War-Induced Energy System Collapse in Tigray: Quantifying Infrastructure Damage, Economic Losses, and Environmental Degradation in Tigray

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Article

War-induced energy system collapse in Tigray: Quantifying infrastructure damage, economic losses, and environmental degradation in Tigray

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Abstract: Armed conflicts increasingly target energy infrastructure, yet empirical evidence from African settings remains limited. The Tigray War (2020–2022) caused one of the most severe energy-system collapses in recent history, triggering a two-year blackout and widespread socioeconomic disruption. This study quantifies the impacts using 1,699 field-verified asset-level observations from Ethiopian Electric Power and Ethiopian Electric Utility, supported by secondary data on electricity sales, project delays, and land-use change. The analysis integrates engineering-based damage assessment, economic loss estimation, and independently validated environmental indicators, an approach not previously applied in African conflict research. Results show US$51.4 million in physical destruction, US$587.9 million in economic losses, 140.8 km of damaged 230 kV lines, 38 collapsed towers, 237 destroyed transformers, and approximately 930 km² of vegetation loss linked to a 628.7% rise in fuelwood extraction. These findings highlight the need for resilient grid reconstruction, decentralized renewables, and integrated environmental restoration in post-conflict recovery.

Keywords: armed conflict; Ethiopia; Tigray conflict; infrastructure vulnerability; deforestation; economic losses; energy infrastructure; electricity disruption

1. Introduction

Dependable, affordable, and sustainable energy systems are fundamental to economic development, social well-being, and environmental sustainability. This centrality is reflected in Sustainable Development Goal 7 (SDG 7), which emphasizes universal access to modern energy services as a prerequisite for achieving multiple development outcomes, including health, education, industrial productivity, and climate resilience (UN, 2015). Ethiopia's energy sector illustrates these challenges vividly. Despite significant investments in hydropower, wind, and transmission infrastructure, the country still faces a considerable electricity access gap, with more than 60 million people lacking access and per capita electricity consumption remaining among the lowest globally (MoWE, 2024; World Bank, 2022). These structural vulnerabilities make Ethiopia's energy system particularly sensitive to political instability and conflict, where disruptions can rapidly reverse development gains and exacerbate existing inequalities.

Globally, armed conflicts are increasingly marked by deliberate attacks on energy infrastructure. Evidence from Syria, Yemen, Iraq, and Ukraine shows that energy infrastructure has become a strategic target aimed at weakening civilian resilience and undermining state capacity. Such attacks generate cascading failures across health systems, water supply, telecommunications, and economic activity, often pushing affected regions into prolonged humanitarian crises (Ivanchenko et al., 2018; Tichý, 2019; Erika Weinthal and Jeannie Sowers, 2020); (Aljohani, 2022; Lee, 2022; Hammoud, T., & El-Jardali, 2023; Hryhorczuk et al., 2024). They also trigger severe environmental consequences, including increased reliance on biomass, accelerated deforestation, and heightened exposure to indoor air pollution (Mhlanga & Ndhlovu, 2023). Against this backdrop, the Tigray War (2020–2022) represents one of the most extreme contemporary cases of energy-system collapse in Africa.

The Tigray War (2020–2022) represents one of the most severe contemporary cases of deliberate targeting of energy infrastructure, resulting in a region-wide blackout lasting more than two years, following. Drone strikes on the Tekeze hydropower plant, attacks on substations in Mekelle, and the systematic dismantling of transmission and distribution networks resulted in a region-wide blackout lasting more than two years, as documented by NASA's Black Marble nighttime satellite imagery (NASA Black Marble, 2021; Martin plaut, 2023). These attacks not only violated international humanitarian law protecting civilian infrastructure (Dinstein, 2004; UNSC, 2017) but also reversed decades of progress toward electrification in one of Ethiopia's most energy-poor regions. The resulting energy insecurity forced households, institutions, and businesses to rely heavily on biomass, exacerbating deforestation and environmental degradation (Manaye et al., 2023; H. Wier D. & Schulte to Bühne, 2022; Gebreslassie & Bahta, 2023). The prolonged blackout severely disrupted health services, communication, and economic activity, forcing households and institutions to rely on biomass and informal energy sources.

Despite growing scholarly attention to the conflict–infrastructure nexus, several critical gaps remain. First, most existing studies rely on remote sensing or qualitative assessments, with limited availability of systematic, asset-level data documenting the physical destruction of energy infrastructure in conflict zones. Second, research has tended to examine economic losses, environmental impacts, and infrastructure damage in isolation, rather than through an integrated analytical framework that captures their interdependence. Third, while the humanitarian impacts of the Tigray War have been widely documented (Tofa et al., 2022; Annys et al., 2021; Guardian, 2022; Africanews, 2022; Meresa, Meseret Meresa, Fikre Belay Tekulu, 2024). Empirical assessments of sector-specific damage remain limited. Recent studies have examined the war's effects on household food insecurity (Aregawi et al., 2023), disruptions to water supply systems (Shishaye et al., 2023), and the broader socio-economic consequences of resource scarcity (Manaye et al., 2023). Finally, no prior research has combined primary field assessments with secondary data to evaluate how conflict-induced energy insecurity contributes to deforestation and increased dependence on biomass.

This study addresses these gaps by providing the first comprehensive, data-driven assessment of conflict-induced energy insecurity in Tigray. Using 1,699 asset-level observations collected in collaboration with the Ethiopian Electric Power (EEP) and

Ethiopian Electric Utility (EEU) in the Tigray regional state, combined with secondary data on electricity sales, project disruptions, and land-use change, the study quantifies the physical, economic, and environmental impacts of the war. First, no prior research has provided asset-level, field-verified data on the destruction of energy infrastructure in African conflict settings. Second, existing studies examine physical damage, economic losses, or environmental impacts in isolation, whereas this study integrates these dimensions into a single analytical framework. Third, despite extensive global research on infrastructure targeting in Syria, Yemen, and Ukraine, empirical evidence from Sub-Saharan Africa remains scarce. It employs a Damage and Loss Assessment (DaLA) framework to distinguish between direct asset destruction and indirect economic losses, while validating environmental impacts through independent peer-reviewed studies. By integrating these dimensions into a single analytical framework, the study advances theoretical debates on energy security in fragile contexts and offering new insights into the conflict–energy–environment nexus. From this review of the literature and context, three research questions guide the analysis: 1) What is the extent and spatial distribution of physical damage to Tigray's energy infrastructure during the 2020–2022 conflict? 2) What are the associated economic losses, including direct asset destruction, lost electricity service, and disrupted energy projects? 3) How has conflict-induced energy insecurity contributed to environmental degradation, particularly deforestation driven by increased reliance on biomass?

By answering these questions, the study offers a multidimensional understanding of how modern conflicts reshape energy systems and provides a foundation for designing resilient, equitable, and environmentally sustainable recovery strategies.

2. Research and data methodology

2.1. Conceptual and analytical framework

This study employs a Damage and Loss Assessment (DaLA) based analytical framework to evaluate the multi-dimensional impacts of conflict on energy infrastructure. The DaLA methodology, developed by the United Nations Economic Commission for Latin America and the Caribbean (UN-ECLAC, 2014), provides a standardized and internationally recognized approach for distinguishing between direct physical damage to assets and indirect economic losses arising from service disruption (Robinson, Jamell; Phillips, 2014; UN-ECLAC, 2014). This framework is particularly suited to conflict-affected regions, where infrastructure destruction generates cascading effects across economic systems, social services, and environmental conditions.

