War on the Climate: A Multitemporal Study of Greenhouse Gas Emissions of the Israel-Gaza Conflict

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Highlights

❖ The projected emissions from 15-months of direct war activities were greater than the annual emissions of 36 individual countries and territories.

❖ The total emissions increase to more than over 41 lowest emitting countries and territories, if we include Hamas' tunnel network and Israel's protective fence or 'Iron Wall,'

❖ The carbon costs of reconstructing Gaza and homes destroyed in Lebanon are about the same as the annual greenhouse gas emissions of Croatia.

❖ These calculations point to the urgent need for increased visibility and mandatory reporting of military emissions for both war and peacetime through the UN Framework Convention on Climate Change (UNFCCC).

Abstract

Following Hamas's surprise attack on October 7, 2023, Israel engaged in an unprecedented military campaign in Gaza which expanded into a regional war including southern Lebanon, Iran and Yemen. One aspect of this war, and indeed of any war, is the less discussed immediate and long-term climate impacts, including the intense greenhouse gas emissions (GHG) associated with the use of combat materials, resource degradation and destroyed buildings and infrastructure. We assess the GHG emissions of the conflict in the Middle East for three distinct periods: emissions from the approximately 15-months of the war (October 2023 – January 2025), construction and fortification activities, and emissions from future reconstruction. We estimate the total carbon emissions due to direct war activities to be 1,898,330.9 tonnes of carbon dioxide equivalent (tCO2e). This figure rises to 32,275,089 tCO2e when pre-conflict and post-conflict related construction activities are included. This final figure ranks higher than 102 individual countries' annual emissions, highlighting the significant carbon footprint of arisings from armed conflicts and the pressing need to account for carbon emissions due to war.

Introduction: The Carbon Costs of Conflict

Israel's ground invasion and aerial bombardment of Gaza, following the attacks by Hamas on October 7, 2023, lead to an unprecedented humanitarian crisis at a scale previously unseen in the region. Entire towns and communities were razed, major cities reduced to rubble, water and sanitation infrastructure decimated, and the remaining population left to contend with hunger and disease. By no means do the figures reflect the cost of the suffering, they are nonetheless staggering.[1] Over a roughly 15-month period, from 7 October 2023 to 19 January 2025, over 46,707 in Palestine and 1,139 in Israel, lost their lives.[2,3] Estimates place 54-66% of Gaza's buildings — homes, schools, mosques, hospitals — as destroyed or damaged,[4] with initial forecasts of future financial cost to Israel expected to reach up to $50 billion,[5] including rebuilding Gaza.[6] On January 17, 2025, a cease-fire deal was finally reached, and many are slowly returning to Gaza.

The conflict did not only take place in Gaza but expanded into a regional war including rocket-fire exchanges and Israeli aerial bombardment of Lebanon, missiles and retaliatory strikes from Iran and Houthis in Yemen. The full impacts of the regional conflict will continue to be felt for decades, including its significant diffuse and understudied climate impacts. We fill this empirical gap with a novel examination of the conflict emissions of the war. We take a practical and ethical approach to accounting the long-term climate damage of military action, responding, in part, to recent calls to produce research that helps elucidate the wider environmental and climate impacts of conflict,[7,8] and scholars varied ethical concerns with the devastating social effects of the war in Gaza.[9,10,11,12]

This analysis is meant to be used as an entry point for a more comprehensive picture of the effects of militaries' long war on the climate – an issue rarely examined by climate researchers.[13] Methodologically, we move beyond the more limited, albeit frequently applied, Scope 1 or direct "tailpipe" emissions and in-direct or Scope 2 and 3 emissions, advocating for a separate scope that *only* includes wartime emissions, called "Scope 3+."[14] In doing so, we use a specific approach of conflict related emissions in this article outlined by de Klerk et al.'s (2024). [15] to enumerate conflict greenhouse gases, including pre-, during, and post-conflict emissions in Gaza and the wider Middle East. In addition to intensive fuel consumption of attack and cargo aircraft, ships, and the rapid deployment of troops, this method includes damage to local environments including fires, emissions from infrastructure damage, displacement of people, aid, and ultimately post-war reconstruction,[14] providing researchers and policymakers better insight to comprehensively quantify many aspects of war usually left out of impact assessments.[a]

In our analysis, we use open-source data on combat operations and military installations to estimate the carbon footprint of the regional war, including the emissions found in related combat and post-combat activities, such as aid delivery and reconstruction. Our analysis covers three time-horizons, in line with de Klerk et al.'s (2024) wartime emissions methodology, including **pre-conflict preparation, the conflict itself,** and **post-conflict**. To verify the reliability and robustness of emissions data, we adopt a robust Monte Carlo uncertainty analysis within each of these three time-horizons. [16] We made all attempts to keep our methodology clear and accessible so that future research can build upon a significant gap in scholarly research around greenhouse gas emissions during war. Our final figure of pre-/post- and warfighting activities is estimated at 32,275,089 tCO2e. This figure ranks higher than 102 individual countries' annual emissions, highlighting the significant carbon footprint of arisings from armed conflicts and the pressing need to account for carbon emissions due to war.

The first time-horizon covers the **pre-conflict** carbon emissions found in the preparations and fortifications prior to the latest conflict over the past 16 years. Over this time-horizon, we consider emissions from the construction of security-related concrete infrastructure in both Israel and Gaza. This calculation stretches back to 2007 to gain insight into the climate impacts of an underappreciated facet of military emissions, the use of concrete in security infrastructure. We include built concrete infrastructure used by Hamas' Gaza tunnel construction which was ramped up to circumvent the Egyptian-Israel blockade put in place in 2007. [17] On the Israeli side, we include emissions for the "Iron Wall" separating Gaza from Israeli controlled territory - both above and below ground. The wall, planned since 2016 and finished in 2021, was built with the intention of protecting Israel from any Hamas attack from the Gaza strip.[18] We

[a] Other significant indirect emissions may also apply due to disruptions and reverberating effects on the economy, such as rerouting of civil aviation, and the disruption of supply chains. These are included in the de Klerk et al.'s (2024) wartime GHG emissions methodology.

specifically include these to draw attention to such carbon-intensive infrastructure, and its centrality in the offensive and defensive dynamics of the war.

To examine the immediate **conflict-related** climate ramifications of Israel's war on Gaza over 15-months, we calculate mainly Scope 1, and some, but very limited, Scope 2 and 3 of the thousands of Israeli bombing raids and reconnaissance flights, tanks and other vehicles, cargo flights, and the emissions associated with the production of the estimated munitions used by Israel on Gaza. Within this same timeframe, we estimate the emissions of Qassam rockets sent into Israel by Hamas during the initial stages of the war. We calculate the aerial bombardment of Lebanon by the IDF, and Hezbollah return of rockets on northern Israel. Long-range missiles fired from Iran and rockets fired by Houthi fighters in Yemen and Israel's air raids in response were also included in our analysis.

Finally, we analyse the carbon costs of future **post-conflict reconstruction** needs in Gaza following the extensive destruction wrought by Israeli bombardment. This estimate is made following de Klerk et al.'s (2024) methods detailing wartime emissions of reconstruction, or the analysis of emissions on the number of buildings destroyed, including housing, schools, medical facilities, water and power infrastructure and more, and then calculating the carbon cost of rebuilding, even to Gaza's previously precarious state. To provide a more comprehensive view, we added Abdelnour and Roy's (2024), insightful calculation of Gaza rubble removal as part of our total reconstruction data.[19]

Difficulty in monitoring and accessing information about combat operations is one of the major reasons for the limited literature on the climate impacts of war, a second, being the lack of rigorous methodologies to track them.[20] This work aims to offer researchers, activists, and policymakers the tools to more robustly track the carbon costs of war, highlighting the underappreciated and up to this point, under-researched, climate costs of the war on Gaza and across the region.

Expanding the Scope 3+ wartime emissions, and why it matters

According to the United Nations Environment Programme's Emission Gap report,[21] military emissions are 'insufficiently accounted for' by the UNFCCC, but even with incomplete data, researchers have found that militaries *still* account for almost 5.5% of global emissions from 'day-to-day' activities. [22] This estimate excludes conflict emissions from warfighting itself yet is still comparable to the combined contributions from civilian aviation (2%) and civilian shipping (3%). The global military sector has largely remained understudied and unreported.[23]

The data gaps clearly complicate estimations for key climate indicators. Furthermore, the global climate change indicators for 2023 show significant changes in just the three years since the IPPC 6th Assessment Report came out. Average annual maximum temperatures on land have warmed by more than 0.6 °C in the past 10 years. Estimates of the remaining global carbon budget have also dropped between 2020 to 2024, from 500 to just 200 gigatonnes of CO_2e for a 50% likelihood of limiting global warming to 1.5°C. The method of estimating remaining global carbon budgets did not take into consideration emissions due to "military actions."[24]

