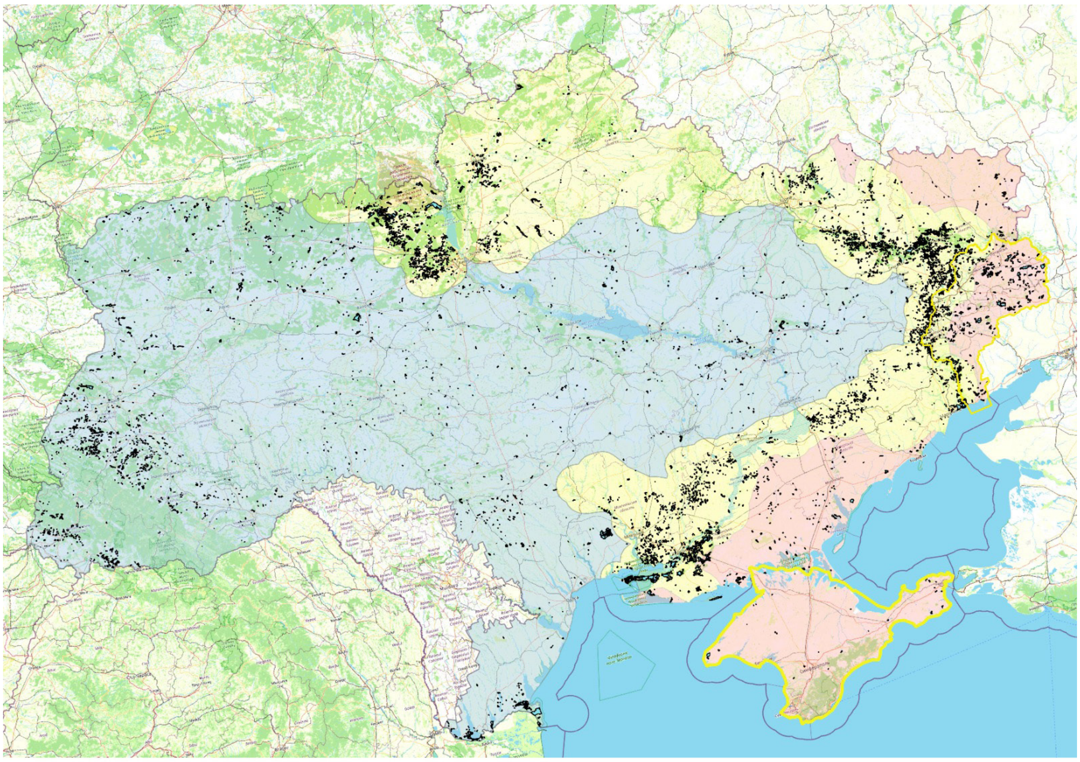

Fig. 12. Location of fires during the 555 days of the war (7,220 fires according to EFFIS)

Data on the number and areas of fires in different zones and different land use categories are presented in Table 15 below for both the pre-war period and war periods.

Zones	Number of fires	Area (Ha)								
		Total area of fires	Forest fires				Other landscape fires	Agricultural land	Built-up land	Other territories*
			Total area	Broadleaf forests	Coniferous forests	Mixed forests				
PRE-WAR PERIOD										
1	120	24,859	7,082	3,830	2,950	302	11,781	5,850	43	102
2	53	10,489	763	619	72	72	4,794	4,778	49	105
3	4	262	0	0	0	0	109	126	0	27
Total	**177**	**35,610**	**7,846**	**4,449**	**3,023**	**374**	**16,683**	**10,754**	**92**	**234**
FIRST YEAR OF THE WAR (365 DAYS)										
1	2,095	131,363	7,906	5,951	1,489	466	25,725	96,439	476	818
2	3,823	323,194	50,697	6,708	41,961	2,028	31,601	236,480	2,736	1,679
3	370	41,661	279	16	263	0	1,253	39,922	141	66
Total	**6,288**	**496,218**	**56,388**	**12,675**	**43,713**	**2 494**	**58,578**	**372,842**	**3,353**	**2,563**
555 DAYS OF THE WAR										
1	2,188	141,366	8,388	6,124	1,704	560	28,529	103,030	485	933
2	4,510	376,248	59,625	7,303	48,919	3,403	54,799	256,979	3,027	1,819
3	522	67,589	1,633	16	780	837	13,267	52,344	204	141
Total	**7,220**	**585,202**	**69,645**	**13,443**	**51,402**	**4,800**	**96,595**	**412,353**	**3,716**	**2,893**

Table 15. Fires in Ukraine during the pre-war period and 555 days of the war, larger than one hectare only [139]

The analysis of the data reveals a significant increase in both the number and area of fires caused by military actions. During the first year of war, the total number of fires increased 36-fold and the total area increased 14-fold. The most significant increase occurred in the zone of active combat (Zone 2) and on the occupied territories of Ukraine (Zone 3). In absolute terms, the most significant increase occurred in Zone 2, which is directly related to active military actions and combat operations. In terms of land use categories, the most significant increase in the affected areas occurred on agricultural fields and built-up areas. However, in absolute terms the largest areas affected, along with the agricultural fields, were in forest areas and other natural landscapes. The increase in the number and area of fires during 2023 is less significant than during 2022, which is explained by both the changes in the fire mapping approach described above and changing dynamics of combat activities.

For more detailed description of the methodological approach and emission factors used,

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[139] Fires on “other territories” are not taken into account during the analysis due to high uncertainty levels

see the Annex and the results of GHG emissions calculation for the pre-war period and war periods presented in Table 16 below.

Zones	Emission of GHG (tCO_2e)							
	Total GHG emissions	Forest fires				Other landscape fires	Agricultural land	Built-up land
		Total from forests	Broadleaf forests	Coniferous forests	Mixed forests			
PRE-WAR PERIOD								
1	1,509,371	1,364,151	754,507	537,454	72,190	82,468	28,751	34,001
2	237,980	144,320	111,896	22,109	10,315	33,554	21,137	38,969
3	3,341	0	0	0	0	761	2,580	0
Total	**1,750,692**	**1,508,471**	**866,403**	**559,563**	**82,505**	**116,784**	**52,468**	**72,970**
FIRST YEAR OF THE WAR (365 DAYS)								
1	3,428,951	1,784,394	1,276,355	378,547	129,492	180,071	1,088,025	376,460
2	17,373,732	12,320,050	1,106,566	10,687,670	525,814	221,207	2,667,968	2,164,508
3	632,104	61,772	1,458	60,314	0	8,769	450,405	111,158
Total	**21,434,787**	**14,166,215**	**2,384,378**	**11,126,531**	**655,306**	**410,047**	**4,206,399**	**2,652,126**
555 DAYS OF THE WAR								
1	3,641,048	1,895,247	1,314,919	429,298	151,030	199,701	1,162,387	383,712
2	19,700,428	14,023,312	1,164,161	12,142,132	717,019	383,589	2,899,237	2,394,291
3	1,155,615	145,774	1,458	164 778	144,316	92,872	590,547	161,645
Total	**24,497,091**	**16,229,112**	**2,480,538**	**12,736,208**	**1,012,366**	**676,162**	**4,652,171**	**2,939,648**
ADDITIONAL EMISSIONS								
Pre-war baseline 555 days	2,256,640	1,922,156	1,048,493	752,427	121,236	162,792	67,102	104,591
Additional emissions	22,240,451	14,306,956	1,432,045	11,983,781	891,130	513,370	4,585,069	2,835,057

Table 16. GHG emissions from fires during the pre-war period and war periods, tCO_2e

Based on the analysis above, **22.2 million tCO_2e** of additional GHG emissions from fires were caused by military activities in Ukraine. Though more than two thirds of land affected by fires were represented by agricultural land, the majority of GHG emissions are associated with forest fires.