Building on this foundation, the study conceptualizes conflict-induced energy insecurity as a cascading system of impacts: a) Direct physical destruction of energy infrastructure (generation, transmission, distribution); b) Interruption of electricity services, including prolonged blackout periods; c) Economic losses, such as reduced electricity sales, halted projects, and increased operational costs; d) Environmental impacts, particularly increased biomass extraction and deforestation due to energy substitution.

The environmental component is validated using independent peer-reviewed studies that document conflict-driven biomass extraction and vegetation decline in

Tigray. These include field-based assessments of fuelwood dependence and remote-sensing analyses of vegetation loss using Landsat and Sentinel datasets (Teka & Welday, 2023; Hishe et al., 2024; H. Schulte et al., 2024). Together, these studies provide robust external validation for the environmental-impact pathway embedded in this framework.

This layered structure aligns with established disaster-impact theory, which emphasizes the distinction between immediate asset destruction and longer-term socio-economic consequences (UN-ECLAC, 2014). It also reflects insights from infrastructure-systems research, which shows that damage propagates across interconnected networks, amplifying economic vulnerability and environmental degradation (Eckhardt et al., 2019; Nijkamp et al., 2025). By adopting this integrated framework, the study captures both the extent of physical destruction and the systemic implications for energy security, economic stability, and environmental sustainability.

2.2. Data sources and validation

Both primary and secondary methods were used to evaluate the damage that the war caused to Tigray's energy infrastructure, which is now uniquely detailed in this paper. The collection of primary data entailed systematic fieldwork undertaken by different personnel from Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU). These data collectors were trained to use a developed template. The template used in data collection was classified as generation stations, substations, transmission lines, warehouse assets, office assets (Physical structure, Vehicles/ Cars and Office equipment), maintenance equipment, their location and the extent of damage (if any).

2.2.1. Primary data

The primary data collection was envisioned as a detailed assessment collected from each sub-district (Tabias) in Tigray, where electricity access exists. The fact that the nature and level of damages on energy infrastructures are different from location to location (town to town, wereda to wereda, and village to village), an entity-based census study was conducted to collect primary data on asset damages. Hence, a coded template list of categorised assets/ was developed with location information (zone, wereda, entity). Training was conducted with data collectors and supervisors from the Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU) in the Tigray region. Researchers, technicians, and engineers carried out physical damage assessments that were visible through inspections, photographs, and GPS coordinates. The dataset comprises 1,699 documented damage case observations across Tigray's six administrative zones.

Damage estimates were made based on pre-crisis unit replacement costs and, therefore, backward-looking. We considered the purchase cost of the assets and took the dollar exchange values in the 2022 rate for conversion. The damage assessment value was made in Birr, and the costs were converted to USD at a rate of 56.6 Birr per 1 US dollar.

2.2.2. Secondary data

Relevant data was assessed from published and unpublished secondary sources, including a review of important documents. We collected vital information about the infrastructure from published and unpublished official reports of the Ethiopian Electric Power, Ethiopian Electric Utility, the Ministry of Water and Energy (MoWE, 2024). Additionally, we referred to articles that have appeared in peer-reviewed academic journals to focus closely on the kinds of impacts we observed being inflicted on energy infrastructure and on the environment, particularly in conflict zones.

2.2.3. Environmental impact validation

Because environmental impacts could not be directly observed from primary energy-sector data, this study validates the environmental component using independent peer-reviewed research that documents conflict-driven biomass extraction and vegetation decline in Tigray. These external sources include: field-based assessments of fuelwood dependence and forest degradation, and remote-sensing analyses using Landsat and Sentinel-derived vegetation indices to detect post-conflict changes in woody vegetation cover.

Together, these studies provide empirical support for the biomass-substitution mechanism embedded in the analytical framework and ensure that the environmental impacts assessed in this study are grounded in independently verified scientific evidence.

2.3. Physical damage assessment model

The physical damage assessment quantifies the direct destruction of energy infrastructure resulting from the conflict. Consistent with the Damage and Loss Assessment (DaLA) methodology, physical damage is defined as the monetary value required to restore or replace damaged assets to their pre-conflict condition. The assessment follows a component-based engineering approach widely applied in post-disaster and post-conflict infrastructure studies (UN-ECLAC, 2014).

2.3.1. Asset classification and damage states

All infrastructure assets documented in the primary dataset were categorized into standard functional classes (generation, transmission, substations, distribution, and support facilities). Each asset was then assigned a damage state based on field verification, using a two-level scale: 0.5 for partial damage (repairable) and 1 for complete destruction (full replacement required). This classification aligns with engineering-based damage scales commonly used in post-disaster and post-conflict assessments.

2.3.2. Aggregation of total physical damage

Consistent with the DaLA methodology, physical damage in this study is estimated using a replacement cost approach, whereby the value of damaged infrastructure is calculated based on the cost required to restore assets to their pre-conflict condition.

According to ECLAC guidelines, damage is defined as the monetary value of totally or partially destroyed physical assets, expressed in terms of replacement costs at current prices (UN-ECLAC, 2022). By applying this standardized approach, the study ensures consistency with internationally recognized methodologies for infrastructure damage assessment.

$$D = \sum_{i=1}^{n} Q_i x C_i$$

where: *D* is the total physical damage, Q_i is the quantity of damaged assets, and C_i is the replacement cost per unit. Replacement costs include materials, labor, transport, installation, and commissioning. This aggregation enables zone-level damage estimation, supports comparisons across different infrastructure types, and informs the prioritization of reconstruction needs.

2.4. Economic loss estimation model

The economic loss assessment quantifies the flow losses resulting from the interruption of electricity services during the conflict. In accordance with the DaLA methodology, economic losses are defined as the reduction in economic flows that would have occurred in the absence of the disruption, including foregone electricity sales, halted projects, and additional operational costs. This component complements the physical damage assessment by capturing the broader economic consequences of service interruption across the energy sector.

$$\mathrm{EL_{total}} = \mathrm{EL_s} + \mathrm{EL_p} + \mathrm{EL_o}$$

where: EL_s is foregone electricity sales, EL_p is project delay and suspension losses, and EL_o is additional operational costs. This structure ensures consistency with DaLA's distinction between stock losses (physical damage) and flow losses (economic impacts), enabling integration with the physical damage and environmental impact assessments.

2.5. Description of the study area

The investigation was conducted in Tigray, Ethiopia's northernmost state, which stretches over approximately 53,386.18 square kilometres (**Figure 1**). Tigray regional state has seven zonal administrations. To the north, Tigray borders Eritrea; to the west, it borders Sudan; to the east, Afar; and to the south, it borders the Amhara region. The topography and ecology of Tigray are nothing short of diverse; this plays a vital role in shaping its socio-economic and environmental aspects. But in November 2020, the northern state of Ethiopia, which is home to around 7 million people, saw an armed conflict break out that had been building up for a year. The military operations were destructive; we will never know the full extent of how many lives were lost during that time.