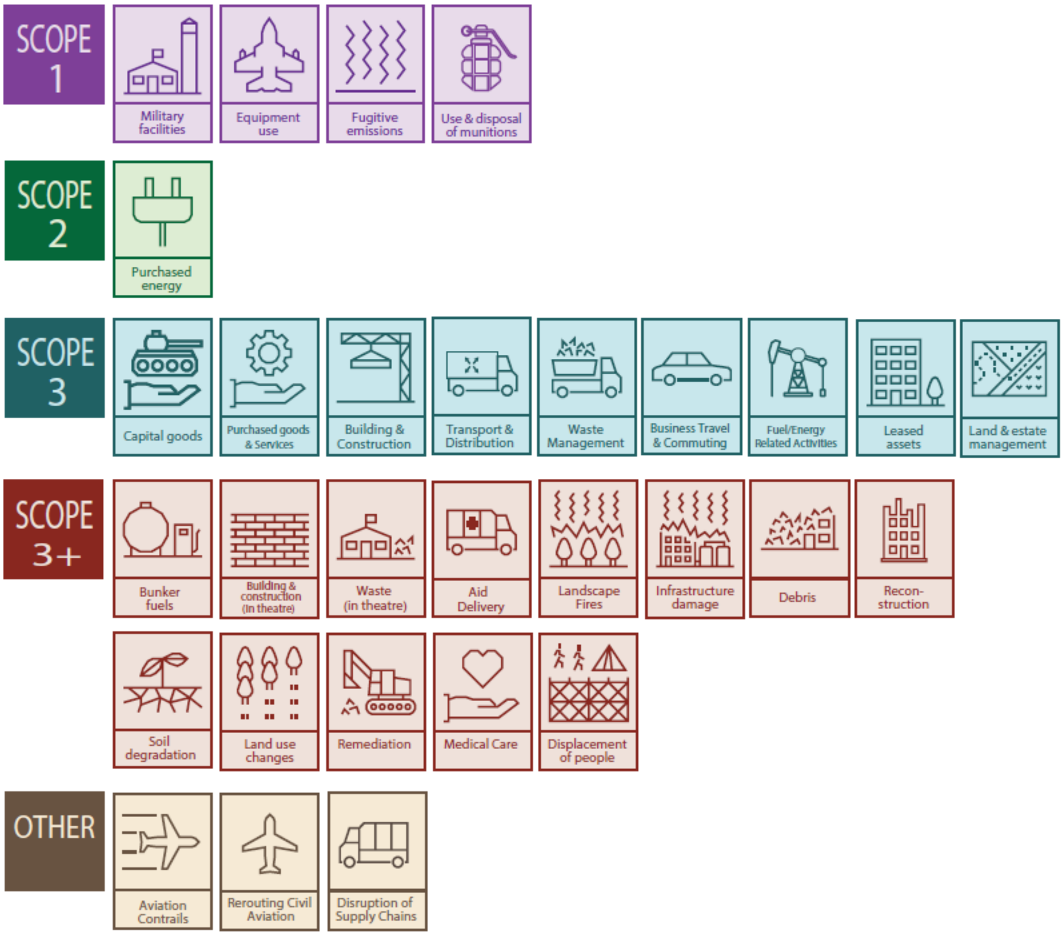
Even within these dire warnings, as far as we are aware, the Israeli military (IDF), as many militaries worldwide, has never reported emissions figures.[2] No specific data on military fuel combustion emissions has been provided in Israel's annual National Greenhouse Gas (GHG) Inventory to the UNFCCC, although requested under the reporting category 1.A.5, which covers emissions from military fuel use.[25] Therefore, to get some understanding of the baseline military emissions from the IDF, which we understand to be significant, we created a rough heuristic to provide some context to our analysis. To create this proxy figure, we take GHG emissions from militaries as a function of total military spending based on an average carbon intensity for each dollar spent in 2019 for the top five European military budgets - France, Germany, Italy, Spain, and the Netherlands. The average military carbon emissions are estimated to be 0.14 kg of CO_2e per US dollar in 2019.[26] Using this baseline, we estimate that Israel's 2023 military budget of US $27.5 billion would result in a total emissions figure of 3.85 million tonnes of CO_2e – about 5% of Israel's annual emissions and roughly the same as the 2023 annual emissions of Bahamas and The Gambia combined.[27,28] This figure is more than the total 2019 emissions figures from all of Palestine (4.8 million tCO_2e).[29] Palestine's military specific emissions are also unreported, however, given the more ad hoc nature of Hamas's offensive capabilities and the lack of data on expenditure by Hamas, we are not confident a similar proxy approach would deliver a meaningful figure.

Clearly, there remain huge data gaps in how we account for specific country's emissions data, particularly during wartime. For instance, the global estimate of 5.5% for military emissions noted above includes key military technology industry and supply chains but excludes emissions from conflict and warfighting activities. Current UNFCCC reporting obligations do not set out requirements to cover certain types of conflict emissions, and there is no commonly

[2] Military GHG emission data reported by governments can be reviewed by clicking on the map available at: https://militaryemissions.org/

agreed methodology or scope. To address this omission, we use a proposed a framework outlining the Scope 3+ categories (see Figure 1, Table 1), as well as the standard Scope 1, Scope 2 and Scope 3 emissions – as set out by the GHG Protocol.[14]

Figure 1: Proposed Scopes 1, 2, 3 and 3+ emissions reporting categories for militaries and armed conflicts[15]



174

Table 1: Proposed Scopes 1, 2, 3 and 3+ emissions reporting categories for militaries and armed conflicts[15]

Scope 1: Direct GHG emissions	**From sources that are owned or controlled by the organisation**
Military facilities	Fuel combustion in static units including solid, liquid or gaseous fuel use for heating, cooling or generators.
Equipment use	Fuel combustion from mobile equipment use, including aircraft, land vehicles, marine vessels and spacecraft (Within the troposphere and stratosphere only).
Fugitive emissions	Fugitive emissions, e.g. methane, arising from treatment and disposal of solid, liquid and gaseous waste and wastewater, in facilities owned or controlled by the military. Also, other fugitive emissions mainly from use of HFCs, PFCs or SF_6 in refrigeration, air conditioning, radar and electrical equipment and from other chemical use (such as de-icers) or losses.
Use and disposal of munitions	Detonation of munitions in training and active combat, including the incineration, detonation, open burning or treatment of end-of-life and obsolete explosive ordnance, in facilities owned or controlled by the military.

Scope 2: Indirect GHG emissions	**From purchased or acquired energy not owned or controlled by the organisation**
Purchased energy	Includes electricity, steam, heat and cooling for use at, e.g. military bases and buildings.

Scope 3: Other indirect GHG emissions	**From other sources resulting from activities of an organisation, but occur from sources not owned or controlled by that organisation**
Capital goods	Includes the raw material extraction, manufacture and transportation of all major military equipment (for land, sea, air, space), civilian equipment (including business transport fleet) and IT systems.
Purchased goods and service	Includes the raw material extraction, manufacture and transportation of other purchased military and civilian goods (such as weapons, combat gear, clothing, IT, office equipment and perishables). Also includes services such as the provision of private military and security companies, logistics, maintenance, IT and telecommunication support, catering etc.
Building and construction	Includes the construction and renovation of buildings and similar assets.
Transport and distribution	Includes the transportation and distribution of products and services purchased not included above, in vehicles not owned or controlled by the military.

Waste management	Disposal and treatment of solid, liquid and gaseous waste and wastewater in facilities not owned or controlled by the military. This includes fugitive emissions (e.g. methane) and emissions from the incineration, detonation, open burning or treatment of end-of-life and obsolete explosive ordnance.
Business travel and commuting	Transportation of military or civilian staff for business-related activities in vehicles not owned or operated by the military. Also includes transportation of military or civilian staff between their homes and place of work in vehicles not owned or operated by the military.
Fuel/energy related activities	Includes the raw material extraction, manufacture and transportation of fuels and energy, not already included in Scope 1 and 2.
Leased assets	Operation of assets leased by the military and not included in Scope 1 and 2 and operation of assets owned by the military and leased to other entities.
Land and estate management	Includes damage to natural ecosystems, deforestation, impacts on agricultural areas, wetlands and fires caused by training and land use practices.

Scope 3+: Other indirect GHG emissions linked to the military	**From other sources resulting from military activity and warfighting not covered above.**
Bunker fuels	Combustion of fuels used for international aviation, spacecraft launches, land-based and maritime transport, and not reported under Scope 1 or Scope 2.
Building and construction (in theatre)	Includes the construction of bases, buildings and similar assets in theatre.
Waste (in theatre)	Incineration, disposal, haulage and treatment of military-derived solid waste and wastewater, from military deployment overseas and not included above.
Aid delivery	Includes the production, delivery, and distribution of equipment, food, water, shelter and/or services, to people or organizations directly in the theatre of war or to displaced populations.
Landscape fires	Includes accidental fires caused by military training exercises and fires caused during active combat. Includes fires in natural forests, plantations, shrub, grassland, pasture, peatlands, agricultural land and peri-urban areas.
Infrastructure damage	Includes fires and damage to infrastructure, as well as any fugitive emissions due to leaks or losses from infrastructure (such as methane, SF_6).
Debris	Includes the building debris generated from the use of explosive weapons during warfighting, haulage and waste management.
Reconstruction	Includes the raw material extraction, manufacture and transportation of construction materials, as well as emissions from the construction activities.
Soil degradation	Includes soil erosion, disturbance and desertification, which can accelerate the loss of carbon from soils and reduce their potential to be effective carbon sinks.

Land use changes	Includes damage to natural ecosystems, deforestation, impacts on agricultural areas, wetlands and fires caused by changes in land-use practices.
Remediation	Includes the raw material extraction, manufacture and transportation of restoration materials, as well as emissions from the remediation/restoration activities and disposal or treatment of any contamination or hazardous waste.
Medical care	Includes military and civilian casualties, and the logistics and provision of medical equipment and facilities, medical staff and management of medical waste.
Displacement of people and humanitarian support	Includes internally displaced people and transboundary refugees, and the logistics and provision of food, shelter, welfare management. Liaison with external humanitarian aid agencies or national governments required.