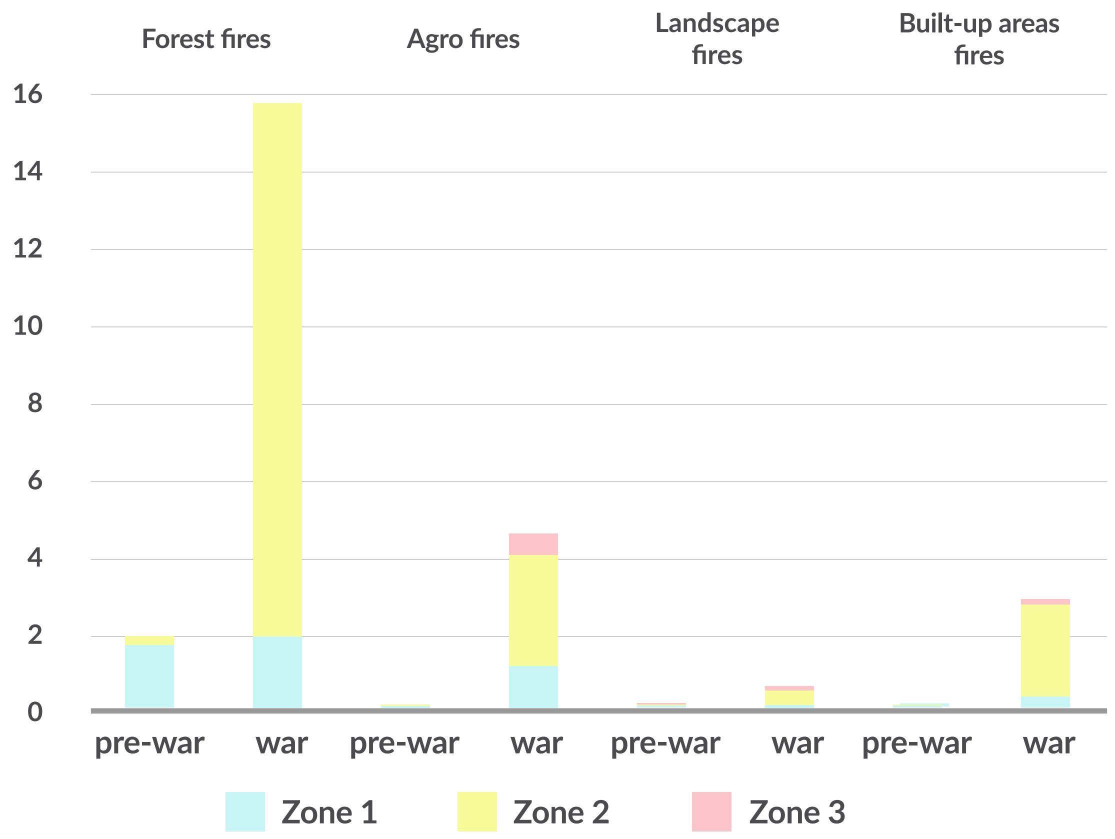

Fig. 13. GHG emissions by different land use categories, tCO2e

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

4.3 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 in May 2023, 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 800,000 refugees have returned home. This will be the last update of emissions as a result of displacement until a next event causes new major migration movements.

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

Refugees

Data on refugees have been drawn from UNHCR[140] in the first interim assessment and in the two updates including this one. Since our May report, the number of registered refugees have decreased by approximately 800,000, suggesting people have returned home. The total number of refugees from Ukraine in Europe amounted to 5.8 million by early September 2023, compared to 6.6 million[141] by the end of March 2023. We have assumed these 800,000 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 2.48 million tCO_2e.

IDPs

Data on IDPs in the first and second reports were drawn from the Ukrainian government. Since then, data have been collected by the International Organization for Migration (IOM), a UN body, through its Displacement Tracking Matrix (DTM).[142] By June 2023, the DTM reported 5.088 million IDPs in Ukraine in addition to 4.757 million returnees. This number is significantly higher than the number of 2.8 million IDPs reported in our first and second reports. The number of 5 million IPDs in 2023 was confirmed by the Kyiv School of Economics in July 2023, quoting the Ministry of Social Policy in Ukraine.[143] Hence, for this

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[140] See https://data.unhcr.org/en/situations/ukraine

[141] In the May 2023 update of this report, the refugee number of 8.2 million was reported, which after the review of data appears to have been incorrect

[142] See https://dtm.iom.int/ukraine

[143] KSE Institute: 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)

update, we have adjusted emissions from transport movements of IDPs, assuming 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[144] 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 estimate the emissions conservatively by assuming 700,000 of them left by airplane over a distance 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

International refugees from Ukraine	0.77
Transport returning empty to Ukraine	0.77
Refugees in Europe visiting Ukraine	0.94
Internal Displaced Persons in Ukraine	0.24
Russians leaving Russia	0.25
TOTAL	**3.0**

Table 17: Overview of transport emissions from refugees, IDPs and Russians, $MtCO_2e$

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

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[144] See https://en.wikipedia.org/wiki/Russian_emigration_following_the_Russian_invasion_of_Ukraine

4.4 Civil 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 km2 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[145].

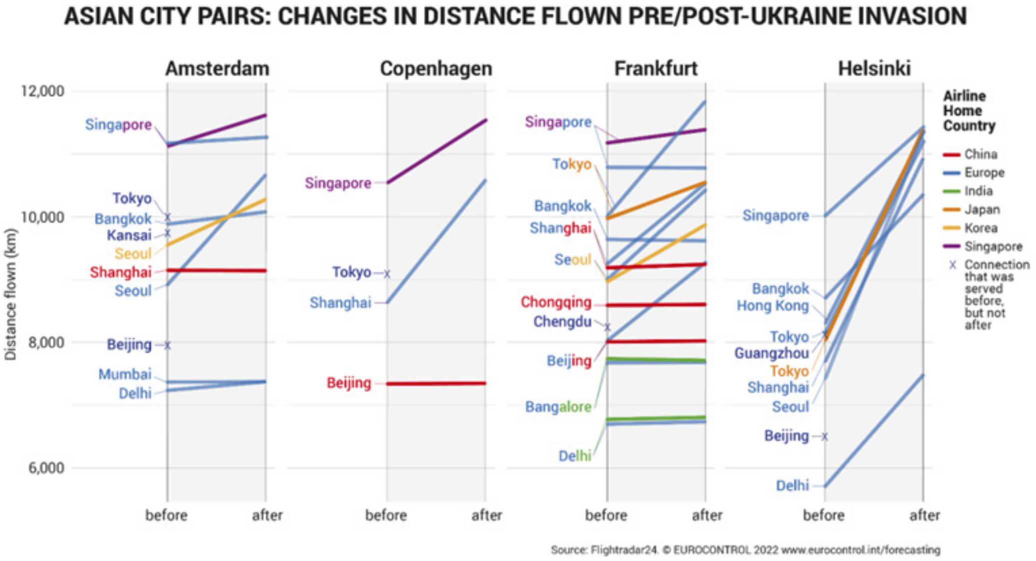

Fig. 14: Asian City Pairs: Changes in distance flown pre/post-Ukraine invasion

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.

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.[146] Qantas' flagship flights from Sydney and Melbourne

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

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

to London currently run via Darwin, with Darwin to London now averaging a marathon of 17.5 hours, and sometimes even longer[147].

Fig. 15: Flying route from London to Tokyo.

Avoiding Russian airspace is having a much bigger impact on Japanese Airlines. Before the war, two of Japan's largest carriers, JAL and ANA, operated about 60 flights per week through Russian airspace between Tokyo and London, Paris, Frankfurt, and Helsinki.[148] 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.[149] 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 could previously. For example, Finnair's routes to Asia had been based on faster turnarounds, allowing one plane to operate out and back from Helsinki within 24 hours.

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

148. 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

149. Ibid

This meant Finnair could offer daily flights on many routes without needing as large a fleet as some other airlines. Yet, with Asia-Helsinki services stretching to 14 hours each way, combined with service time on the ground, it became impossible to serve every destination at the frequency Finnair did before. The pass-through of the costs has also affected passenger demand for long-haul flights to and from Asia.

Some Western airlines have abandoned routes to East Asia as a result of these challenges. Virgin Atlantic put an official end to its London to Hong Kong route in March 2023 after almost 30 years of service, citing the logistical impact of the detour. London to Hong Kong flight times would have needed to be extended by approximately 60 minutes and Hong Kong to London by 1 hour and 50 minutes if the flight were to remain operational.[150] 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.

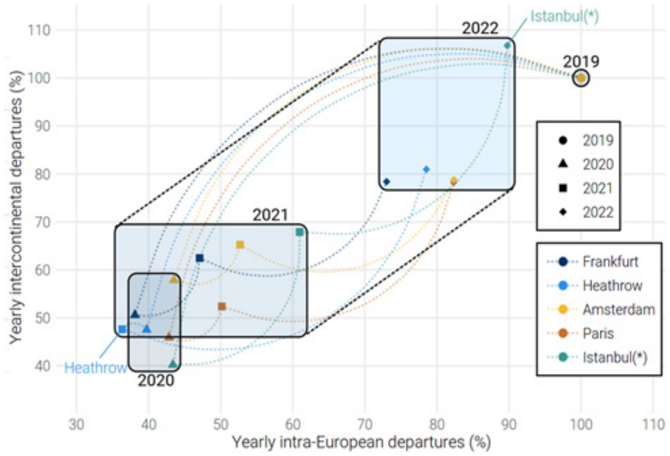

Fig. 16: Path to recovery for the top 5 airports (in 2019)[151]

Some of the European data also shows potential redirection of passenger flows. For example, the number of yearly intercontinental departures from Istanbul grew disproportionately in 2022 compared to other European hubs[152].