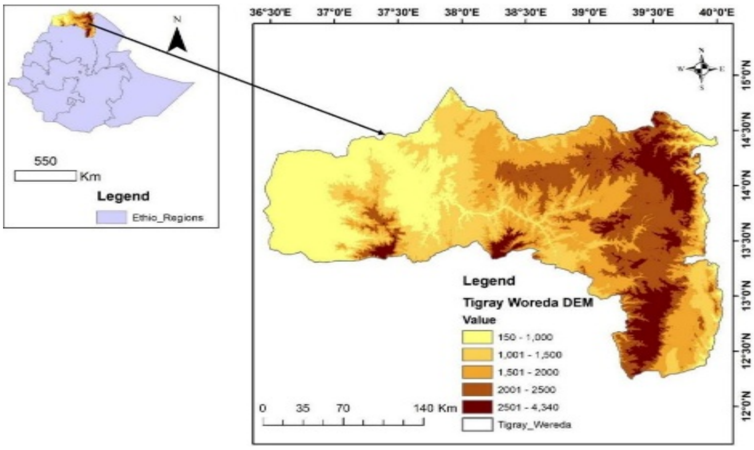

Figure 1. Map of the Study area.

2.6. Scope of the work

The data from the study were collected from the period of November 2020 to July 2022. The researchers directed their efforts toward the gathering of data from the Mekelle Special Zone, as well as multiple other zones in the immediate area: southern, southeast, central, and northwest. For security concerns, some areas were not included in the data collection that extended from the western zone in Tigray, as well as parts of the eastern and northwestern zones. The data structure is depicted in **Figure 2**. Blue dots serve to indicate the location of damaged energy infrastructures, as well as various other administrative divisions (with the Wereda names in red) in the region.

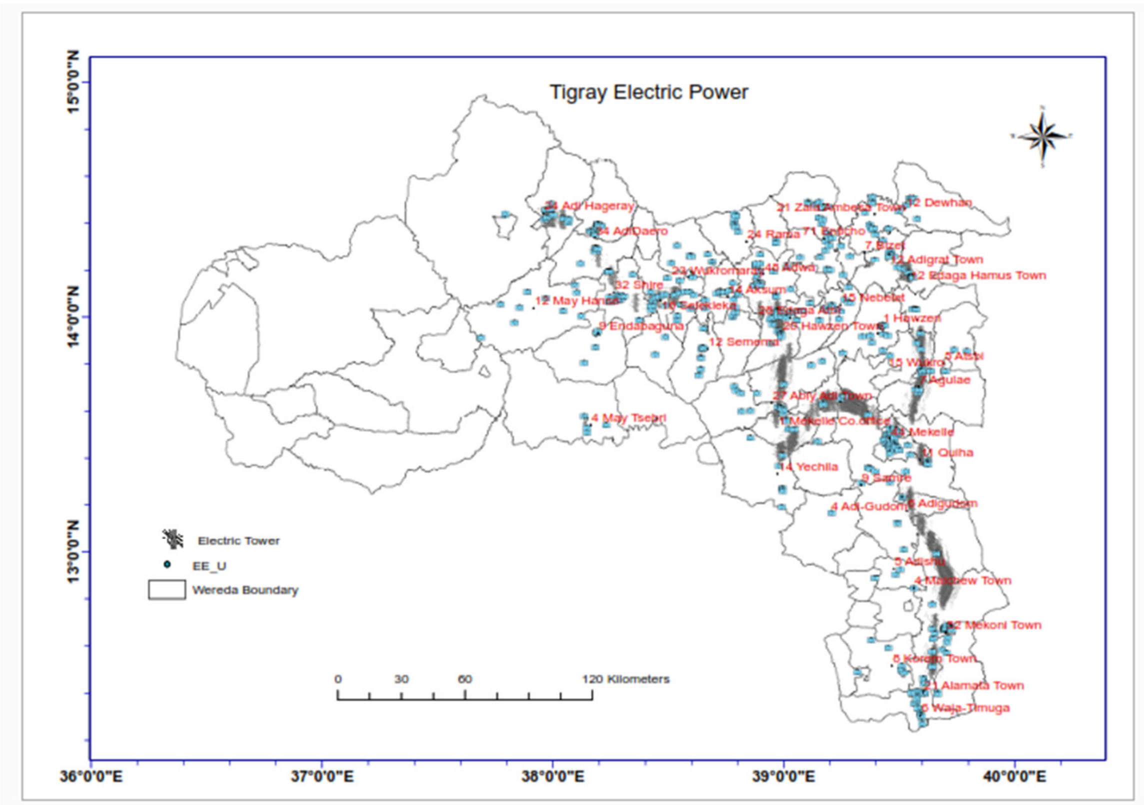

Figure 2. A visual representation of the distribution of assessed areas (authors own figure and illustration).

3. Baseline energy infrastructure in Tigray

3.1. Generation and transmission infrastructure

Currently in the Tigray region Tekeze hydropower station and the Ashegoda Wind Farm are the two energy sources connected to the national grid of Ethiopia. Tekeze is the biggest generation station in Tigray with an anticipated annual power generation capacity of 981 GWh using four units, 75 MW each. The power generated in Tekeze is connected to the national grid in Lachi substation, which is located in Mekelle. In addition, there is a high voltage tension from the Tekeze hydroelectric power plant to the substation in Axum that also feeds the substation in Shire Indasillasie town.

The current transmission lines in Tigray are of type 230 kV, 132 kV or 66 kV. The 230 kV transmission line covering length of 852 km is supported by 1,864 towers, while the 132 kV line encompasses 263.02 km which is supported by 606 towers and the 66 kV line supported by 165 towers, covers 48 km length. The double circuit high voltage (230 kV) transmission line from Tekeze hydroelectric power plant spans 105 km from its substation to Lachi, Mekelle. This transmission line passes through Guia, Sheweate Hugum, Abergele, Menewe, Hagereselam, Alasa, Romanat. Whereas, Ashegoda is 15 km from the Lachi substation. The region is connected to the national grid via the substation in Mokoni and the length of the high voltage transmission line from Mokoni to Mekelle is 100 km. These lines were a victim of the war that causes blackouts in the majority of the region many times. The detailed information on existing transmission lines (voltage level, transmission total length and number of towers) in the Tigray regional state is indicated in **Figure 3**.

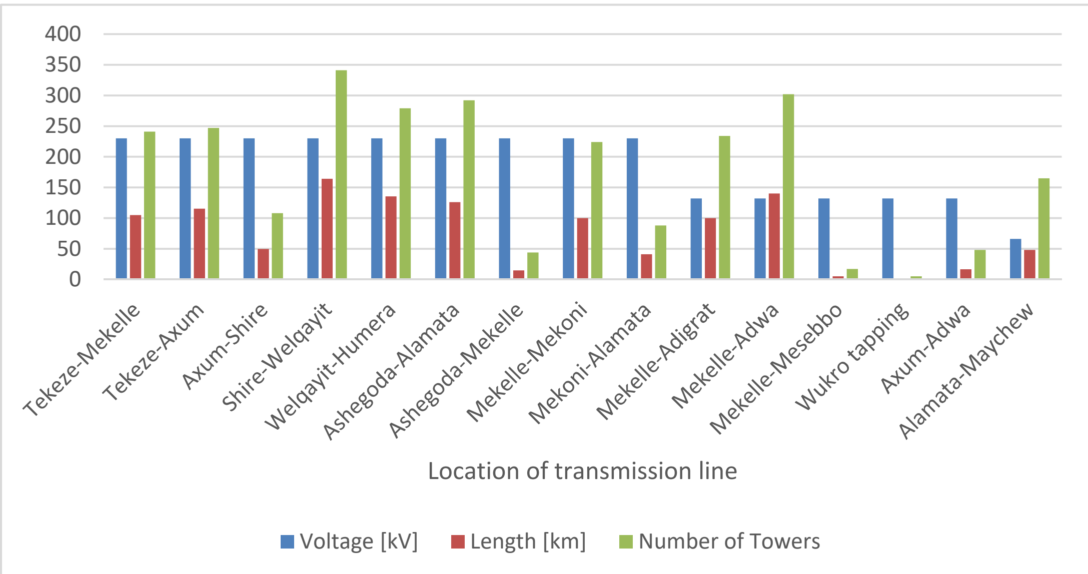

Figure 3. Detailed information on existing transmission lines in Tigray (author's own figure and illustration).