Other	**Description**
Aviation contrails and non-CO_2 effects	Aircraft and spacecraft flying in the stratosphere can cause non-CO_2 climate change contributions and a CO_2 emissions weighting factor can be used to approximate these non-CO_2 climate change contributions.
Civil aviation	Covers rerouting of civil aviation.
Disruption of supply chains	Includes disruption to maritime transport and shipping lanes.

The Scope 3+ framework originally developed by Cottrell (2022), was adapted and applied for the initial and follow-on conflict emission estimates from Russia's invasion of Ukraine,[8] and draws attention to the primary emission sources, highlights the scale of otherwise hidden emissions and could be used to hold Russia accountable for the climate damage caused. The process also highlights the inadequacy of the current reporting obligations, and failure of the UNFCCC's structure to enable accounting of certain conflict emissions. Under the current reporting obligations, military emission data is provided on a voluntary basis only and limited to military fuel use.[3] Unfortunately, data on military emissions is either left-out or embedded within a country's overall emissions reported to the UNFCCC, and there is no consideration of the contribution from other wartime activities such as fires and reconstruction needs.

Scope 3 accounting follows a life cycle approach, evaluating the full emissions associated with raw material extraction, manufacturing or processing, transportation, use, and end-of-life

[3] Military use of other GHGs (SF_6 and perfluorocarbons under category 2.G.2.a) is also requested by the UNFCCC but only reported by the UK and Japan.

management of goods or services. The GHG Protocol provides clear and transparent methods on accounting.[30] However, most organisations reporting on their GHG emissions fail to fully include Scope 3 emissions, including the military and the military industrial sector. A2023 survey reported that just 10% of companies surveyed were comprehensively measuring all their emissions.[31] Scope 3 emissions can be a significant proportion of an organisation's total emissions, meaning that the total carbon footprint for the military can be to 5 to 6 times higher than from the operational Scope 1 and 2 GHG emissions alone.[14]

The distribution of emissions across these Scope 3+ categories will vary depending on the conflict setting, duration, nature of warfare, type of weapon systems used, and post-conflict recovery. For Ukraine, researchers also identified additional indirect emissions resulting from closure of international airspace and the need to reroute flights, plus from the wider impact on Ukraine's economy and on the European energy sector.[32] Similarly, in Gaza and wider unrest in the Middle East has disrupted international shipping through the Red Sea and caused significant indirect emissions. Estimates suggest that emissions by shipping from East Asia to the Mediterranean increased by 63%, when compared to the same period before the conflict.[33] This was due to a combination of longer shipping routes, faster sailing speeds needed, and use of older, less efficient vessels. There are also emissions from the wider escalation of the conflict, including missile strikes across the Lebanon-Israel border, which has killed civilians, damaged buildings and resulted in large fires,[34] and between Israel and Iran. There is already abundant guidance on GHG accounting, and whilst the framework does not replicate quantification methods, it sets out the key categories for consideration and focus. Acquiring datasets relating to a conflict remains challenging, including Scope 3 and 3+ emissions linked to fires, military procurement and other civil equipment and supply chains.

The framework sets out for the minimum requirements that militaries should use to account for their GHG emissions - including in times of war - and is a useful starting point given the lack of agreed measurements tools. In 2023, NATO published its own GHG reporting methodology although this explicitly excludes emissions from NATO-led operations and missions, and other activities such as training and exercises. There is also no mention of warfighting emissions or how these may need addressing in the future.[35] Clearly, Scope 3+ would be a significant step forward in our ability to understand and analyse the climate impacts of war, however, as we demonstrate in this article, there are many challenges to calculating such 'real-time' carbon assessments. We elaborate on these limitations of data gaps in our discussions section.

Methodology of Carbon Emissions during War in Gaza

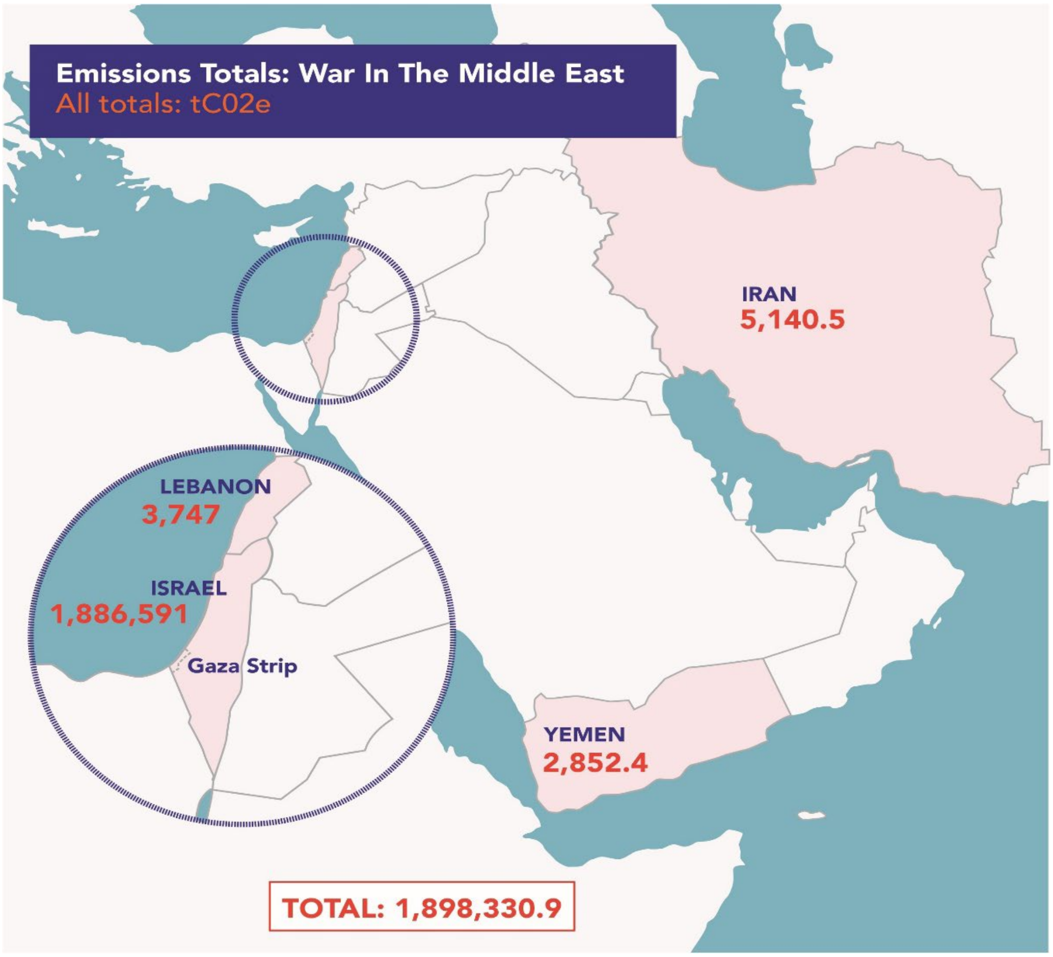
The methods employed in calculating emissions follow the guidance on assessment of conflict-related greenhouse gas emissions offered by de Klerk et al. (2024).[15] We define three distinctive time periods for estimating carbon emissions, including pre-conflict, conflict and post-conflict based on their framework for calculating conflict related greenhouse gases. We also closely follow de Klerk et al.'s recommendations of setting clear geographical boundaries and exactly what counts within each specific Scope, including direct and indirect emissions.

Pre-conflict emissions refer to greenhouse emissions resulting from activities such as construction of fortifications prior to the beginning of the war. The pre-conflict emissions we measure relate to the construction of thousands of tunnels in Gaza by Hamas and the construction of the Iron Wall by Israel. Emissions from direct warfare and the supply of fuel, aid and materials constitute conflict emissions. This includes bombing raids with aircrafts, the use of artillery, bombs and rockets, supply of goods using lorries, aircrafts and ships, and the fuel used by ground vehicles. Post-conflict emissions are calculated from reconstruction of destroyed buildings, roads and other infrastructure. Due to the rapid nature of the conflict, it has been difficult to obtain official data and reliable numbers of equipment being used, sorties conducted, or resources used. We rely on open-source information from media sources, as well as reports from independent aid organisations such as United Nations agencies working in Gaza and Israel. Following de Klerk et al.'s (2024) work in wartime emissions in Ukraine, we have triangulated data of the same emissions related activity from multiple sources, including news reports, think tanks and government reports, to support our calculations. We understand that there is significant variability within complex systems, especially those involving such as non-deterministic features in wartime climate emissions calculations,[36] and therefore we have developed a robust Monte Carlo uncertainty analysis to validate our data explained in the section below.

We standardised our emissions factors calculations, using Inventory of Carbon Energy Database (ICE) and International Organization for Standardization (ISO) and Intergovernmental Panel on Climate Change (IPCC) emissions calculations. To provide context for our findings, we compare carbon emission estimates to the latest data from Emissions Database for Global Atmospheric Research (EDGAR).[37] To ensure consistency and like-for-like comparison, our equivalent carbon emissions (CO_2e) is compared to the total carbon emissions from individual countries which is also provided as CO_2e.

Our geographical boundaries were guided by de Klerk et al. (2024), helpful guidance, stating that: "the geographical boundary refers to the physical location where the conflict's impacts occur, rather than where the resulting emissions are generated." such conflict boundaries need to be "clearly defined" and to "differentiate between impacts that are directly related to the conflict and those that extend beyond borders (transboundary impacts)." We explain in detail later in the article how we calculate where conflict impacts emissions are generated and our emissions totals for the different areas involved in the regional conflict, Gaza, Israel, Iran, Yemen, and Lebanon, displayed on the map below (Figure 2).