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%.[153] 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

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[150] 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

[151] Source: Eurocontrol

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

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

emissions assigned to each state as per ICAO rules when compared to 2019 data.[154] 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.

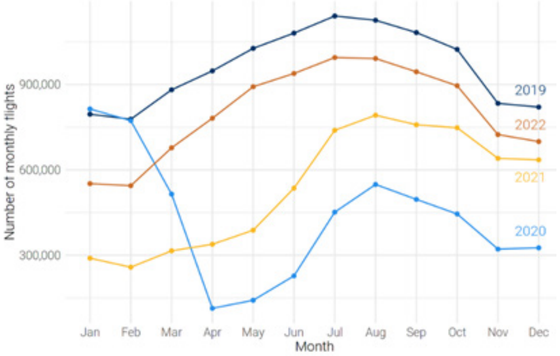

Fig.17: Network traffic as monitored in the Eurocontrol member states[155]

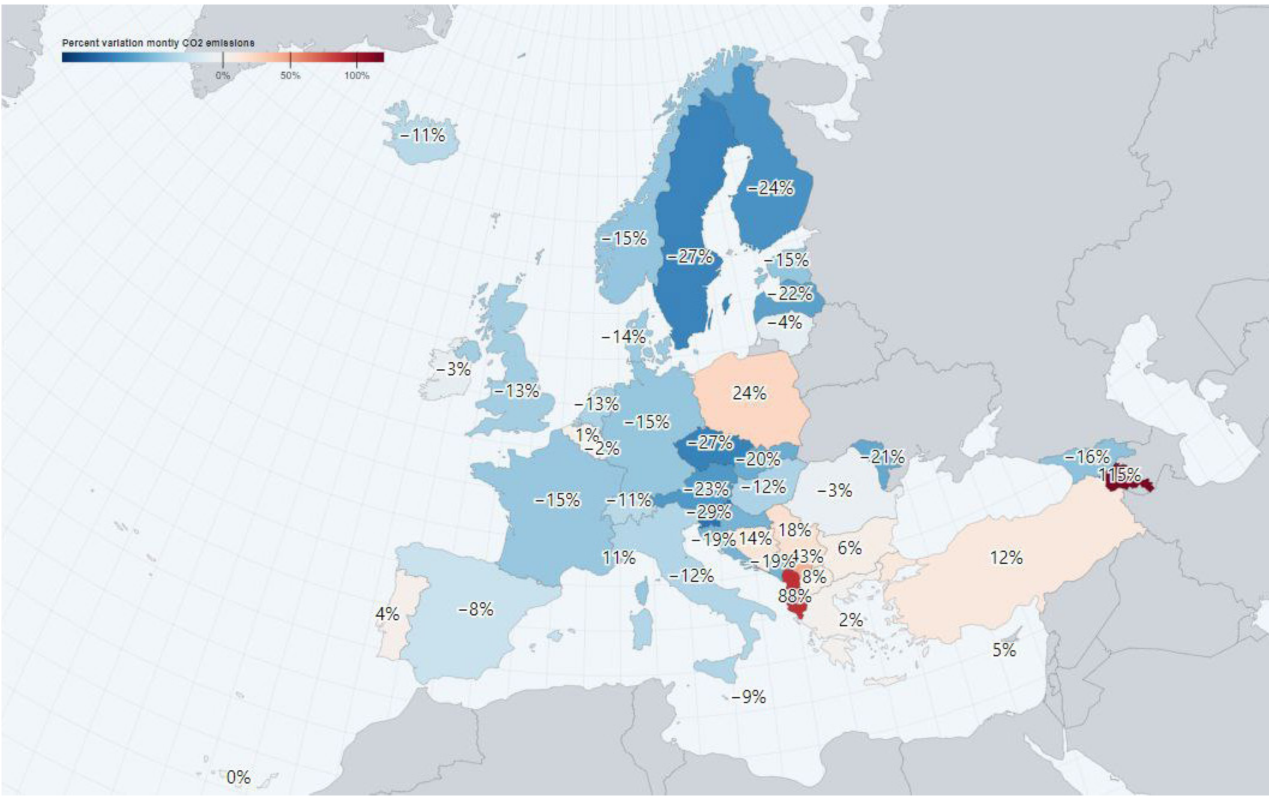

Fig. 18: Percent variations in monthly CO2 emissions, March 2021 to April 2023[156]

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

The actual impact of additional fuel consumption resulting from re-routing of specific flights is harder to see using the aggregate data set, as the impact of re-routings is masked

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

155. Source: Eurocontrol

156. Source: Eurocontrol

by cancellation of routes and drops in passenger flows to and from Russia, Belarus, and Ukraine, cancellation of some of the Asian routes, and a decrease in the service frequency on some of the affected routes. Furthermore, the growth of carbon intensity of European traffic would need to be decoupled from carbon intensity growth in the years preceding the war, when CO_2 emissions were observed to be increasing faster than air traffic due to larger aircraft use and servicing farther distances, with emissions increase being significant enough to even offset improvements in aircraft and flight efficiency.

Nonetheless, if air traffic intensity were assumed to be constant between 2021, 2022 and mid-2023, the incremental increase that could be potentially attributed to re-routings, among other factors, over the period 24 February 2022 to 1 September 2023 could reach just over **18 million tCO_2e**, based on the Eurocontrol data[157].

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[157] This number only reflects carbon-dioxide and no other greenhouse gases. Also the radiative forcing by contrails has not been taken into account

4.5 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, hospital, 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 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.

The 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 third carbon assessment, we have used the KSE report on damage and losses assessment for the period of 24 February 2022 – 1 June 2023.[158] This reporting period is shorter than ours (which runs until 1 September 2023), but since there has not much additional damage in the period of 1 June – 1 September 2023, there will only be a slight underreporting of reconstruction emissions.

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[158] Report on damages and losses to infrastructure from the destruction caused by Russia's military aggression against Ukraine as of June 2023, https://kse.ua/wp-content/uploads/2023/09/June_Damages_ENG_-Report.pdf