Though the original expansion plan was much bigger than the existing one, calling for 10,127 km of medium-voltage lines and 2,050 km of high-voltage lines; but only a total of 1,348.05 km of medium-voltage lines and 6,785 km of high-voltage lines were completed (Team of experts, 2020). **Figure 4**, shows the transmission lines in Tigray, with blue lines indicating high-voltage lines and light gray lines showing district boundaries that may be at risk of conflict.

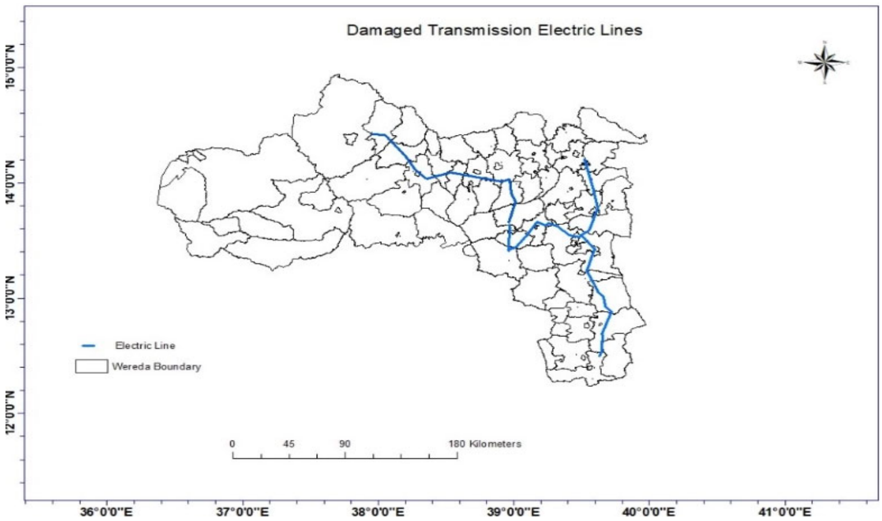

Figure 4. Existing Transmission Lines in Tigray (Blue lines: high-voltage lines) Authors' Illustration.

3.2. Substations

Though it is not sufficient, investment has been made in substation construction. Currently, there are 12 substations, which are described in **Figure 5**. The Tigray region substations operate at different voltage levels, as illustrated in **Figure 5**. Mekelle, Humera, Shire, and Maichew are the highly loaded substations, followed by Axum and Welqayt.

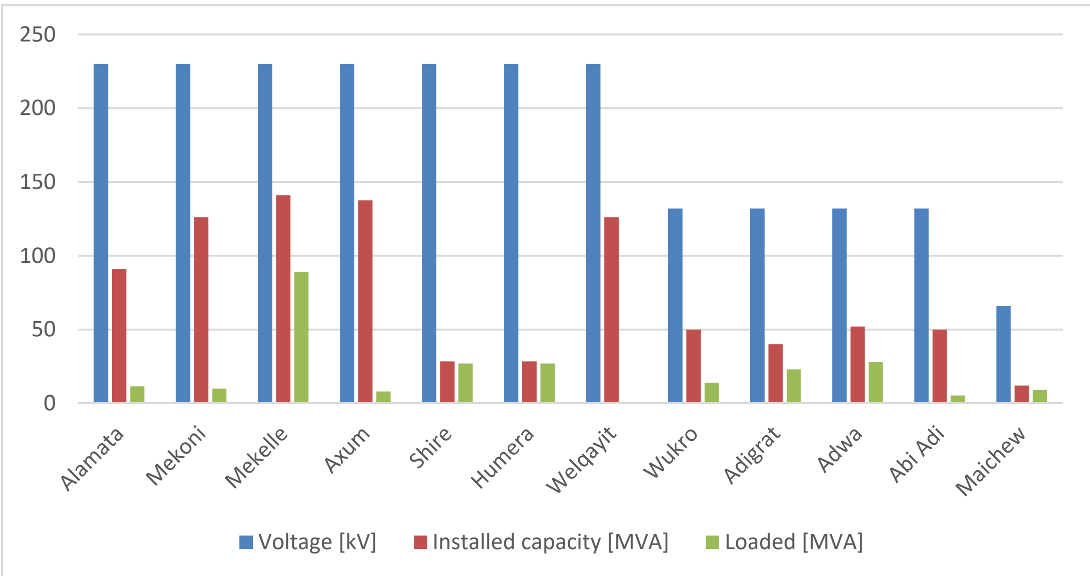

Figure 5. Existing substations in Tigray (Authors' chart and illustration).

3.3. Electricity distribution infrastructure

A significant investment is made in all the distribution systems throughout the region as the distribution system consists of medium and/or low voltage transmission lines, transformers, switchgears and protection apparatus. The voltage level on the consumer side is 220 V for single-phase and 380 V for three-phase customers.

4. Results

4.1. Physical damages

The conflict caused extensive and systematic destruction of Tigray's energy infrastructure, affecting transmission lines, substations, distribution networks, and support facilities. Artillery bombardments and drone strikes damaged 140.8 km of 230 kV transmission lines and destroyed 38 towers, severing the region's high-voltage backbone. Medium-voltage and low-voltage networks were also heavily impacted, with 330 km of MV lines, 75 km of LV lines, 237 distribution transformers, and 861 reactive meters destroyed. These losses resulted in a near-complete collapse of the electricity supply across the region.

The financial valuation of these damages shows a total physical destruction cost of US$51.4 million, comprising:

- US$23.6 million in transmission infrastructure
- US$26.0 million in distribution systems
- US$1.6 million in vehicles
- US$0.2 million in buildings

Drone attacks on the Tekeze and Mekelle substations (**Figures 6 and 7**) illustrate the targeted nature of the destruction. These substations are critical nodes in the regional grid, and their incapacitation contributed directly to the prolonged blackout documented by NASA's Black Marble imagery.