Figure 2: Emissions Totals for the Middle East Conflict in tCO2e



Estimation of Carbon Emissions

For each time-horizon (pre-conflict, conflict, and reconstruction), we estimated emissions under scope 1, 2, 3 and 3+, as summarised in Table 2 below.

Table 2: Summary of Scope Type Across the Three Time-Horizons

Time-horizon	*Scope 1*	*Scope 2*	*Scope 3*	*Scope 3+*

Conflict	✓	✓	✓	✓
Pre-conflict	✓	✓	✓	
Post-conflict		✓	✓	✓

For our study, we use scope 1 covers emissions due to Israeli bombing raids (primarily conducted by F-16s), tanks and other vehicles, cargo flights, and patrol flights by other aircraft, including F-35s, and the emissions of the estimated munitions used by Israel on Gaza. We also include a limited scope 2 analysis of purchased electricity use, and Scope 3 from the manufacturing of bombs and rockets used by both Israeli Defense Forces (IDF) and Hamas. Our scope 3 analysis also covers fuel used in generating electricity using diesel-generators for essential services in Gaza, as well as the delivery of aid using trucks.

We estimate the emissions from transport-related activities using open-source information on reported transport and estimated total amount of fuel consumed. Following de Klerk et al. 2024, total fuel consumed was multiplied by the emission factor listed in Table 3 to obtain the associated emissions. The formula used is summarised as:

$$CE = NT \times FCT \times EF_x$$

Where *CE* is the total carbon emissions from an activity, *NT* is the number of trips, *FCT* is the fuel consumed per trip, and EF_x is the emission factor for the fuel x (jet fuel, petrol or diesel) used. EF is expressed in terms of carbon dioxide equivalent (CO_2e), which is used to compare the various greenhouse gases emitted by the burning of a particular fuel based on their global-warming potential (GWP). We estimate transport-related emissions using DEFRA's standard emission factors for freight. This is the common approach is used for restocking the IDF by the US and international aid shipments to Gaza.

The emissions due to the use of bombs, artillery and shells was based on estimates of the amount of steel and explosives used and is in line with the supply chain methodology used in de Klerk et al. 2024 study of Ukraine emissions from explosives. The emissions from Hamas rockets and Israeli bombing raids was approximated by multiplying the estimated items of munitions used by the specific emission factors reported in Ukraine.[8]

We estimate the carbon emissions from Hamas tunnels and Israel's iron wall by triangulating open-sourced information with media reports on the dimensions of tunnels and walls. We then estimated the total amount of concrete and steel used in these tunnels and walls and applied standard emission factors as described below to obtain the total carbon emissions. The formula used is summarised as follows:

$$CE = C \times EF_c + S \times EF_s$$

Where *CE* is total carbon emissions from construction activities, *C* is total concrete used in the construction. EF_c is the emission factor for concrete, *S* is the total amount of steel used in the construction, and EF_s is the emission factor for steel. The materials and emission factors used for construction are in-line with the standards outlined in Inventory of Carbon Energy Database (ICE) and International Organization for Standardization (ISO) found in Neimark (2024) are presented in Table 3 below.

Units and Emission Factors Used in Calculations

The burning of jet fuel, diesel and petrol release various greenhouse gases including carbon dioxide, nitrous oxide and methane. Similarly, carbon monoxide and carbon dioxide are the predominant greenhouse gases emitted with the use of explosives, as well as particulates. The emission factors presented in Table 3 are given in CO_2e to account for the various greenhouse gases emitted in the production or use of a particular fuel or resource. The results from our calculations are expressed in carbon dioxide equivalent (CO_2e) to account for various greenhouse gases emitted. Our primary source of emission factors for calculations in this study are from the IPCC. We use alternative emission factors where a value could not be obtained from the IPCC as indicated in Table 3 below.

Table 3: Emission factors used in calculating carbon emissions from Israel-Gaza War

Emission Source	***Emission Factor Used***	***Reference***
Diesel	2.7 kgCO_2e/litre	IPCC, 2006[38]
Petrol	2.7 kgCO_2e/litre	IPCC, 2006[38]
Jet Fuel	2.52 kgCO_2e/litre	IPCC, 2006[38]
Concrete	180 kgCO_2e/tonne	ICE, 2024[39]
Steel	1.55 kgCO_2e/kg	Neimark et al., 2024[7]

Cement	900 $kgCO_2e$/tonne	ICE, 2024[39]
155mm artillery	139$kgCO_2e$/artillery	de Klerk et al, 2023[8]
Explosives (TNT)	5.06 $kgCO_2e$/kg	de Klerk et al, 2023[8]

Monte Carlo Uncertainty Analysis for Carbon Emission Estimates

We adopt a commonly used robust methodology for estimating carbon emissions by selecting a discrete set of war fighting activities and implied carbon costs from both military and civilian construction projects.[40,41] In this approach, emissions from an activity is estimated by multiplying the activity data by emission factors, yielding estimates at different temporal and spatial scales. This calculation is applied to the data obtained from media reports and other sources to obtain estimates of carbon dioxide equivalent emissions due to the war in Gaza. We calculate lower and upper bound carbon emissions for each activity to account for the range of possible emissions obtained from various sources. For example, we estimate the total weight of artillery shells used to be 8,000 tonnes, giving a lower estimate of emissions from artillery and rockets to be 12,000 tCO_2e. However, if all artillery used by IDF are 155mm shells, the embodied carbon could be as high as 139kg CO_2e for each artillery.[8] This is based on an emission factor of 60.35$kgCO_2e$ for the manufacturing of composition B explosive and 75.62 $kgCO_2e$ for the manufacturing of steel casing, and therefore, our higher estimate for artillery used by IDF is 13,900 tonnes of CO_2.

We applied Monte Carlo uncertainty simulations to determine the lower and upper bounds for each wartime activity that we collected data. In the example used for artillery used by the IDF, our mean estimate is 12,950 tCO_2e with a 7.3% uncertainty. This mean estimate was then used in Monte Carlo simulation which involved estimating the uncertainty in the emission factors as well as the data used in estimating carbon emissions for each.

The main sources of uncertainty in our computations stem from wartime activity, emission factors, and materials (e.g., exact quantities of materials used, such as fuel, concrete, and steel). Hence, we use the best available estimates, list the level of uncertainty with the estimates, and computed the uncertainty in carbon emissions using Monte Carlo simulations with R software. Monte Carlo simulation is a mathematical approach used to estimate the probability of a variety of outcomes of a process that involves a level of uncertainty. [42]

The IPCC recommends the use of country-specific emission factors wherever possible to ensure that the carbon emission factors used reflect the production technology, as this give rise to low uncertainty (5–10%).[43] However, due to lack of country-specific data for the study areas, we use emission factors based on UK (ICE 2019) and global data, hence assuming the maximum, i.e. 10%, uncertainty to these figures.

For activity data, we use the minimum and maximum estimates to generate a distribution for each variable using the *runif* () function in base R. Where there is only a single-value estimate, we assign 10% uncertainty based on Weidema and Wesnaes' (1996) reliability indicator for data quality matrix. We then applied a simulation model, as a product of the activity data and emission factor, set it to run 100,000 iterations for the carbon emissions resulting from each activity or source of carbon emissions, and returned a distribution of results as output.

$$\text{Total emissions} = \sum_{k=1}^{n} (XiEi)$$

Where k is number of iterations, n= 100, 000; X is the quantity of input material *i*, E is the emission factor for input material *i*.

The mean, standard deviation and 95% confidence intervals are computed. In the results, we present the mean, and the lower and upper limits of confidence interval.

Results: Carbon Snapshots of the Middle East Conflict

For each activity, we provide a lower and upper estimate of the total greenhouse gas emissions as shown in Tables 4 – 6. The lower and upper estimates are based on the 95th percentile confidence level from Monte Carlo simulations as explained above. For simplicity, we present the mean values in this results section.

1. Pre-Conflict Estimates

The estimates presented in Figure 3 and Table 4, respectively, represent a snapshot of the pre-conflict emissions associated with mainly two activities – the massive use of concrete and iron used in fortifications, the Iron Wall and Tunnel Network, prior and during the conflict. Again, for each activity, we provide a lower and upper estimate of the total greenhouse gas emissions. The basis for these estimates is explained in the methodological section.