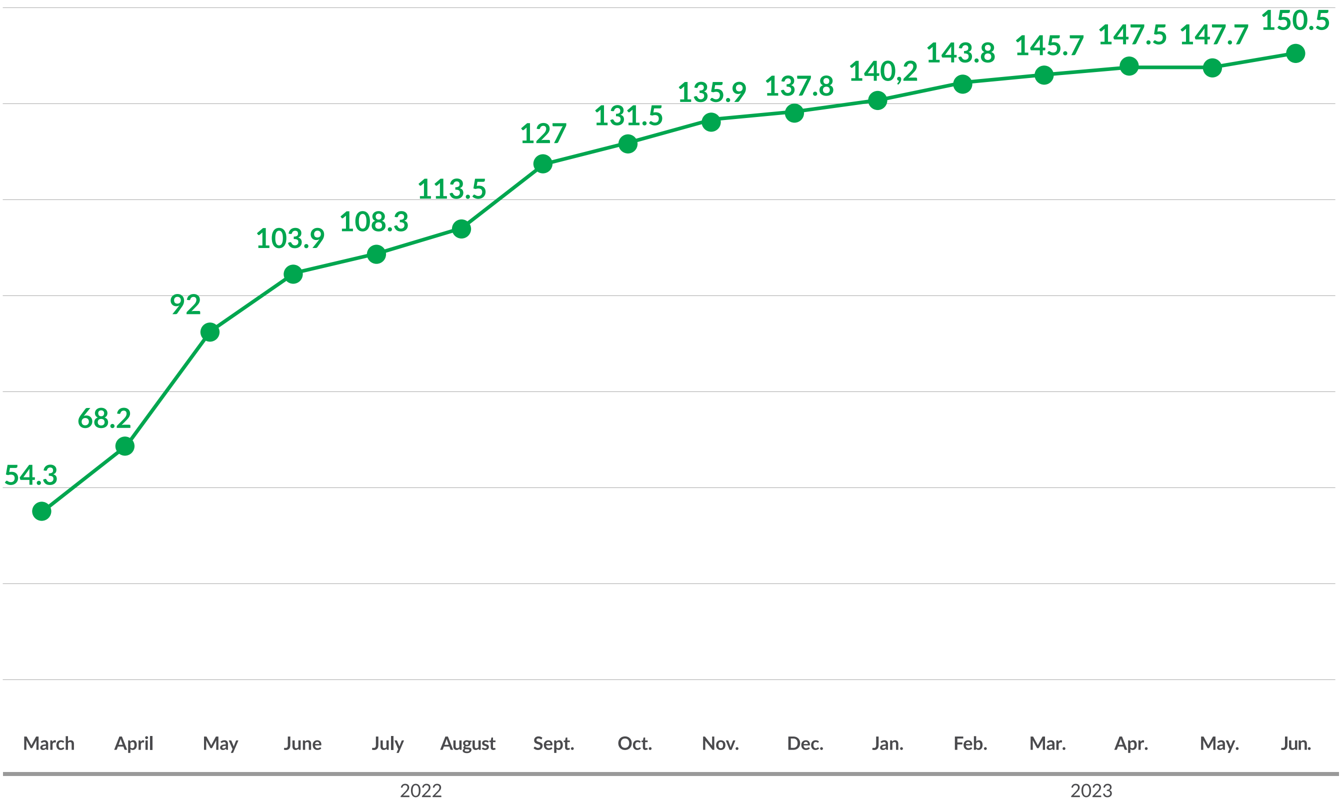

Fig. 19: Dynamics of the aggregate assessment of direct damages to Ukraine's economy, bn. USD. Source: Kyiv School of Economics

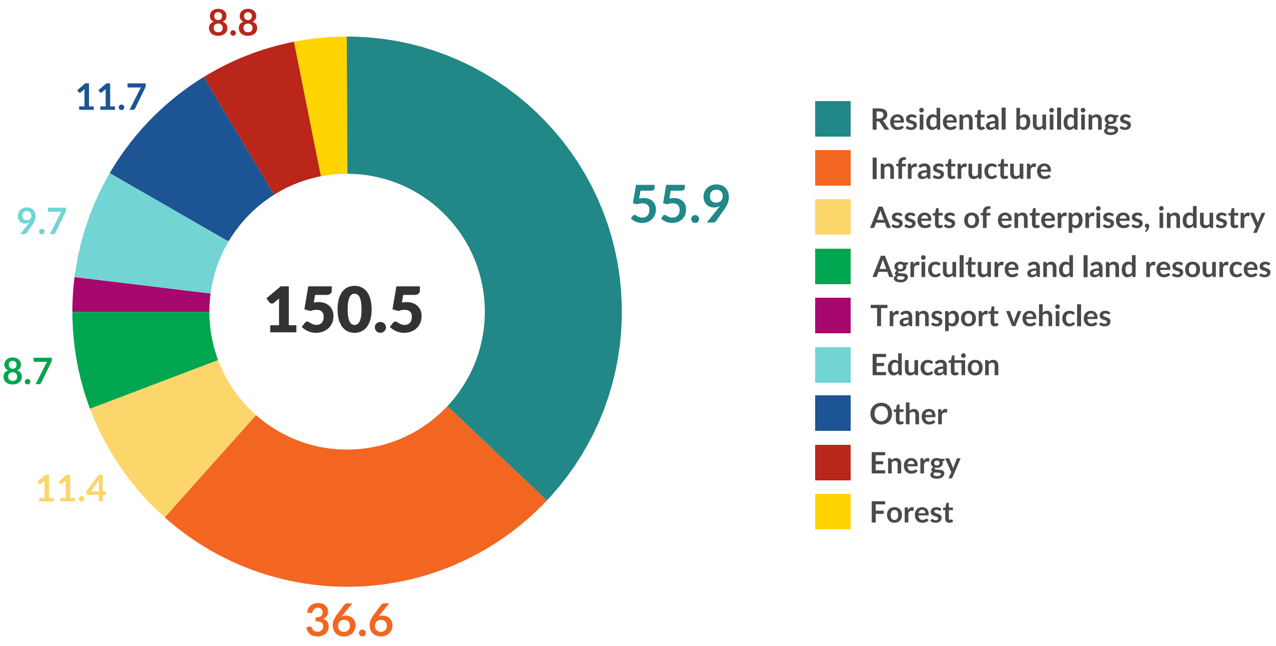

Fig. 20: Direct damages by type of property, bn USD

The largest damage in monetary terms was faced by the residential sector (housing) followed by infrastructure. Most damage was done during the first six months of the war, while in the following 12 months period, the growing rate of damages decreased, as shown in the graph above. This is mainly caused by the fact that the front lines have hardly moved and, where objects were located close to the front lines, many objects had already been destroyed during the first months.

The destruction of the Nova Kakhovka dam was the most significant event since our previous interim assessment. Besides the destruction of the dam itself, significant damage was caused to infrastructure by the flooding downstream.

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

	STOCK (units)	DAMAGED (units)	DESTROYED (units)
Apartment buildings	178,921	13,729	5,367
Private houses	8,977,862	87,451	60,318
Dormitories	7,114	256	91

Table 18: Overview of residential housing available before the war (baseline) and units damaged or destroyed

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 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.

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. 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 damaged road or tCO_2e of 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 hence 100% of the embodied or spend-based emission factor is therefore applied. For damaged property, a 33% factor was applied to the embodied carbon factor unless a prorate adjustment could be derived from replacement value for destroyed and damaged property.

The results over the first 18 months of the war are provided in the table and graph below. Compared to 12 months of war, this constitutes an increase of just under 10%.

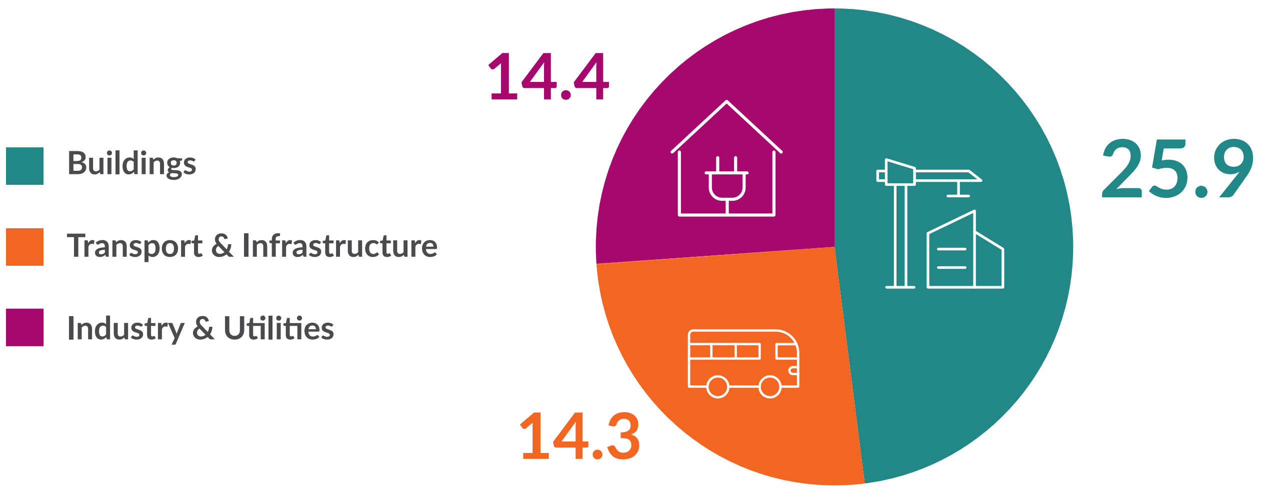

Fig. 21 GFG emissions of post-war reconstructure ($MtCO_2e$)

CATEGORY	EMISSIONS ($MtCO_2e$)	PERCENTAGE (%)
Buildings	25.9	47
Transport & Infrastructure	14.3	26
Industry & Utilities	14.4	27
TOTAL	54.7	100

Table 19: 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).

WARFARE:

War stages and climate impact

0
PHASE

Second half of 2021 –
24 February 2022

PREPARATION STAGE

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

CLIMATE IMPACT

1
PHASE

24 February –
mid-April 2022

LARGE-SCALE INVASION

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

CLIMATE IMPACT

2
PHASE

mid-April –
June 2022

FOCUS ON THE EASTERN FRONT

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

CLIMATE IMPACT

3
PHASE

July –
September 2022

FRONT STABILIZATION AND START OF UKRAINIAN COUNTER-OFFENSIVE

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

CLIMATE IMPACT

4
PHASE

October – November 2022

CONTINUATION OF UKRAINIAN COUNTER-OFFENSIVE

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

CLIMATE IMPACT

5
PHASE

December 2022 – January 2023

FRONT STABILIZATION

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

CLIMATE IMPACT

6 PHASE

February 2023
– 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

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

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

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

In Norway[2], for instance, the life cycle greenhouse gas emissions from the defence sector have been estimated at 0.8 million tCO_2e, corresponding to approximately 1.1% of the national emissions (consumption-based). Fuel use by military equipment and systems (vehicles, ships, and aircraft) is the largest single contributor to GHG emissions from the sector and has been estimated to be responsible for around 31% of emissions. However, upstream activities were defined as the main contributor to emissions (68%) in general with the most significant impact attributed to buildings and construction activities, including embodied carbon of construction materials (18% from the total); procurement of goods and materials required for operational purposes (12% from the total); as well as procurement of assets used for transportation and transportation services related to business travel, in particular air travel (8% and 7% of the total, respectively).