A detailed examination of equipment-level damage reveals clear patterns of strategic targeting. The All-Aluminum Alloy Conductor (AAAC) ASH 180 mm² was the most frequently damaged component, with 102 incidents, accounting for nearly 20% of all equipment losses. These conductors are essential for medium-voltage transmission, and their destruction indicates deliberate attempts to disable power flow between key nodes. Distribution transformers, particularly 100 kVA (56 cases) and 315 kVA (30 cases) units, were the second most affected category, highlighting systematic attacks on voltage regulation and local distribution capacity. Damage to Optical Ground Wire (OPGW) occurred 31 times, undermining both lightning protection and fiber-optic communication essential for grid monitoring. The loss of 44 LV reactive meters and 28 automatic circuit breakers further indicates targeted disruption of grid protection and control systems. Collectively, these patterns suggest a coordinated strategy aimed at disabling the grid's operational integrity rather than causing random collateral damage. The destruction was not limited to high-voltage assets. LV ABC cables critical for last-mile service delivery were damaged in 25 incidents, demonstrating that even household-level connections were systematically disrupted. This breadth of destruction across voltage levels underscores the comprehensive nature of the attacks. Table 1 summarizes representative transmission line damages. The Alamata-Mekoni-Mekelle 230 kV line suffered the most extensive conductor loss, with 140.78 km of AAAC(ASH)180 mm² destroyed. The Alamata-Ashegoda-Mekelle corridor experienced 64.7 km of ACSR 180 mm² conductor damage, while the Tekeze-Endaslassie-Shire line lost 47.8 km of AAAC(ASH)180 mm². These losses collectively severed the region's connection to the national grid.

Overall, the physical damage assessment reveals a pattern of deliberate, systematic, and technically informed targeting of Tigray's energy infrastructure. The destruction of conductors, transformers, OPGW, and protection devices indicates an intent to disable the grid's structural and operational capacity. These findings have significant implications for reconstruction planning, highlighting the need to prioritize conductor replacement, transformer deployment, and restoration of grid protection systems.

Figure 6. Fire at the Tekeze substation due to drone attack (own photograph in the aftermath of the attack).

Figure 7. Damages on the Mekelle substation due to drone attack.

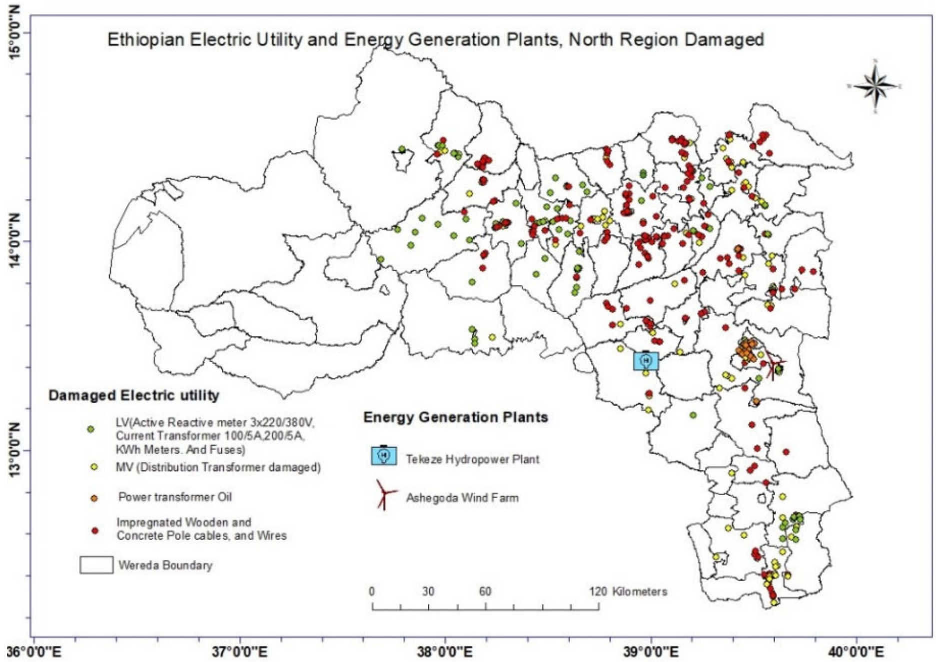

Figure 8. Specific location of the damaged substations, and distribution systems.

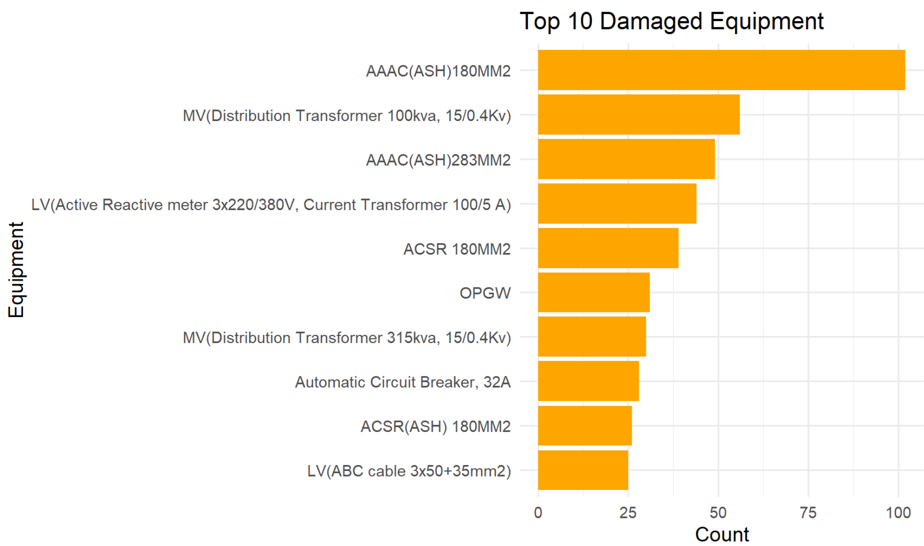

Figure 9. Distribution of damage across 10 most critical equipment types.

In Table 1, damaged transmission line representatives are present. The damage study result reveals targeted destruction of Tigray's energy infrastructure for the AAAC(ASH)180MM2 conductors along the transmission lines of Alamata-Mekoni-Mekelle, which were about 140.78km, followed by Alamata-Ashegoda-Mekelle stranded conductor (ACSR 180 mm^2) of about 64.7km.

Table 1. Representative damage to the transmission lines.

Damaged Transmission routes	Type	Length (km)
Alamata-Mekoni-Mekelle 230 kV Transmission line	AAAC(ASH)180 mm^2 conductors	140.78
Mekoni-Mekelle 230 kV Transmission line	Optical Ground Wire (OPGW)	37.20
Alamata-Ashgoda-Mekelle 230 kV Transmission line	stranded conductor (ACSR 180 mm^2)	64.7

Alamata-Ashgoda-Mekelle 230 kV Transmission line	Optical Ground Wire (OPGW)	3.4
Mekelle-Tekeze 230 KV Transmision Line	AAAC(ASH)283 mm^2	11.046
Mekelle-Tekeze 230 KV Transmision Line	Optical Ground Wire (OPGW)	2.42
Tekeze-Endaslasse Shire 230 kV Transmission line	AAAC(ASH)180 mm^2 conductors	47.832
Tekeze-Endaslasse Shire 230 kV Transmission line	Optical Ground Wire (OPGW)	25.63
Shire-Sheraro 230 KV Transmission line	AAAC(ASH)180 mm^2 conductors and OPGW	37.327

4.2. Geographic distribution of damage levels

The war-related energy infrastructure damage across Tigray amounts to close to 1,700 cases were collected. The analysis reveals catastrophic and geographically widespread destruction of Tigray's energy infrastructure, with near-total collapse observed across all administrative zones, **Table 2**. The Central zone suffered the most severe impacts, recording 569 cases, with 95.40% classified as complete destruction, while the North-Western zone experienced 360 cases and an almost total destruction rate of 99.70%. The Southern zone and the "Common" (cross-zonal transmission) category both show 100% destruction, indicating that key transmission corridors were systematically dismantled. All 331 cases of Common transmission infrastructure that connect multiple zones were completely destroyed, confirming deliberate efforts to sever regional power flow. These patterns demonstrate systematic and coordinated targeting of the regional grid, with particularly severe consequences for rural and peri-urban communities that rely heavily on distribution-level infrastructure.