Figure 3: Graphic of Pre-Conflict Activities in tonnes CO_2 equivalent (tCO_2e) for 15-months of Conflict

Table 4: Estimations of Pre-Conflict Activities in tonnes CO_2 equivalent (tCO_2e)

Emissions Activity	*Brief description*	*Emission factor used*	*Lower estimate (tCO_2e)*	*Mean Estimate (tCO_2e)*	*Upper estimate (tCO_2e)*
Hamas' Tunnel Network	500km of tunnels. 10cm/20cm thick, 2m tall and 1m wide. 300,000 to 600,000 cubic meters of concrete and 30,000 and 60,000 tonnes of steel used.	Concrete: 180kg CO_2e/tonne Steel: 1,550kg CO_2e/tonne	263,874.8	264,135	264,395.2
Israel's 'Iron Wall'	65km long, 6m tall, 3mconcrete below ground.		293,097.6	293,224	293350.4
Total Pre-Conflict Emissions			556,972.4	557,359	557,745.6

a. Hamas Tunnels

We have assumed, based on detailed descriptions of the 500 km network, that the tunnels are two meters tall, 1 meter wide and have a thickness of between 10 and 20 centimetres.[44,45,46,47,48] Thus for the four sides of the tunnels, we estimate that a total of 300,000 to 600,000 cubic meters of concrete was used in constructing the tunnels. This gives a total on 720,000 to

1,440,000 tonnes of concrete used in the construction of tunnels in Gaza based on a factor of 2.4tonnes/m^3 of concrete work. Assuming that there are 100 kg of steel in each cubic meter of concrete, we estimate that between 30,000 and 60,000 tonnes of steel have been used in the tunnels. We have calculated the total amount of concrete and steel used and applied the emission factor of concrete (180kgCO_2e/tonne)[39] and steel (1.55tCO_2e/tonne)[7], respectively, to obtain 264,135 tCO_2e emissions resulting from the Gaza Metro/tunnel construction.

b. Israel's "Iron Wall"

Designed to monitor movement and deter Hamas fighters from entering Israel, the 'Iron Wall' features monitoring and surveillance cameras and underground sensors, along with basic materials such as razor wire, a 6-meter-high metal fence, and large concrete barriers. It runs along most of the border between Israel and Gaza for about 65km and is assumed to be 0.5 metres wide. In calculating emissions due to Israel's Iron Wall, we applied the same methodology used for Gaza's tunnels. Emissions from above ground features were estimated using media reports that 140,000 tonnes of steel has been used in the wall's construction.[49] Based on an emission factor of 1.55 tCO_2e/tonne of steel, we estimate 217,000 tCO_2e as the emissions due to the steel used in construction of the above-ground component of the Iron Wall. Although the underground component of the wall is said to be several meters below ground, the actual depth remains undisclosed. We use a lower and upper estimate of 3m and 5m respectively for the depth of the below-ground concrete component of the iron wall, giving a total of 97,500 to 162,500 cubic meters of concrete work. We then apply a conversion factor of 2.4 tonnes/m^3 [50] to obtain the weight of concrete used to be between 234,000 and 390,000 tonnes. We estimate that 9,750 – 16,250 tonnes of steel reinforcement was used in the below-ground component of the Iron Wall based on 100 kg of steel per cubic meter of concrete work. The construction of the Iron Wall is estimated to have a carbon footprint of 293,224tCO_2e.

2. Conflict Emissions

The estimates presented below (Figure 4 and 5 and Table 5), show conflict emissions for a range of activities – from Cargo Flights to Delivering Aid in Gaza and Hamas Bunker Fuels and Hamas Rockets.

Figure 4: Graphic of Conflict Activities for 15-months of War in tonnes CO_2 equivalent (tCO_2e)

Figure 5: Graphic of Conflict Activities for 15-months of War in tonnes CO_2 equivalent (tCO_2e), continued.

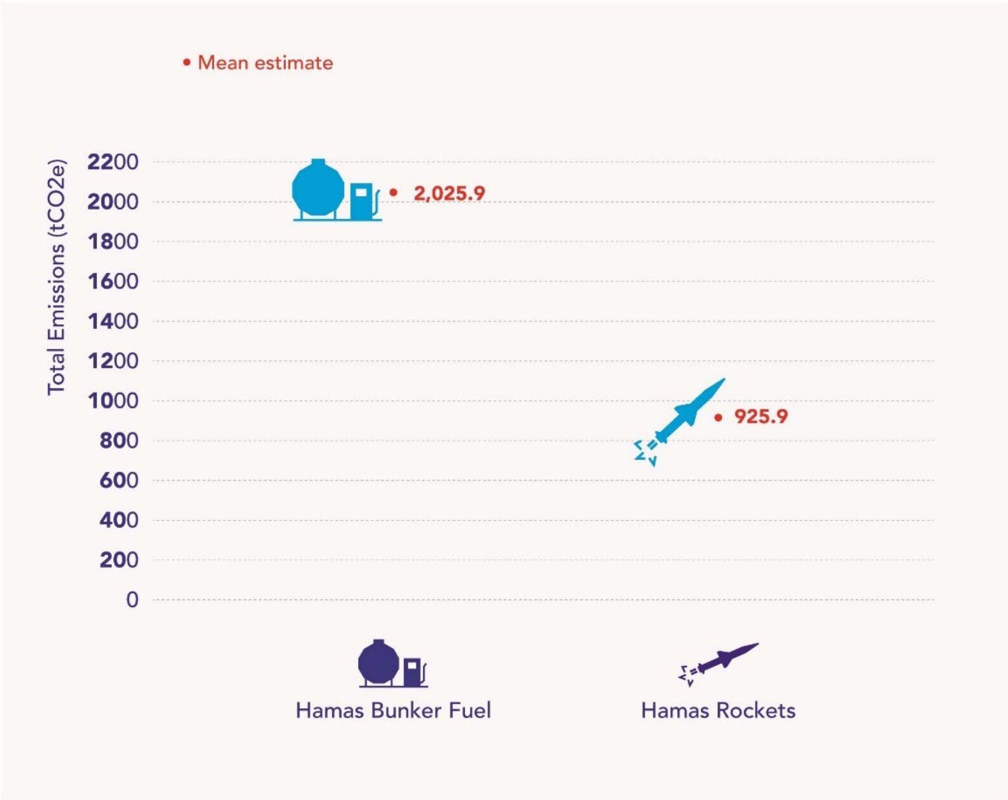


Table 5: Estimations of Conflict Activities for 15-months of War in Tonnes CO_2 equivalent (tCO_2e)

Emission Activity	*Brief description*	*Emission factor used*	*Lower estimate (tCO_2e)*	*Mean Estimate (tCO_2e)*	*Upper estimate (tCO_2e)*
Cargo Flights	500 flights and 277 shipping trips carrying around50,000 tonnes of goods in total.	1.03629 kgCO2e per tonne of aid delivered for each kilometre travelled. 1.099 kgCO2e per tonne of aid delivered for each kilometre flown. 0.01321 kgCO2e per tonne of aid delivered for each kilometre travelled by ship.	555,142	555,777.2	556,412.3
Bombing and Reconnaissance Flights	Israeli F-16 & limited F-35 flights - 300 flight hours each day	2.52 $kgCO_2e$/litre of jet fuel	252,083.8	252,490.6	252,897.5
Tanks and Vehicles	We assume a total of 750 vehicles involved in ground operations each day; 250 tanks and 500 Infantry Fighting Vehicles (IFVs).	2.7$kgCO_2e$/litre of diesel/petrol	47,777.8	47,838.2	47,898.6
Israeli Bombs and Artillery	100,000 ground artillery items, totalling about 8000 tonnes of steel and explosives used. About 45,000 air-dropped bombs used on Gaza. Sizes range between 150kg and 1000kg.	139$kgCO_2e$/ Artillery	77,338.5	78,305.8	79,291.8
Hamas Rockets	9,500 Qassam rockets fired into Israel.	1500$kgCO_2e$ / tonne munition	925.1	925.9	926.8

Gaza Electricity Production	Between 60,000 and 180,000 litres of fuel delivered daily to Gaza. A total of 24 to 72 million litres over the 400-day period.	2.7 kgCO_2e/litre of diesel/petrol	131,550.7	131,791.4	132,032.1
Hamas Bunker Fuels	Hamas is estimated to have stored between 0.5 and 1 million litres of fuel prior to the latest conflict.	2.7 kgCO_2e/litre of diesel/petrol	2,023.4	2,025.9	2,028.5
Gaza Aid Delivery (Trucks)	~67000 trucks on a 600 km return journey between Egypt and Gaza to deliver 1.3 million tonnes of aid.	1.03629 kgCO2e per tonne of aid delivered for each kilometre travelled by road. 1.099 kgCO2e per tonne of aid delivered for each kilometre flown. 0.01321 kgCO2e per tonne of aid delivered for each kilometre travelled by ship.	817,015.0	817,436.0	817,856.9
Totals for Israel and Gaza			**1,883,856.3**	**1,886,591**	**1,889,344.5**

Other Regional Conflict Totals	***Brief description***	***Emission factor used***	***Lower estimate (tCO_2e)***	***Mean Estimate (tCO_2e)***	***Upper estimate (tCO_2e)***
Isreal and Lebanon	9300 Bombs and artillery fired by Isreal and 2100 Rockets launched by Hezbollah	139kgCO2e/ artillery. 1.55kgCO2e /kg of steel used in bomb and rocket manufacturing. 5.06kg/kg of TNT used.	**3,747**	**3,747**	**3,747**
Israel and Iran	530 missiles fired between Isreal and	1.55kgCO2e /kg of steel	**4,248**	**5,140.5**	**6,033**

	Iran, and 1060 interceptor missiles as well as jet fuel consumed	used in bomb and rocket manufacturing. 5.06kg/kg of TNT used. 139kgCO2e/ artillery. 2.52kg/litre for jet fuel			
Israel and Yemen	400 rockets launched by Houthis and 100 missiles fired by Isreal, plus jet fuel consumed	1.55kgCO2e /kg of steel used in bomb and rocket manufacturing. 5.06kg/kg of TNT used. 139kgCO2e/ artillery. 2.52kg/litre for jet fuel	**2,461.8**	**2,852.4**	**3,243**
Total Conflict Emissions from All Countries			**1,894,313.1**	**1,898,330.9**	**1,902,367.5**

c. Cargo, Arial Bombing and Reconnaissance Flights

The United States supplied 50,000 tonnes of military and other goods to Israel using 507 aircraft and 107 ship journeys between October 7, 2023, and January 2025.[51] These goods were supplied to Israel from US stockpiles across Europe making the estimates of flight and shipping distances difficult to estimate. For simplicity, we use the distance between the US and Israel (approximately 10,000 kilometres) in our calculation based on the assumption that all goods supplied from Europe will be replenished from stocks in the US. In estimating the carbon emissions from cargo delivery, we have assumed that 500 aircrafts delivered 25,000 tonnes of goods while the remaining 25,000 tonnes were delivered by ships. We estimate the total emissions from cargo delivery to be between 555,777.2 tCO2e. This is based on air freight of 25,000 tonnes of goods over 20,000 kilometres return journey with an emission factor of 0.65 kgCO2e/km and 1.099 kgCO2e/km which excludes or includes the radiative forcing from the emissions respectively. The emissions from shipping 25,000 tonnes of goods over the same distance was estimated based on an emission factor of 0.01321 kgCO2e/km. The other key aspect under this category is the jet fuel Israel burned running aerial bombardment of Gaza. The bombing and reconnaissance campaign has been conducted primarily with F-16s, while F-