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[3]. The estimates for the armed forces include emissions from estate (military bases

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1. 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

2. 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

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

and civilian buildings) and equipment (marine vessels, aircraft, and land vehicles) and constitute about 3 million tCO_2e or almost half of the total production-based emissions of the military-industrial sector. Emissions from UK arms/ defence industry (including MOD-orientated work and exports) was estimated at the level of approximately 1.5 million tCO_2e. The remaining part of emissions was attributed to the supply chain within the UK (elements of the supply chain outside the UK have not been considered). Total production-based emissions represented about 1.4% of the total national emissions.

For the European Union, the carbon footprint of military expenditure in 2019 was estimated at approximately 24.8 million tCO_2e[4]. The estimate was based on the analysis of GHG emission figures for the combined sectors of the armed forces and military technology industry of the six case study countries (France, Germany, Italy, the Netherlands, Poland and Spain) and extrapolation of the results to the EU as a whole. The estimated value corresponds to about 0.7% of GHG emissions in the EU, however, the authors of the report underline that due to poor data availability, the estimate should be treated as conservative.

In the case of the US, conservative estimates of military emissions for the period FY 2001-2018 were 1,267 million tCO_2e. The emissions from overseas contingency operations (war-related emissions for the operations in major war zones, including Afghanistan, Pakistan, Iraq, and Syria) were estimated to be more than 440 million tCO_2e or approximately 35% of the total[5]. The average annual value over this 18 years period would be 70.4 million tCO_2e, including 24.4 million tCO_2e on average for the overseas contingency operations. The total value corresponds to approximately 1% of average GHG emissions in the US during this period[6] 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[7].

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4. 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

5. Pentagon Fuel Use, Climate Change, and the Costs of War. Neta C. Crawford, Boston University, https://watson.brown.edu/costsof-war/files/cow/imce/papers/Pentagon%20Fuel%20Use%2C%20Climate%20Change%20and%20the%20Costs%20of%20War%20Revised%20November%202019%20Crawford.pdf

6. GHG data are available at the EPA web-site https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks and the average value during 2001-2018 is about 7 billion tCO_2e.

7. Hidden carbon costs of the "everywhere war": Logistics, geopolitical ecology, and the carbon boot-print of the US military, Oliver Belcher, Patrick Bigger, Ben Neimark, Cara Kennelly, https://doi.org/10.1111/tran.12319

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

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

Fuel consumption by aviation

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

Based on other sources, the number of sorties during the initial stages of the war was even

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[8] 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

higher and reached 200[9] – 300[10] sorties per day but reduced to dozens missions per day by the end of 2022. In July 2022, the Air Force Command of UA Armed Forces reported that the number of sorties of Russia's operational and tactical aviation has exceeded 6,400[11] (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[12]. For comparison, Ukrainian aviation conducted 5-10 sorties per day[13] at the beginning of the war while during the first year of the war fighter jets conducted over 5,300 sorties[14] (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-55 /55SM, and Kh-22/32. As of early 2023, 824 of such missiles attacked Ukraine from the beginning of the war[15]. In 2023 (as of 28 April), additional 132 missiles were launched by strategic bombers during five waves of attacks[16], bringing the total number to 956 missiles. The number of launches per sortie depends on the type of strategic bomber involved, types of the missiles used, weapon load on board, and other factors (e.g. Tu-95MS can carry six or eight missiles depending on their type[17]). The number of launches, however, could be significantly lower than the maximum carrying capacity. For instance, during the attack on 9 March 7, Tu-22M3 and 10 Tu-95MS strategic bombers launched 34 missiles (i.e. two missiles per aircraft on average). Besides, there could be a significant number of sorties without launches, including those conducted for training purposes and those simulating launches for other goals. For the purpose of analysis, an assumption of a total of 1,000 sorties conducted by strategic bombers has been applied.

[9] 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/

[10] Defence Intelligence, https://twitter.com/DefenceHQ/status/1599656741381328896

[11] 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/

[12] 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

[13] 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/

[14] Air Force Command of UA Armed Forces, https://www.facebook.com/kpszsu/posts/ pfbid0Yu8ga2bNGzkVmqDA5Co5YMxa2qVi-wncJH8FBB1jrNZEfwfXxNFRmSGiCfRezVUwGl

[15] See the infographic shared by the Minister of Defence, https://twitter.com/oleksiireznikov/status/1611449870040109058

[16] See https://twitter.com/MassDara/status/1634300311744438272 for the estimates as of 10 March 2023. On 28 April, 23 missiles were launched.

[17] What Is Special About the Tu-95MS Strategic Bomber, And Why This Aircraft Is Chosen For Strikes On Ukraine, https://en.defence-ua.com/analysis/what_is_special_about_the_tu_95ms_strategic_bomber_ and_why_this_aircraft_is_chosen_for_strikes_on_ukraine-5261.html

PARAMETERS	FIGHTER JETS	STRATEGIC BOMBERS	HELICOPTERS
Sorties	100 sorties per day	1,000 sorties in total	50 sorties per day
Distance per sortie	1,000 km	2,000 km	200 km
Comments	Assumed radius of action is 500 km (distance from the main air bases to the Ukrainian border is 200-300 km; combat range is >1000 km)	Assumed based on the approximate distance from the bases to the typical launch areas (about 1,000 km)	Assumed based on the need to protect temporary bases from the long-range precision artillery strikes (at 100+ km)[18]
Specific fuel consumption19	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 20. Information on assumed aviation activity data and estimated fuel consumption[20]

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

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.[21] 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.[22]

[18] 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

[19] 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%20 Change%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)

[20] All assumptions are indicative to demonstrate potential fuel consumption volumes

[21] 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.

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

Russia's forces involved in the war, at least at the initial stages, 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.

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.[23] 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.[24] Fuel is consumed in large quantities during combat marches conducted by BTGs and manoeuvring in the course of offensive and defensive operations (e.g. envelopment, encirclement, breakthrough, frontal attack, and evasive movement).[25]

DATA	1 BTG	100 BTGS	150 BTGS
Fuel in fuel tankers, t[26]	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 21. Estimated fuel consumption by BTGs[27]

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,

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23. See typical structures of BTGs at https://www.globalsecurity.org/military/world/russia/army-btg.htm and https://www.thefivecoat-consultinggroup.com/the-coronavirus-crisis/ukraine-context-d60. As mentioned above, typical fuel tanker size is 5.5 or 7m^3.

24. 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

25. 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

26. Assumed based on the average number of four fuel tankers of a BTG (28 m^3 of fuel or approximately 24 tonnes). Corresponds to daily fuel consumption with daily refuelling cycle.

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

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[28] 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.[29]

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.[30]

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.[31] Also, older tanks and armoured fighting vehicles (AFVs) do not have auxiliary power units to run for recharging their batteries and hence, the main engines have to run periodically to recharge the batteries.

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

Table 22. Fuel use efficiency for some typical military equipment[32]

Apart from vehicles and equipment included in BTGs, there are other fuel consumers,

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

29. 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

30. 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.