Mekelle, the regional capital, experienced a 93.8% destruction rate - slightly less than surrounding zones but still representing near-complete infrastructure collapse, slightly lower than surrounding zones, but still representing near-complete functional collapse of the city's electricity system (see **Figures 7–9**). The Eastern (96.9% destruction), Central (95.4%), and South-Eastern (92.3%) zones all sustained damage levels exceeding 90%, indicating uniformly severe and coordinated attacks across the region. The destruction of medium and low-voltage lines is illustrated in **Figure 12** further shows that last-mile distribution networks were also systematically disabled.

Table 2. War damage distribution across zones of the Tigray Regional state.

Zone	Total Damages	Destroyed	% Destroyed
North-Western	360	359	99.70%
Southern	97	97	100%
Common	331	331	100%
Eastern	226	219	96.90%
Central	569	543	95.40%
Mekelle	65	61	93.80%
South-Eastern	26	24	92.30%

The geographic distribution of damage reveals clear patterns of strategic targeting. Transmission infrastructure suffered complete destruction regardless of location, while zone-specific damage rates consistently exceeded 90% in all documented areas. The minimal variation between zones (92.3%-100% destruction) suggests the Tigray war's comprehensive impact on energy systems, with even the least affected areas still experiencing near-total infrastructure loss.

These results highlight the unprecedented scale of infrastructure destruction in Tigray. The near-uniform severity across zones, combined with the complete elimination of transmission networks, indicates a systematic dismantling of the region's energy capacity. The data underscores the need for complete reconstruction rather than repair, particularly for the cross-zone transmission lines that are critical for regional power distribution. The small number of unclassified cases (24) has a negligible impact on these overarching findings.

The material damage costs in the energy sector of the six Zones are presented in Figure 10. At Zone level, Central, Eastern, Northwestern, and Southern Zones are the four most damaged ones with 15,104,606 US$, 5,409,902US$, 4,737,312US$ and 3,507,145US$, respectively, sharing of 45.59%, 16.33%, 14.3% and 10.58% of the total damage cost (US$ 33,130,884) occurred at infrastructures stationed on the zonal areas excluding transmission lines.

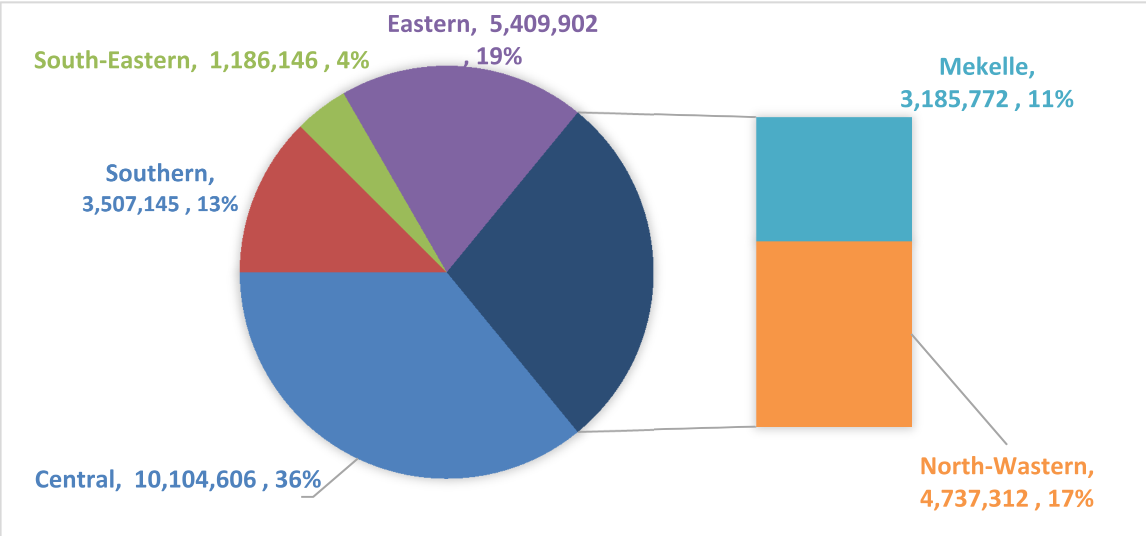

Figure 10. Zone-wise damage and percentage share (authors' char and elaboration).

4.2.1. Physical damage cost and share by category

The cost of physical destruction was determined based on the type of equipment, repair costs for damaged assets, and replacement costs (market value of replacing destroyed assets) obtained from Ethiopian Electric Power and Ethiopian Electric Utility. Total physical damages amounted to $51.42 million, with US$23.58 million (46%) from transmission damage, US$26.6 million (51%) from distribution, US$1.60 million (3.12%) from vehicles, and US$ 0.2 million (0.35%) from buildings (see **Figure 11**).

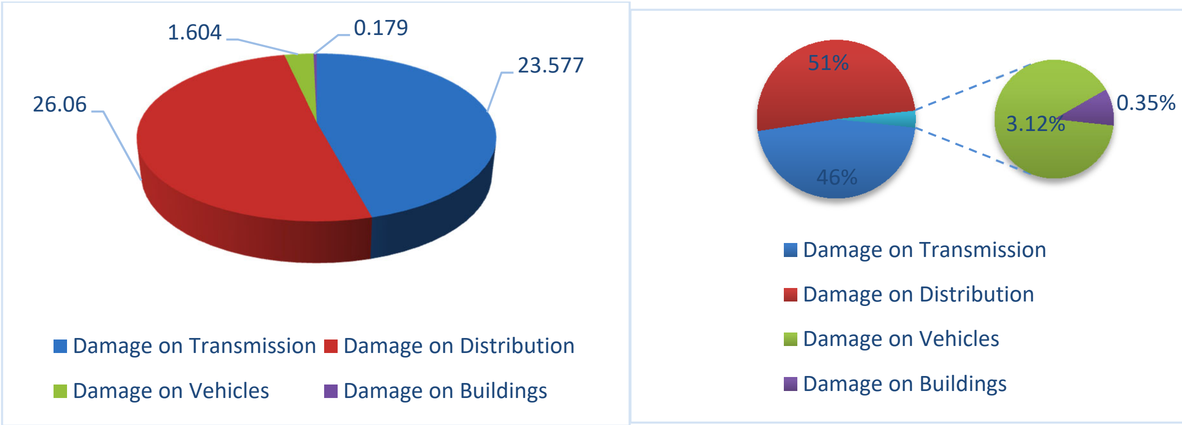

Figure 11. Damage cost (Million US$) by category and share (%).

Figure 12 displays the positions of transmission line tower structures impacted by the conflict in the Tigray region. These towers are vital for upholding stable high-voltage connections over long distances.