35s have been flying patrol missions.[52] The over 200 fighter jets the Israeli military has used in this conflict logged around 15,900 flight hours in the initial 120-day period.[41] For the F-16, each flight hour would burn 2,800 – 9,000 litres of jet fuel.[53] Although the F-35 burns 40% more fuel than the F-16, the lower fuel consumption for the F-16 has been used as a conservative estimate. This amounts to an estimated 57.2 – 143.1 million litres of JP-8 jet fuel used. The total carbon emissions from bombing flights is estimated at 252,490.6 tCO2e. The combined emissions from fighter jets and cargo delivery with air freight and shipping is estimated at 808267.8 tCO2e. This is based on an emission factor of 2.52 kgCO2e/litre of jet fuel used (Table 3).[4] We exclude aerial bombing and reconnaissance over Lebanon because we don't have sufficient data on them.

d. Bombs, Artillery and Rockets

i. Israel and Hamas in Gaza

Following de Klerk and colleagues,[8] we adopt the emissions factor of 139kgCO2e of embodied carbon from steel casing and explosives production for each tonne of artillery and rocket used by Hamas or IDF in this conflict. This emission factor also includes emissions at the point of detonation and is based on an average weight of 80kg per artillery piece – approximately 1.5kgCO2e per kg of artillery. In the initial assault on October 7 and for several weeks following the start of Israel reprisals, Hamas fired around 9,500 Qasam rockets.[54] These rockets are estimated to weigh between 50 and 80kg each. Therefore, the estimated total weight of these rockets is 475-760 tonnes with an estimated carbon emission of 926tCO2e. Meanwhile, Israel fired approximately 100,000 shells with a weight of 80 kg/round since the war began on 7th October 2023. Israel has also reportedly used 45,000 air-dropped bombs on Gaza through sorties from fighter jets since the conflict began in October 2023. It is difficult to know the types of bombs used with certainty. However, information available indicates that these bombs weigh between 150 and 1,000 kg each. The IDF are also widely reported to have used larger MK-85 bombs weighing about 1000 kg each. Five thousand of these bombs were supplied to Israel by the US at the start of the war in October 2023. Media reports indicate that Israel has dropped between 20,000 and 25,000 tonnes of bombs on Gaza.[6] and we have used these values

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[4] In our estimation based on available evidence, total crude oil imports since October 2023 until February 2024 were 3,802,420 tonnes, which, if consumed, equates to 11,288,054 tCO2e. Total jet fuel delivery since October 2023 until February 2024 were roughly 977,127 barrels or 125,072 tonnes, which equates to 343,949 tCO_2e. Please note that the estimated emission value includes production, refining, transportation and consumption (Scope 3).

as the lower and upper limits for estimating emissions due to bombing raids. We assume a proportional amount of TNT and steel used in the production of larger bombs compared to MK-82. Therefore, for each tonne of bomb dropped, we estimated that there was 386 kg and 614 kg of explosives and steel respectively. The 100000 artillery shells used by the IDF is estimated to cause 12,950.0 tCO2e in emissions. Carbon emissions from bombs dropped on Gaza by the IDF is estimated to be 65,355.8tCO_2e based on an emission factor of 5.06kgCO_2e/kg for explosives and 1.55kgCO_2e/kg and steel. The total carbon emissions from the production of ground artillery and air-dropped bombs used by the IDF since the war began is estimated to be 78,306 tCO_2e.

ii. Israel and Hezbollah in Southern Lebanon

We include carbon emissions from sporadic exchanges of firepower between the IDF and Hezbollah. Hezbollah is estimated to have launched about 2,100 rockets. Assuming these rockets have the same mass and explosives as a 155mm artillery shell, we apply an emission factor of 139 kgCO2e per rocket and obtain total carbon emissions of 292 tCO2e. The IDF has launched 9300 bombs and artillery shells into Lebanon in this wider regional conflict. We assume that half (4650) of these are MK82 bombs containing ~90 kg of TNT and 140 kg of metal casing and other components.[55] The remain half is assumed to be 155mm artillery shells. For MK82 bombs, we apply an emission factor for TNT is 5kg CO2e/kg and 1.55 kgCO2e/kg for steel while maintaining 139kg CO2e per artillery shell. The total carbon emissions from bombs and artillery fired into Lebanon by the IDF is estimated at 3747 tCO2e.

iii. Israel and Iran

There have been two large scale exchanges of missiles between Israel and Iran since the start of the latest conflict. In April 2024, Iran fired 150 cruise and ballistic missiles towards Israel and followed this with another 180 missiles in September 2024, giving a total of 330 missiles fired by Iran. These missiles are estimated to weigh between 700 and 1200kgs each. We assume that a third of the weight of these missiles is explosives (TNT) while two-thirds is made of steel. This gives 38.5 - 66 tonnes of TNT and 23.9 – 10.9 tonnes of steel used in the manufacture of these missiles. We applied 5kgCO2e/kg as an emission factor for TNT, 1.55 kgCO2e/kg for steel, and obtained a total of 847tCO2e as the total carbon emissions from missiles fired by Iran towards Isreal. In October 2024, the IDF launched retaliatory attacks on Iran utilizing about 100 aircrafts (F-16 and F-35) and over 200 missiles. We assume that the 100 aircrafts involved in this operation travelled about 2 hours on average and consumed up to

9000 litres per hour of flight. The total fuel consumed in these flights is estimated at 1.8 million litres with total carbon emissions of 4536 tCO2e based on an emission factor of 2.52 kgCO2e/litre of jet fuel. We estimate that the total carbon emissions from the 200 missiles used in these attacks was 133 tCO2e, assuming the missiles were all MK82 type. Most of the missiles fired by Iran and Isreal were intercepted by air defense systems - Iron Dome operated by Isreal and its allies including the United States and United Kingdom, and S300 air defense systems operated by Iran. We assume that for each missile fired, two air defense missiles were fired to intercept them. Therefore, a total of 1060 air defense missiles were used in response to the 330 and 200 missiles fired by Iran and Isreal respectively. The Iron Dome uses Tamir missiles which is 3meters long and weighs 90kg – approximately twice the weight and size of a 155mm artillery shell. The S300 uses 9M82 and 9M83 missiles weighing 130 kg each. We use an emission factor of 287 kgCO2e for each air defense missile which is twice that of a 155mm artillery shell. The total carbon emissions from repelling the Iranian attacks is estimated at 295 tCO2e. We estimate the total carbon emissions from missile exchanges between Israel and Iran to be 5,140.5 tCO_2e. This is likely a significant underestimate since it omits emissions from aircrafts and other vehicles used in repelling the attacks.

iv. Israel and Houthis in Yemen

The Houthi's have launched an estimated 400 rockets into Israel. This has approximately 55 tCO2e emissions based on assuming they are like 155mm artillery shells. In return, Israel has launched several airstrikes utilising over 50 aircrafts travelling for approximately 2 hours each. These fighter jets are estimated to have consumed between 280,000 to 900,000 litres of fuel and emitted a total of 1,468 tCO2e with over 100 missiles fired by the IDF into Yemen and 800 air defense missiles used to shoot down Houthi attacks contribute 919 tCO2e. The total emissions from Houthi – IDF exchanges is estimated at 2,462 tCO2eThe figures estimated here are based on the amount of steel and explosives used in the manufacture of artillery and air-dropped bombs. We exclude emissions from firing and detonation of bombs due to lack of data, and since emissions from their manufacture are more significant. For the war in Ukraine, estimated emissions from firing and detonation were around 1.5% of the total emissions from the use of artillery ammunition.[8]

e. Tanks and Vehicles

The Israeli Defense Force is estimated to have 2,500 tanks and over 5,000 Infantry Fighting Vehicles (IFVs) in total.[56] Israel has lost several tanks and vehicles while others have been immobilised by Hamas fighters.[57] We assume that about 10% of these of pre-war vehicles were used in the conflict between October 2023 and January 2025, we estimate that about 250 tanks and 500 Infantry Fighting Vehicles (IFVs) have been involved in the ground operations in Gaza on daily basis. Considering the small size of the frontline, each vehicle is assumed to travel between 10 and 20 km each day. Based on estimates used by de Klerk and colleagues (2023)[8] in their carbon accounting of the ongoing Ukraine war, we assume that each tank and IFV uses 2.4 and 0.77 litres per kilometre travelled, respectively. Therefore, for approximately 400 days of the war, 3.94 –7.88 million litres of fuel were consumed by frontline vehicles. We adopt the assumption from Klerk et al., 2023[8] that for each litre of fuel used on the frontlines, 3 litres are used by logistics and other supporting vehicles elsewhere, bringing the total fuel used by vehicles to 11.82- 23.64 million litres. The use of vehicles is estimated to have contributed 47,838.2 tCO_2e based on an emission factor of 2.7 $kgCO_2e$/litre of diesel and petrol (Table 3). Although Hamas has also used vehicles in its initial assault on October 7, 2023, and subsequently during the war, it is difficult to estimate the total number of vehicles involved. However, we have accounted for total fuel used by Hamas which will include the fuel used for these vehicles and have not provided a separate estimate.