31. 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

32. 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

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.[33] 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.[34,35]

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

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33. 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

34. 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/

35. John J. McGrath, The Other End of the Spear: The Toothto-Tail Ratio (T3R) in Modern Military Operations, https://apps.dtic.mil/sti/pdfs/ADA472467.pdf

Emissions from the use of ammunition

Functional unit - artillery shell	Total 152/155 mm ammunition weight of various models of projectiles ranges from 42.6 to 46.9 kg and the explosive fill weight ranges from 5.85 to 11.30 kg (the weight of propellant is not included)[36]. Artillery ammunition consist of warhead, propellant charge, and fuze. Generic 155 mm ammunition, for which life cycle assessment of environmental impact has been reported, has the overall weight of 77 kg with container, including: • warhead – 44.5 kg, including 35.5 kg of steel casing and 8.5 kg of composition B explosive; • propellant charge – 9.67 kg, including 9.5 kg of triple base powder; • fuze – 1 kg; • steel container – 22 kg (reusable). There is no information on carbon footprint of other artillery ammunition types (152 mm and 122 mm shells used by Russia) and therefore the assessment is based on the data for generic 155 mm ammunition.
Emissions from energetic material manufacturing	Global warming impact of energetic materials used in explosives varies from 5.06 to 42.4 kg CO_2e per kg of material with most estimates in the range of 5.06 to 12.9 kg CO_2e per kg of material (i.e. 5.06 kg CO_2e for TNT, 6.53 kg CO_2e for nitrocellulose, 8.59 kg CO_2e for RDX)[37]. For composition B explosive, which is typically used in artillery projectiles and other ammunition (standard composition include 59.5% RDX and 39.4% TNT phlegmatized with 1% paraffin wax), the weighted average global warming impact would be 7.1 kg CO_2e per kg of material.
Emissions from artillery shell manufacturing	Thus, the carbon footprint of materials used for the manufacturing of 155 mm projectile would be 136 kg CO_2e and would consist of: • 60.35 kg CO_2e for the manufacturing of composition B explosive; • 75.62 for the manufacturing of steel casing[38].
Emissions at point of firing	Carbon dioxide emissions at point of firing (associated with the generic 155 mm ammunition) is 2.74 kg CO_2e.
Emissions during detonation	Carbon dioxide emissions during detonation (associated with the generic 155 mm ammunition) is 0.19 kg CO_2e per 155 mm ammunition shell.

Table 23. Specific emission factors related to ammunition

Data on fortifications

As of early April 2023, based on the analysis of satellite images, the total length of fortification structures identified was 2,837 km. As of 24 August 2023, the length of identified trench lines increased to 3,309 km. All objects can be identified and well distinguished on the Sentinel-2 L2A satellite images with the minimum trench width of 150 cm. Identification was carried out during the periods of clear weather and absence of clouds

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36. Explosive weapon effects – final report, GICHD, Geneva, February 2017, http://characterisationexplosiveweapons.org/studies/annex-b-152-155-artillery-version/
37. 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
38. Assuming the emission factor of 2.13 kg CO2e 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

and precipitation.

Tools used:

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

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

Step 1 - Fragment of the satellite image from Sentinel hub

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

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

Dragon’s teeth lines

Installation of “dragon’s teeth” obstacles was reported in many locations, including Kherson, Zaporizhzhia, Donetsk, and Luhansk regions and Crimea, as well Russian regions bordering Ukraine.

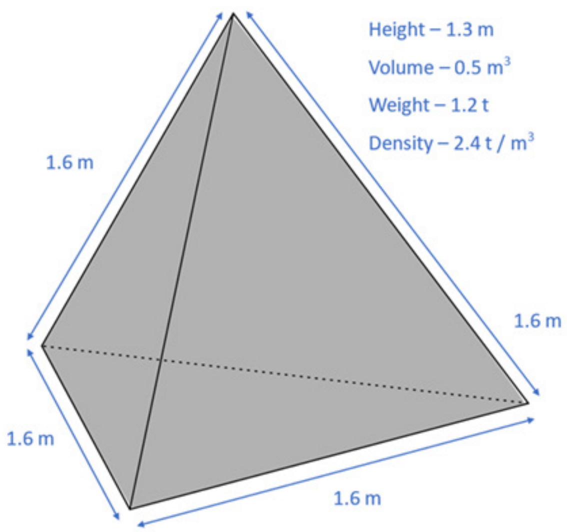

Fig. 22. Parameters of concrete tetrahedrons used as “dragon’s teeth” obstacles

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.[39] Similar defensive lines were installed near Medvedivka village on the north-east of the peninsula along the E105 road, where the width of the land between Syvash waters is about 3 km. Miles of fortifications, which also included sections with “dragon’s teeth,” were built on the western part of Crimea near Vitino Village. Piles of “dragon’s teeth” were also visible on the satellite images to the north of Armiansk town on the north of Crimea, where the width of the strip of land between Syvash and the Black Sea is about 9 km. Besides, additional defensive lines with concrete pyramids were installed along the North Crimea Canal, in particular near Maslove and Novoivanivka villages.[40] 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.[41] Thus, in Crimea alone the length of fortification lines with dragon’s teeth reaches dozens of kilometres.

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

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

[41] Brady Africk, https://twitter.com/bradyafr/status/1645754948297138176/photo/1

In Zaporizhzhia region, dragon's teeth lines were observed to the north of Tokmak town, around Berdiansk airport to the north of Berdiansk town,[42] to the north of Mykhailivka town,[43] 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).[44]

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.[45] Manufacturing of such obstacles was also reportedly started in Crimea with the capacity of 5,000 units per month.[46] 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.[47] Thus, dozen thousands of concrete pyramids were manufactured each month starting from the end of 2022 and used for the construction of fortifications.

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[42] 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

[43] See https://twitter.com/Tatarigami_UA/status/1645651237415575553

[44] 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

[45] Расследование: «Зубы дракона» выпускают минимум 6 беларусских предприятий, и ими укрепляют границу в Брянской области, РФ, https://motolko.help/ru-news/zuby-drakona-vypuskayut-minimum-na-6-i-belarusskih-predpriyatiyah-imi-ukreplyayut-graniczu-v-bryanskoj-oblasti-rf/

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

[47] "Мы сейчас только с Мелитополем работаем. Все в том районе". Как Россия возводит укрепления на оккупированных территориях Украины, https://www.bbc.com/russian/features-64055785

Data on embodied carbon in military equipment

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

Russian equipment losses

Equipment	Indicative weight, t	Indicative embodied carbon, t	Amount of destroyed equipment	Amount of damaged equipment	Indicative mass of destroyed equipment, t	Indicative mass of damaged equipment, t	Emissions, tCO$_2$e
Tanks	40	240	1,533	130	61,320	5,200	453,984
Armoured fighting vehicles	8	48	654	29	5,232	232	38,227
Infantry fighting vehicles	14	84	1,959	110	27,426	1,540	201,163
Armoured personnel carriers	11	66	238	9	2,618	99	19,087
Infantry mobility vehicles	6	36	151	7	906	42	6,624
Self-propelled artillery	27	162	399	31	10,773	837	79,574
Multiple rocket launchers	14	84	208	19	2,912	266	21,605
Trucks, vehicles and jeeps	8	48	2,212	54	17,696	432	128,448
Aircrafts	12	72	84	8	1,008	96	7,488
Helicopters	11	66	91	13	1,001	143	7,550
Naval ships	-	-	11	5	19,437	5,319	152,709
TOTAL	-	-	7,540	415	150,329	14,206	1,116,460

Table 24. Information on Russian equipment losses and associated emissions[48]

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[48] Calculated based on 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	Amount of destroyed equipment	Amount of damaged equipment	Indicative mass of destroyed equipment, t	Indicative mass of damaged equipment, t	Emissions, tCO_2e
Tanks	40	240	432	54	17,280	2,160	129,600
Armoured fighting vehicles	8	48	232	9	1,856	72	13,536
Infantry fighting vehicles	14	84	545	49	7,630	686	56,582
Armoured personnel carriers	11	66	212	25	2,332	275	17,450
Infantry mobility vehicles	6	36	227	30	1,362	180	10,238
Self-propelled artillery	27	162	154	48	4,158	1,296	33,048
Multiple rocket launchers	14	84	32	9	448	126	3,528
Trucks, vehicles and jeeps	8	48	541	18	4,328	144	31,507
Aircrafts	12	72	74	1	888	12	6,422
Helicopters	11	66	32	2	352	22	2,587
Naval ships	-	-	9	1	5,257	3,154	45,419
Total	-	-	2,490	246	45,891	8,127	349,919

Table 25. Information on Ukrainian equipment losses and associated emissions[49]

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.[50]

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

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49. Calculated based on 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

50. 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

manufacturers could be based on different methodology, system boundaries, and input data.[51]

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 26. Data on the carbon footprint of some construction equipment [52]

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.

A study on climate impact of Norwegian defence sector also used proxy from the closest civil type of equipment to estimate the emission factors for the production of military

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[51] Volvo CE carbon footprint principles, https://www.volvoce.com/-/media/volvoce/global/global-site/our-offer/brochures/environmental-product-declarations/life-cycle-assessment-carbon-footprint-methodology-volvoce.pdf

[52] 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

equipment since corresponding values for military equipment are unavailable (even though development, production, and cost differ). The research derived from the following emission factors for manufacturing of military systems based on Ecoinvent database data.[53]

Ships and boats:

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

Aircrafts:

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

Vehicles:

- 33.7 tCO_2e per unit of heavy vehicles (i.e. a building machine);
- 24.4 tCO_2e per unit of medium vehicles (i.e. a 16 metric ton lorry);
- 6.8 kg CO_2e per kg of weight of light vehicles (i.e. a diesel passenger car; weight values of 1,200 and 2,000 kg were used).