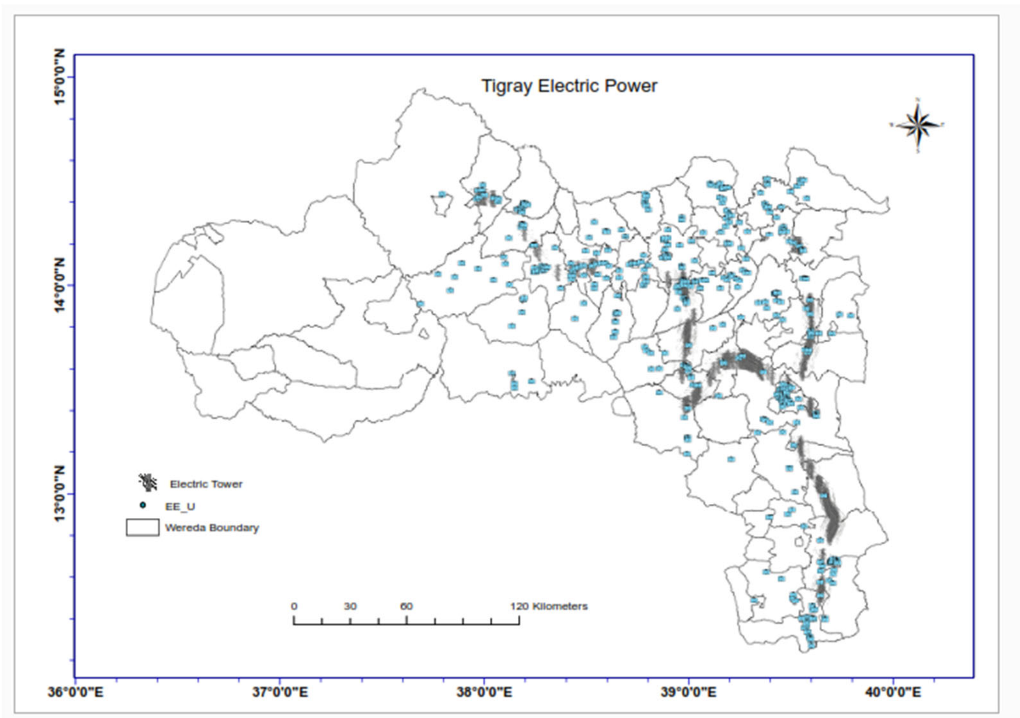

Figure 12. Map showing the distribution of transmission line towers in Tigray regional state.

As depicted in **Figure 13**, extensive damage has occurred to the medium and low voltage distribution lines and poles due to attacks involving machine guns and explosives. This has led to the complete destruction of the infrastructure. Approximately 330 km of medium voltage distribution lines and over 75 km of low voltage distribution lines have been impacted. Additionally, about 237 medium voltage distribution transformers and 861 active reactive meters have also been damaged.

Figure 13. Damaged on distribution systems (authors photo and elaboration).

4.3. Economic losses

Total economic losses amounted to $587.9 million (2021–2022), comprising $63.58 million in lost service (e.g., lost revenue due to electricity sales), $440.73 million in affected projects (e.g., Romanat and Sheraro substations), $83.01 million in additional costs, and $0.38 million in governance/risk **Table 3**. These affected health, education, and industry, worsening socio-economic problems.

Table 3. Estimation of the loss of energy infrastructure in the Tigray region.

Loss category	Total loss (US$ Millions)	Share (%
Loss due to declined service	63.58	10.82
Loss due to disruption of planned projects contracts and salaries	440.73	74.97
Additional costs for unexpected expense	83.01	14.12
Governance loss	0.15	2.55
Risk and vulnerability loss	0.38	6.46
Total	587.85	100

5. Discussion

The findings of this study reveal a pattern of systematic, technically informed destruction of energy infrastructure in Tigray regional state that aligns with global evidence on the strategic targeting of energy infrastructures during conflict. Similar to documented cases in Syria, Yemen, and Ukraine (Daiyoub et al., 2023; Ullah & Bavorova, 2025; Takeaways, 2023). The Tigray war demonstrates how attacks on substations, transmission lines, and grid-control equipment are used to undermine civilian resilience and disrupt essential services. Studies from Syria and Yemen show that the destruction of the energy system produces cascading failures across health, water, and communication systems, effects that closely mirror the prolonged blackout observed in Tigray. However, the near-uniform destruction across all administrative zones in Tigray, with destruction rates exceeding 90%, represents a level of comprehensiveness rarely quantified in African conflict settings.

The magnitude of economic losses identified in this study, US$587.9 million, also aligns with global findings that infrastructure destruction generates long-term economic stagnation. Research from Ukraine and Iraq similarly documents that the war has led to severe damage to energy infrastructure, affecting electricity generation and distribution, imposing far greater economic losses than the physical damage itself

(Abou Zahr, 2023). In Iraq, decades of conflict have led to a protracted crisis, heavily impacting energy systems and increasing the vulnerability of women and children living in war-torn areas (Ait Youssef and Kai Wangle, 2020). Yet, unlike these contexts, Tigray's pre-existing energy access gap and limited redundancy in transmission networks amplified the severity of the blackout, resulting in a complete regional grid collapse rather than partial service interruptions.

Environmental impacts observed in Tigray also resonate with the global literature linking conflict-induced energy insecurity to increased dependence on biomass. Studies from the Democratic Republic of Congo and South Sudan show that conflict accelerates deforestation as households substitute for fuelwood (Butsic et al., 2015; Toto, 2024). (Mlambo & Dlamini, 2019) emphasize that violence and conflict affect socio-economic conditions by disrupting access to essential resources, making sustainable energy more difficult to achieve. The estimated 930 km^2 of woody vegetation loss in Tigray, combined with a 628.7% increase in fuelwood extraction reported by independent studies, places the region among the most severe documented cases of conflict-driven environmental degradation. Unlike other contexts, however, Tigray's two-year blackout created a prolonged and region-wide reliance on biomass, producing environmental impacts that are both spatially extensive and ecologically significant, leading to rippling environmental, economic and socio-economic effects that have sharply set back progress toward achieving Sustainable Development Goal 7 (SDG 7) for access to affordable, reliable, sustainable and modern energy (UN, 2015).

This study also contributes novel empirical evidence by integrating asset-level field data with economic and environmental assessments, an approach rarely applied in African conflict settings. While global literature often relies on remote sensing or qualitative assessments, this study provides a uniquely detailed, ground-verified dataset of 1,699 damaged assets. The explicit quantification of conductor destruction, transformer losses, and OPGW damage offers insights into the technical logic of infrastructure targeting, complementing global analyses that emphasize strategic intent but lack engineering-level detail. The following sub-sections elaborate on these findings by examining the economic, environmental, technological, and legal dimensions of the conflict's impact on Tigray's energy system

4.4. Economic and social impacts

The military conflict in Tigray, Ethiopia, considerably affected the energy infrastructure of the region. This impact has led to serious economic and social consequences, mainly due to the destruction of distribution networks, substations, transmission systems, and other facilities. Tackling these consequences is essential to understanding the wider implications of military actions on communities that depend on electricity for means of subsistence and development.