f. Gaza Electricity Production and Fuel Consumption by Hamas

Prior to the start of the war, about half of Gaza's electricity supply came from Israel. The rest of Gaza's energy was supplied by a 65MW diesel-fuelled power plant and a wide array of rooftop solar photovoltaic (PV) panels.[58,59] Up to 25% of Gaza's electricity was generated through PV panels prior to the war, representing one of the world's highest shares.[58,60] With most of the solar PV's and the sole power plant destroyed, electricity supply in Gaza now largely depends on diesel-powered generators. At the start of the latest conflict on October 7, 2023, fuel delivery into Gaza was severely restricted by the IDF. However, these restrictions were eased in November 2023 following pressure from the international community, allowing between 60,000 and 180,000 litres of fuel to be delivered daily. We estimate that between November 2023 and the ceasefire in January 2025, 24 – 72 million litres of fuel have been delivered into Gaza with total carbon emissions of 131,791.4 $tCO2e$.[5] We assume that this fuel was used for electricity generation as well as running essential services including ambulances. Hamas reportedly had between 500,000 and 1,000,000 litres of fuel stored prior to the start of

[5] The month that international fuel deliveries began.

the war. The carbon emissions from burning this fuel are estimated at 2,026 tCO2e. These estimates of carbon emissions from fuel usage is based on an emission factor of 2.7kgCO2e per litre of diesel or petrol (Table 3). Emission reductions due to a decline in economic activity are likely, but difficult to even broadly estimate given the uncertainty in energy consumption, the impact from the loss of Gaza's solar photovoltaic (PV) panels and fuel use patterns. PV panels generated around 25% of Gaza's electricity prior to October 2023.

g. Aid Delivery

Food, medicines and other essential goods have been delivered to Gaza by various organisations including the United Nations Relief and Works Agency for Palestine Refugees in the Near East (UNRWA) and the World Food Program (WFP). These organisations coordinate the deliveries of supplies to Egypt from where trucks carry the goods on a 600km return journey for delivery to Gaza. Some aid have also been delivered from Jordan and ports in Isreal. Aid delivery has faced various obstacles and thus have not been consistent. However, about 66,747 trucks as well as air planes and ships have delivered an estimated 1.3 million tonnes of aid to Gaza between October 2023 when the conflict began and January 2025 which is the period under study.[61] 1,309,230 tonnes of aid have been delivered by trucks mostly making a 600km return journey from Egypt. The emission factors for delivery of goods depends on the amount of load the truck carries, expressed as percentage Laden. Our lower estimate assumes that these trucks were half full (50% laden) with an emission factor of 1.31188kgCO2e for each km travelled with a tonne of goods. The upper estimate is based on assumption of 100% laden trucks with an emission factor of 1.58748 kgCO2e for each km travelled with a tonne of goods. The delivery of aid with trucks is estimated to have caused an emission of 814,146.00 tCO2e. 7,249 tonnes of aid were air dropped into Gaza with the majority originating from Jordan over a return journey of 400km. The total emissions from this category of aid is estimated at 3,187 tCO2e. There was an estimated 9,710 tonnes of aid that were delivered through ships from Cyprus – over a return distance of 800 km – contributing a total of 103 tCO2e in emissions.

The total estimate of carbon emissions due to delivery of aid to Gaza is 817,436.0 tCO2e. We have not included emissions from flights that deliver these supplies to neighbouring countries for onward deliveries to Gaza because we have not been able to obtain accurate data on these flights.

3. Post-Conflict Emissions

By far the largest carbon emission output comes from the reconstruction needs of Gaza. Intense bombing of Gaza has decimated infrastructure, including hospitals, apartment buildings, roads, water and wastewater treatment plants, sewer networks, schools and universities, and water wells. Below is a graphic representation (Figure 6) of the different emission outputs and a table of the calculations (Table 5).

Figure 6 and 7: Long Term Carbon Costs of Rebuilding Destroyed Infrastructure in Gaza and Lebanon in tonnes CO_2 equivalent (tCO_2e)

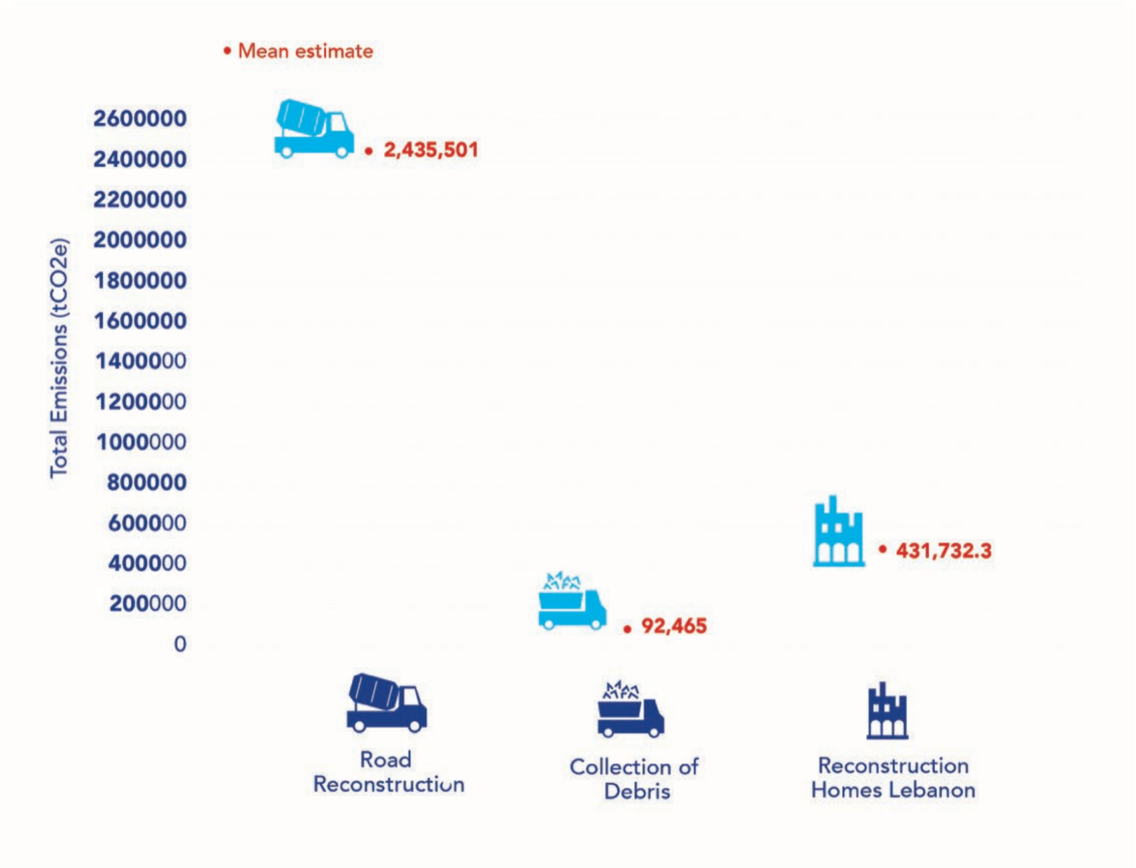

Table 6: Long-Term Carbon Costs of Rebuilding destroyed infrastructure in Gaza and Lebanon in tonnes CO_2 equivalent (tCO_2e)

Emissions Activity	*Brief description*	*Emission factor used*	*Lower estimate (tCO_2e)*	*Mean Estimate (tCO_2e)*	*Upper estimate (tCO_2e)*
Reconstruction of Homes in Gaza	53 to 61 million tonnes of concrete debris and 2.22-2.54 million tonnes of steel reinforcement	0.18 tCO2e/tonne for concrete and 1.5 tCO2e/tonne for steel	26,842,841	26,856,643	26,870,445
Road Reconstruction in Gaza	3045 kilometres of roads destroyed, damaged or severely affected. 5km of new road construction.	1192 kgCO2 per km	2,431,827	2,435,501	2,439,174
Collection of Debris in Gaza	Between 53.3 and 61.1 million tonnes of debris to be collected using trucks	See Abdelnour and Roy (2024) for complete description of emissions factor used	82,316	92,465	102, 614

Reconstruction of Homes in Lebanon	3600 homes destroyed. Each building assumed to be 200-300 square meters	480 kgCO2e per square meter	366,905.0	367,205	367,505.2
Total Post-Conflict Emissions			**29,723,889**	**29,751,814**	**29,779,738.2**

We estimate that the carbon cost of reconstruction of infrastructure damaged or destroyed during the war to be 16.8 million tonnes of carbon dioxide equivalent (see Table 6). By February 2024, it was estimated that roughly 156,000 to 200,000 buildings have been destroyed or damaged in Gaza.[62,63,64] This includes residential, commercial, and industrial buildings.[65] Building vary by storey height, construction type and floor plan areas. However, data reported from the UN-Office for the Coordination of Humanitarian Affairs (OCHA) estimated that approximately 436,000 apartments each having a total of 150 square meters space have been destroyed in Gaza.[66] Additionally, 486 schools, 21 hospitals, 140 government offices, 72 mosques and 2 churches have been destroyed during the war - a total of 721 buildings.[67] We apply a conservative estimate of 600 square meters of space for each of these larger buildings. Commercial and office buildings have higher embodied carbon and hence higher emission factor than residential buildings. However, because the number of residential flats far outnumber the number of commercial ones, we apply a residential building embodied carbon emission factor of 408kgCO2e/m^2 in our calculation for all buildings in Gaza.[8] We estimate that the total carbon emissions from destroyed flats to be 26,683,200 tCO2e. The embodied emissions from the 721 other buildings is estimated at 176,500.8tCO2e. Therefore, the total carbon emissions from reconstructing destroyed buildings in Gaza is 26,859,700 tCO2e. This figure also includes the production and transport of steel and concrete that will be required to reconstruct these buildings. However, it dose excludes emissions from clearing of debris from the various sites, which is calculated separately below. The embodied emissions used is consistent with benchmark values in estimating carbon footprints of building in other neighbouring countries.[68]

The carbon emissions from collecting and disposing off 32 million tonnes of debris from Gaza to was estimated to be 55,513 tCO2e.[66] We extend this estimate to cover the latest estimates of debris in Gaza used above. Following the methodology used by Abdelnour et al., (2024), we estimate the total carbon emissions for collecting debris from Gaza to be 99,231tCO2e.