These data demonstrate wide variations in emission factors as well as limitations related to comparison of civilian equipment and military equipment types. For instance, for vehicles, the emission factor varies from 8.2 to 33.7 tCO_2e per unit depending on the type of vehicles.

For the purpose of climate damage assessment, the indicative value used for Trucks, Vehicles and Jeeps category is 48 tCO_2e per unit, which reflects a greater weight of military equipment. For Aircrafts and Ships, the difference in values is more significant, which is related to the very different potential types and sizes of equipment in these categories.

Analysis of a more detailed inventory of destroyed military equipment and additional research on embodied carbon of military equipment is required for a more precise estimation of the climate damage.

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[53] 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

A2. FIRES

Historical data on fires

The impact of the war has been estimated by comparing the areas of fires during the war period (555 days) with historical data on fires. Data from the European Forest Fire Information System (EFFIS) for the territory of Ukraine are available starting from 2020.

Ukrainian official statistics on landscape fires, including forest fires, has significant limitations and allows recording only a part of the fires that occurred. Based on long-term statistical data, there are three or four years with significantly higher numbers and areas of forest fires each decade, with weather conditions, in particular the amount of precipitation during April-September, being the key factor influencing fire risks.[54] Large-scale single events or an unusually high number of fires during a particular year significantly impact the average values for historical periods. During 1990-2021, there were 3,519 fires registered affecting about 6,800 ha on average per year. However, if years with unprecedented large areas of fires (>5,000 ha) are excluded, the average values will be reduced to 2,817 fires affecting about 2,300 ha of forests.[55]

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

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

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[54] S. V. Zibtsev, O. M. Soshenskyi, V. V. Humeniek, V. A. Koren (2019), Long term dynamic of forest fires in Ukraine, Ukrainian Journal of Forest and Wood Science, 10(3):27-40, https://nubip.edu.ua/sites/default/files/u184/13113-29360-1-sm1.pdf

[55] Calculated based on the information provided by the Statistical Service of Ukraine, https://ukrstat.gov.ua/druk/publicat/Arhiv_u/07/Arch_dov_zb.htm

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

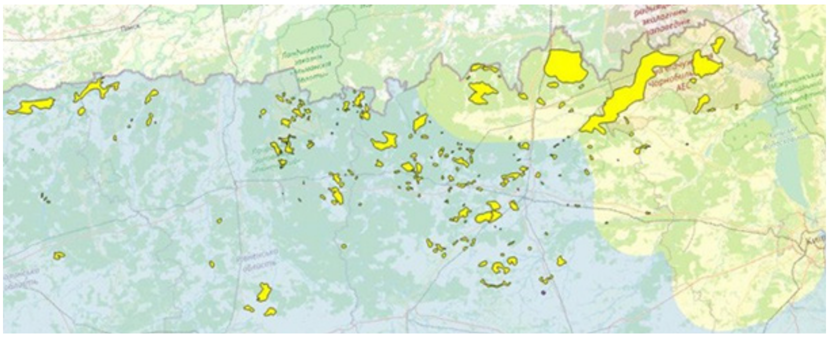

Fig. 24. Fires during the period of 28 March – 29 April 2020 in the northern regions of Ukraine

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

Areas affected by the war

The war resulted in a significantly increased number and area of fires, including forest fires. During 2022, there were 133 fires with an area exceeding 500 ha and some fires exceeding 1,000 ha, with the largest fire recorded affecting more than 6,000 ha. The largest number of fires was observed in March and July 2022.[56]

The whole territory of Ukraine has been affected by the war for some extent; however, the level and nature of impact differs in the following three zones (Fig. 26)[57]:

- Zone 1 – (55.9% of the territory of Ukraine) where ground military operations were not conducted;
- Zone 2 – (27.8% of the territory of Ukraine) zone of active hostilities (ground hostilities were conducted for more than 24 hours);
- Zone 3 – (12.3% of the territory of Ukraine) occupied territories, in which ground military operations were conducted for not more than 24 hours or did not take place at all.

Fig. 25. Frontlines and territory distribution by zones: Zone 1 (blue), Zone 2 (yellow), and Zone 3 (red)

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

Additional spatial-temporal analysis of the relationship between air raid alerts[58] in Ukrainian regions and locations of fires recorded by the EFFIS service in such zones during 555 days of the war revealed that most of the fires occurred during the periods of and in locations with air raid alerts. During this period, air raid alerts were announced 30,531 times, including 1,230 air raid alerts that started on one calendar day and ended on the next day. Thus, for the purpose of analysis, out of 31,761 "location - calendar day" pairs, the unique

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

57. The breakdown of the territories has been updated from the initial assessment to reflect the changes in the frontlines. In particular, the zone of active hostilities has been increased from 19.5% to 27.8% of the territory of Ukraine.

58. Statistics of air raid alerts in Ukraine, https://air-alarms.in.ua/en

combinations (i.e. excluding duplicates reflecting cases where air raid alerts were announced several times per day) were used. Most of the air raid alerts were announced on a regional basis, though around one fifth of them were announced on a level of specific settlements.

As a result, the following unique combinations were used for the analysis:

- 8,861 unique pairs ("region - calendar day") for 24 regions of Ukraine;
- 1,002 unique pairs ("location - calendar day") for 60 settlements of Ukraine.

For such spatial-temporal combination, we analysed the fires registered by the EFFIS service in respective regions or cities (including at the distance of 1 km from the cities) during the days with air raid alerts.

The total area of fires recorded in Zone 1 was 141,366 ha and 85% of the area was affected by fires that started during the periods of air raid alerts (with an area of 120,012 ha). Similarly, in terms of the number of fires, in Zone 1 almost 83% of them started during the days with air raid alerts (1,806 fires out of 2,188). Only 382 fires with an area of 21,354 ha were recorded during the periods without active air raid alerts. This figure is comparable with the area of fires in Zone 1 during the pre-war period (24,865 ha). Thus, it is assumed that an increase in the number and area of fires in Zone 1 is attributable to the war either due to the direct impact of missiles and drones or other factors limiting the ability to ensure early response to the fires (e.g. focusing on response and/or potential need to respond to fires within the settlements that could affect human lives and infrastructure damage, while most of the fires occur on agricultural land and in natural areas).

The relationship between fires and air raid alerts in other zones is naturally less significant as there are other key drivers of fires.

Territories in Zone 2 were most severely affected by increased areas of forest fires due to the direct impact of combat operations. The frontlines changing during the course of the war as reported by OSINT[59] are indicated on figure 26. The 12-mile zones on both sides of the changing front lines were applied to map Zone 2.

In Zone 3, which covers occupied territories, the attribution to the war is explained by the lack of efficient fire-response actions or even cases, when occupying forces prohibited local population to respond to fires in natural ecosystems, as well as additional impacts due to the military operations. According to the provisions of the Convention on the laws and customs of war on land[60] (Hague, II) (29 July 1899), articles 23, 43, and 55, the occupying country is responsible for the fires on the occupied territory.

The analysis of potential impact of lightning strikes on fires in natural landscapes was conducted with the support of the Ministry of Emergency Situations of Ukraine and the Ukrainian Hydrometeorological Institute and using the data of the Ukrainian segment of the Earth Networks Total Lightning Network (UkrENTLN).[61] The system detects two types of lightning (cloud-to-ground and intra-cloud) with a spatial location accuracy of less than 500 m for the territory of Ukraine. Based on the correlation analysis of lightning strikes automatically recorded on the territory of Ukraine and detected fires, 121 lightning strikes that were recorded on the first day of the fire — either within the boundaries of the fire territory or at a distance of 1 km from its boundaries — were identified. Overall, out

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59. https://liveuamap.com/uk

60. Laws of War: Laws and Customs of War on Land (Hague II); July 29, 1899, https://avalon.law.yale. edu/19th_century/hague02.asp

61. Ukrainian segment of ENTLN, https://uhmj.org.ua/index.php/journal/article/view/89/87

of all fires for 555 days of the war, there were 43 fires with a total area of 5,196 ha, which could have been potentially caused by a lightning strike. This represents less than 1% of the total area and number of fires. Most of the fires were located in Zone 2 (32 fires with an area of 2,877 ha), mainly located on agricultural lands and on natural landscapes. On the occupied territories (Zone 3), there were 7 fires identified with an area of 615 ha. Thus, the overall impact of lightning strikes on fires is not significant but the war also affects the response measures to such fires, both on the territories controlled by the government and on the occupied territories, where occupation forces practically did not carry fire response measures.

Emissions from fires

A general methodology to estimate the emissions of individual greenhouse gases for any type of fire is provided by the IPCC[62]:

- $L_{fire} = A \cdot M_B \cdot C_f \cdot G_{ef} \cdot 10^{-3}$, where:
- L_{fire} – amount of GHG emissions from fire, t of each GHG (e.g. CH_4, N_2O);
- A – area burnt, ha;
- M_B – mass of fuel available for combustion, t per ha; this includes biomass, ground litter, and dead wood, but when Tier 1 methods are used, then litter and dead wood pools are assumed zero;
- C_f – combustion factor, dimensionless;
- G_{ef} – emission factor, g per kg of dry matter burnt.

The area affected by fires has been determined based on satellite observations as provided by open fire prevention information systems: the US-based Fire Information for Resource Management System (FIRMS) and the European Forest Fire Information System (EFFIS). The areas of fires have been classified in several land use categories, including forest land, agricultural land, other natural landscape area, as well as built-up territories. To improve the accuracy of the estimates, the areas of forest fires have been analysed with the breakdown by the types of forests (broadleaf forests, coniferous forests, and mixed forests) and region, as both the type of forests and climatic characteristics of the region significantly affect the amount of biomass available for combustion.

The mass of fuel available for combustion during forest fires has been estimated using the data on average values of stocks of forest stands (stocks of stem wood) for each region of Ukraine.[63] However, the biomass of stem wood represents only a fraction of total biomass in the forest (approximately two thirds), while other biomass includes branches, leaves, stumps, and various forest vegetation.[64] Therefore, the value of biomass content in forest stands has been converted into overall above-ground and below-ground biomass content in forests in tonnes of dry matter per hectare using the approaches applied in the national GHG emissions inventory.

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62. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories, Equation 2.27, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

63. Provided in Ukraine's Greenhouse Gas Inventory 1990-2021, Table A3.3.8. Average stock of forest stands in forests of the State Forest Resources Agency of Ukraine, m^3/ha, p. 490

64. Lakyda P.I., Vasylyshyn R.D., Matushevych L.M., Zibtsev S.V., Wood biomass energetic of Ukrainian forests using in conditions of global climate change, https://nv.nltu.edu.ua/Archive/2009/19_14/18_Lak.pdf

For forest ground litter, the default value of 10t of dry biomass has been applied in line with the national GHG emissions inventory.[65] For crown fires, the amount of fuel available for combustion includes both trees and ground litter. During the low-intensity surface fires, only litter and grass are assumed to be affected while trees remain mostly intact.

Fires usually start as surface fires but may transfer to canopy causing crown fires if not extinguished timely. Since most of the forest fires were recorded in the active combat zone, the ability to respond to them was limited. Lack of fire suppression allows low intensity and medium intensity fires evolve into high intensity fires spreading on large territories due to topography characteristics, wind, and fuel availability. Besides, coniferous forests (75% of forests affected by fires in Ukraine in 2022[66]) are more vulnerable to fires and face a greater risk of crown fire development. Additional analysis of the areas of forest fires, for which hotspots were initially detected by FIRMS and then the fires were mapped using satellite imagery by EFFIS, revealed that over 85% of forest fires could be classified as crown fires. Fires not detected by FIRMS were assumed to be surface fires since tree canopy and lower level of mid-infrared radiation from such fires obscures fire detection by the FIRMS service. Such an approach, however, has limitations, as the distribution of area affected by crown fires and surface fires within the overall area of each particular fire could be very different and needs to be analysed during post-fire field studies.

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

The severity of fire impact could be assessed based on spectral indices from remote sensing imagery, in particular, a difference between the pre-fire and post-fire normalized burn ratio index (delta NBR or dNBR), which was designed to identify burnt areas.[67] Due to the lack of such analysis for the affected areas, the default value of the fraction of biomass lost in fires equal to 0.7, as provided in the national GHG inventory,[68] was applied to crown fires.

The Tier 1 assumption is that all of the biomass assumed to be lost results in emissions in the year of disturbance (i.e. in the year of fire). In practice, however, such biomass loss occurs over time due to gradual degradation of forests and death of affected trees, cutting of damaged trees, and biomass decay.

Emissions from fires also include other greenhouse gases, or precursors of greenhouse gases, that originate from incomplete combustion of the fuel. These include carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOC), and nitrogen (e.g., N_2O, NO_x) species.[69]

Default emission factors provided by the IPCC for all main greenhouse gases were used in

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

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

67. Normalized Burn Ratio (NBR), https://un-spider.org/advisory-support/recommended-practices/recommended-practice-burn-severity/in-detail/normalized-burn-ratio

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

69. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

calculation of GHG emissions from fires[70]:

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

The final emission factors in tCO_2e per hectare of land affected by fires for different land categories are presented in table 27 below.

Land category and fire type	Emission factor, tCO_2e/ha	Source of information
Forests – crown fires	Regional data in the table below	The National Center for GHG Emissions Inventory.
Forests – surface fires	17.6	Calculated based on the provisions of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Ukraine's Greenhouse Gas Inventory, and assumptions described above.
Agricultural land	11.3	
Other nature/landscape	7	
Built-up areas	792	The methodology for calculating of unorganized emissions of polluting substances or mixtures of such substances into atmospheric air as a result of emergency situations and/or during martial law and determining the amount of damage caused[71]. The methodology provides emission factor of 2.64 tCO_2e per tonne of material and an example of a shopping mall with the combustible material content of 0,03 tonnes per m^2 (300 tonnes per ha).

Table 27. Emission factors for different land categories [72]

Estimated emission factors for coniferous and deciduous forests in each region of Ukraine are presented in the table below. The average value has been applied for mixed forests.

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70. Table 2.5 (all other forest types), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

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

72. Calculated based on the information presented in Ukraine's Greenhouse Gas Inventory 1990-2021, Table A3.3.8. Average stock of forest stands in forests of the State Forest Resources Agency of Ukraine, m^3/ha, p. 490

REGION	EMISSION FACTOR FOR CROWN FIRES, tCO_2e/ha	
	CONIFEROUS	DECIDUOUS
Ukraine (average)	323.3	263.5
AR Crimea	209.3	192.6
Vinnytsia	314.5	293.4
Volyn	308.9	217.0
Dnipropetrovsk	330.0	214.8
Donetsk	249.1	193.7
Zhytomyr	300.1	227.0
Zakarpattia	414.2	382.0
Zaporizhzhia	165.0	98.5
Ivano-Frankivsk	399.8	321.1
Kyiv	346.6	263.5
Kirovohrad	262.4	225.9
Luhansk	241.4	183.8
Lviv	342.2	317.8
Mykolaiv	179.3	115.1
Odessa	170.5	184.9
Poltava	305.6	262.4
Rivne	249.1	189.3
Sumy	395.3	315.6
Ternopil	334.4	265.7
Kharkiv	355.5	292.3
Kherson	196.0	111.8
Khmelnytskyi	330.0	259.1
Cherkasy	353.2	285.7
Chernivtsi	332.2	284.6
Chernihiv	387.6	272.4
Kyiv city	346.6	263.5
Sevastopol city	155.0	155.0

Table 28. Regional emission factors for crown fires

Opportunities for a more detailed analysis of the areas affected by fires will be explored in future assessment reports (e.g. distribution by crown fires and surface fires, assessment of the amount of combustible materials in built-up areas, etc.).

A3. 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.[73] These factors may vary slightly depending on the country.

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[73] Deloitte, Energy Security. America's Best Defense, https://legacy-assets.eenews.net/features/documents/2009/11/11/document_gw_02.pdf

A4. 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 29. 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 emissions of GHG, i.e. emissions that would not have occurred in the absence of the war. Therefore, stages B4-B5 are not taken into account as replacement and refurbishment of buildings would have also happened in the damaged or destroyed buildings. The End-of-Life stages C1-C3 will occur first 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[74], 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	401
Industrial production buildings	398
Office buildings	379
Retail and wholesale buildings	401
Warehouses	305

Table 30. 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.[75] 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

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[74] One Click LCA website: https://www.oneclicklca.com

[75] 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

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.

Asphalt pavement sub-system	**Dual-3 lane**	**Dual-2 lane**	**Single-1 lane**
	tCO_2eq 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 31: Embedded emissions estimated for the different sub-systems of asphalt pavement over an assumed time period of 40 years

For passenger vehicles, more research[76] is available to determine embodied carbon. For the purpose of this study, we have taken the lower end of estimations at 5.6 tCO_2e/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_2e/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

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