About 3,045 kilometres of roads have been destroyed, severely damaged or affected by the conflict in Gaza. The IDF has also recently constructed 5 kilometres of new roads to aid movement of troops in Gaza, bringing the total affected roads to 3,050km. For our lower estimates, we assume that all these roads are single lanes and apply an emission factor of 711tCO2e/km. Our upper estimates assume that all roads have double lanes and use an emission factor of 1672 tCO2e/km. We further assume that about two-thirds of each road will need to be rebuilt. The total estimated emissions from road reconstruction is estimated at 2,435,501 tCO_2e.

The exchanges between the IDF and Hezbollah is reported to have caused the destruction of 3600 homes in Southern Lebanon. We adopt a conservative estimate that each house has total area of between 200-300 square meters and estimate that the total carbon emissions from reconstructing homes in Southern Lebanon will be between 431,732.3 tCO2e.

Discussion and Conclusion: Limits to our Analysis and Further Research Needs

Our aim in this article is to provide an indication of the major carbon emissions associated with the recent war in the Middle East. We used openly available data to estimate carbon emissions for the three distinct periods: 15-months of war, pre-war infrastructure, and post-war reconstruction. This analysis provides a conservative estimate of the emissions from war-related carbon intensive activities. The selected categories were chosen due to the expertise of our team in calculating military-related concrete emissions and access of readily available data.[7] There are, however, several significant categories of operations that will be important to quantify to gain a more complete picture of the climate ramifications of the war, as well as ongoing attacks in the West Bank, increased skirmishes on the Israel-Lebanon border, and associated military operations against Iranian proxies in Syria and Iraq. In particular, missing datasets include: (1) damage to buildings in Israel and the West Bank (2) replenishing of weapons stockpiles and equipment, (3) the emissions and reduced carbon sequestration potential created through land clearance and degradation, (4) future emissions costs of flights by the US and other Israeli allies to deliver material to the region, (5) landscape fires and fires from direct damage to infrastructure, (6) rescue operations, medical treatment and transportation of the wounded, and (7) Hamas and Israeli ground transportation beyond tanks and ground-based weapons systems. Other significant categories includes a full detailing of reconstruction of Gaza beyond only carbon analysis of concrete buildings, and finally, a Scope 2, 3 and 3+ reporting of material, troop deployment and even diplomatic and humanitarian assistance, including ceasefire talks and aid delivery.

Populations in Gaza, Israel, and the wider region, are already experiencing the effects of climate change. This includes intense heat, increased flash floods, more periodic drought, and wildfires. Conflict exacerbates the climate precarity of these populations, making them less resilient and able to adapt to the effects of climate change.[69] We believe that this emission's study of the war demonstrates why a better understanding of the climate impacts is important as it affects current populations in Gaza and elsewhere in the region. It also highlights the vital need for better data availability, demonstrating just how significant emissions during wartime can be, and providing a baseline model for other conflicts. There remains the need for the much wider accounting of the environmental effects of war however, including the impact on environmental governance and regulation, water and air pollution, deforestation, ecological damage, loss of cultural heritage, soil and land degradation, resource depletion and generation of waste and debris.

Recent studies have been conducted in Ukraine, [8,70, 41] and work is on-going. Similarly, there the need for better documentation of the environmental-human effects to ensure that the full range of impacts are understood of each conflict and how they differ, and that data is available to aid those working to address the consequences.[6, 41] For instance, due to the scale, duration and context, the make-up of emissions, the war in Ukraine does differ from Gaza in a few distinct ways. In Gaza, most of the region's infrastructure, including roads, housing, hospitals, has been damaged or destroyed. In Ukraine, the conflict has affected large areas of agricultural land and forestry, as well as targeted attacks on energy infrastructure, industrial complexes and critical infrastructure such as the Kakhovka dam and Nord Stream gas pipelines. A reduction in emissions within a conflicted-affected region may also be expected due to impacts on the local economy and transport. However, assessments of the war in Ukraine noted that regional reductions had largely been offset by increased emissions elsewhere. For Ukraine this included a shift of iron and steel production overseas given highly globalised market and competition and to an extent, emissions from the consumption of goods and services by refugees transferring with them to other countries or other part of Ukraine.[8] The situation in Gaza differs in that most refugees remain within the Gaza strip and have very limited access to resources. Israel's long-term military operations, closures and trade restrictions have also significantly

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[6] The 2022 Political Declaration on the use of Explosive Weapons in Populated Areas (EWIPA) acknowledges the impact on the environment – see https://www.gov.ie/en/publication/585c8-protecting-civilians-in-urban-warfare/#political-declaration-on-ewipa and https://ceobs.org/joint-statement-the-importance-of-addressing-the-environmental-consequences-from-the-use-of-explosive-weapons-in-populated-areas/

constrained the economy in Gaza, and the territorial emissions per capita are considerably lower than Israel or other neighbouring countries – i.e. for 2022, the annual CO_2 emissions per person were 0.7 tonnes for Palestine, compared to 6.2 tonnes for Israel, 2.3 tonnes for Egypt and 2 tonnes for Jordan.[71] Using an assumption of a 50-80% reduction in emissions per capita, over 400 days this would equate to an estimated reduction of between 250,000 to 400,000 tonnes of emission for an estimated population of 2.1 million people in Gaza. Our study also highlights the pre-war infrastructural preparation, namely defensive wall and tunnels, which is significantly different to pre-war carbon emissions in Ukraine, which did not include similar infrastructure.

As noted, the dynamics of each conflict will not always be the same. This means that governments and civil society institutions must examine and understand the climate and environmental costs within pre-war planning, enabling military's climate and environmental costs pre-, during, and post-conflict to be scrutinised and held to account.[7] It is unlikely that accounting of environmental and climate costs of war alone will be a significant deterrent to military action, particularly in cases where belligerents have a demonstrable disregard for civilian casualties. But beyond casualties and monetary resources, at the very least, emissions accounting could be used to demonstrate how impacts can be minimised, contributing to calculating a more holistic reparation costs that would address the expected environmental and climate damage of war.

While the war gained the attention of delegates and civil society organisations at the UN Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP) 28 and 29 meetings in Dubai and Baku, its climate dimensions of the war, nor any other war, were not acknowledged within the formal proceedings.[72,73,74] Peace, conflict and climate change were included in the UNFCCC programme, with the launch of a Relief, Recovery and Peace Day at COP28.[75] Outputs included publication of the COP28 Declaration on Climate, Relief, Recovery and Peace, and the Baku Call on Climate Action for Peace, Relief and Recovery, but there was no meaningful dialogue on military or conflict-related GHG emissions, or the need to reduce them, and no constructive outcomes. Indeed, no UNFCCC outcome document acknowledges military or conflict-related GHG emissions. It is important to correct this lapse

[7] A legal framework on the Protection of the Environment in Relation to Armed Conflict (PERAC) was adopted in 2022. This sets out how the environment should be protected before, during and after armed conflicts as well as in situations of occupation and includes recognition of the potential to exacerbate global environmental challenges, such as climate change and biodiversity loss – see https://ceobs.org/states-adopt-new-legal-framework-on-the-environmental-impact-of-war/

for COP 30 in Brazil and to highlight gaps in current military emissions reporting,[76] while pushing for greater transparency on their emissions, and meaningful commitment to cut military emissions as an economic sector where governments have direct authority to manage operations.

Moving forward, we hope researchers build on this work to provide a more complete picture of the climate implications of the conflict and conflict-related emissions, and to continue to push for transparent reporting of global military emissions to the UNFCCC.[14] Until there is mandatory emissions reporting obligations for militaries and conflicts through the UNFCCC, this work will need to be completed by civil society and academic researchers. To this aim, we have made all attempts to clearly describe our methodology and make it as accessible as possible so that those interested in calculating wartime emissions can adopt our approach, and others described in this article, as a guide. [14,15, 20, 41]

Outside of the black box of emissions from war, the everyday operations of militaries and training around the world remain significant emitters of greenhouse gas emissions. Due to existing loopholes in reporting to the UNFCCC there is a lack of comprehensive data. Carbon accounting by militaries remains voluntary, and many do not report their emissions at all. Research by the Military Emissions Gap suggests that just 4 countries in the 2023 reporting cycle provided military fuel emission data which aligned to UNFCCC reporting obligations.[14] This work is meant to draw attention to the climate impacts of war and militarism – an underappreciated aspect of the climate crisis. We do not seek to divert attention away from the human suffering the war has caused, especially for millions living in fear of losing their lives in Gaza due to Israeli bombardment or those still being held hostage by Hamas. This exercise attempts to offer some evidence of the wider environmental and climate effects of the conflict, which are inseparable from the wider humanitarian costs of war.

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