The TIGRAY region previously was undergoing a developing energy network aimed at promoting economic growth. However, military actions have led to the dismantling of the essential components of this network, including substations that regulate the distribution and transmission systems of electricity, which transport energy to large distances. With damaged or destroyed electrical installations, access to electricity has decreased considerably. The inhabitants of Tigray faced frequent power outages, limiting the operation of any activities like schools, hospitals and businesses.

The physical destruction of the energy infrastructure, valued at US$51.4 million, included, in particular, severe damage to the distribution and transmission systems. This destruction contributed 8% to Ethiopia's 5,355.77 MW capacity pre-war. To provide perspective, consider that Ethiopia's annual investment in the power sector has ranged from US$500 million to over $1 billion over the last decade, mostly in large hydropower projects (World Bank, 2022). Despite these substantial investments, the impact of the Tigray damages on the local economy and the resulting humanitarian consequences cannot be overstated. Meanwhile, considering that Ethiopia's GDP was US$111 billion in 2022 (World Bank, 2023). The damage accounts for about 0.04% of national GDP, again with their localised impact has had disproportionately severe consequences in the one affected area. This comparison indicates that the disaster has left residents of Tigray severely lacking in energy access and services, despite their energy poverty level aligning with the national average.

Damage to key assets like the Tekeze hydroelectric plant (300 MW) and other energy infrastructures disrupted power to the whole community of Tigray that had been connected to the national grid before the war. Similar energy infrastructure destruction in Syria affected approximately 500,000 households and 50 hospitals, exacerbating socio-economic challenges (Hammoud, T., & El-Jardali, 2023). In Tigray, the effects of these disruptions included economic losses amounting to US$587.9 million from 2021 to 2022, degradation of service (US$ 63.58 million), disturbance of project and salary payments (US$440.73 million), and other out-of-the blue costs (US$83.01 million), severely affecting health, education and industrial productivity (EEU Tigray region, 2021), (UNDP, 2022). The results of this study resemble the cascading effects in Ukraine (Dunayev, I., Kuchma, M., Byelova, L., Jatkiewicz, P., Bilichenko, O., & Poberezhets, 2024; Hryhorczuk et al., 2024), and Yemen (Erika Weinthal and Jeannie Sowers, 2020).

The economic consequences in Tigray are deep. The absence of a stable power supply prevents companies from operating normally. Local and international investors hesitate to invest in TIGRAY due to the increase in operational risks associated with unreliable electricity. This reluctance can lead to job losses and greater economic stagnation in a region where many families depend on small businesses for survival. As indicated in a study by Tesfay, Gebreslassie and Lia, the sustainability of hydroelectric projects and their economic implications become even more pressing in the midst of such crises, because the interrupted electrical supply affects not only income, but also the overall development of communities (Tesfay et al., 2024).

Socially, the branches of damage to electrical infrastructure is extended. In Tray, electricity is not only a commodity; It is an essential resource that supports education and health services. The education of children has suffered, with schools closing or having limited hours due to the lack of electricity. Hospitals and clinics face challenges in care, as medical equipment is often based on electricity, compromising the quality of health services. The sharp drop in social services contributes to an increase in feelings of despair among the population, leading to a greater humanitarian crisis. Lavers and its colleagues underline how, under the revolutionary democratic front of the Ethiopian people (EPRDF), the production of electricity was considered crucial for the growth of the nation, but the situation in Tigray contrasts strongly with these ambitions (Lavers & Paper, 2021).

4.5. Environmental consequences

Independent empirical studies show that fuelwood extraction increased by 628.7% during the conflict (Teka & Welday, 2023), resulting in 268–365 hectares of forest loss annually. Remote-sensing analyses corroborate this pattern, with Landsat-based indices indicating a 403 km^2 vegetation decline (Hishe et al., 2024) and Sentinel-derived NDVI showing approximately 930 km^2 of woody-vegetation loss (Hishe et al., 2024). These findings support the study's conclusion that electricity interruption significantly intensified biomass extraction and deforestation.

The shift toward fuelwood as the primary energy source during the blackout has been widely documented (Birhane et al., 2025). This substitution accelerated deforestation, increased CO_2 emissions, and contributed to biodiversity loss. In eastern Tigray, for example, forest cover declined sharply as households relied on firewood for survival (Mugulat Mezgebo et al., 2024).The removal of woody biomass releases stored carbon, exacerbating climate change and undermining Ethiopia's climate-resilience efforts (Eshetu Abebaw, 2024; IPCC, 2022). Conflict-driven biomass use in Tigray is estimated to have emitted 1.2 million tonnes of CO_2-equivalent and reduced regional biodiversity by up to 15% (Negash, D., & Hoag, 2021); (Eickemeier et al., 2019; H. Schulte et al., 2024).

Biodiversity impacts extend beyond carbon loss. Deforestation has destroyed habitats, reduced species populations, and disrupted ecosystem services essential for local livelihoods (Birhane et al., 2025; Tadesse & Hailu, 2024). The conflict also interrupted long-standing conservation practices, as communities prioritized immediate energy needs over sustainable resource management (H. Schulte et al., 2024). Evidence from pre-war forest-closure initiatives shows that protected areas can rapidly restore above- and below-ground carbon stocks (Gedion Tsegay and & Xiang-zhou Meng, 2021), underscoring the importance of post-conflict ecological rehabilitation.

The environmental toll of the war highlights the urgency of reforestation and sustainable energy transitions to meet SDG 7.2 targets (Belay and Mengstu, 2020), (FAO, 2022). Expanding off-grid renewable energy systems and promoting agroforestry can reduce biomass dependence while supporting ecological recovery (Debela, 2019). These strategies are essential for restoring degraded landscapes, rebuilding community resilience, and preventing further environmental decline.

4.6. Broader implications and limitations

The conflict in Tigray, Ethiopia, has provided critical lessons on how communities can recover from the war. The recovery led by the community is essential in conflict areas because it allows local populations to rebuild their lives and restore their environment. Tigray's experience shows that when communities are involved in the recovery process, they can adapt more relevant strategies for their specific needs and contexts. Such involvement not only builds confidence between community members but also promotes resilience to future conflicts (Birhane et al., 2025).

One of the important implications for conflict recovery concerns the Sustainable Development Goal (SDG) 7, which focuses on access to affordable, reliable, durable and modern energy for all. In Tray, the devastation caused by the conflict seriously affected access to energy, highlighting the need for a targeted approach to energy recovery (Gebreslassie & Bahta, 2023). Tigray communities have exploited various sustainable energy options, including solar energy, to reduce the impact of energy shortages and provide essential services to their communities (Owen Grafham, 2022). This evolution towards renewable energies has broader implications for SDG 7, which suggests that the regions affected by conflicts could benefit from investment in renewable sources rather than rebuilding traditional energy systems, which may not be durable in the long term.

However, it is essential to recognize the limits of the data surrounding recovery in areas still occupied by external forces, such as the Western zone of Tigray. This data gap implies that recovery efforts can be wrong if they do not consider the real needs and practices of the local communities. For example, understanding the impacts of conflicts on ecosystems and agriculture may require localized studies that may not be available (Jones et al., 2022). Reliable data may shed light on political decisions, ensuring that recovery efforts are aligned with community needs and sustainable development principles.

Renewable energy technology can also support the restoration of ecosystems, which is increasingly important in the areas devastated by conflicts. As the communities rebuild, they can use renewable energy sources to fuel initiatives aimed at restoring degraded landscapes. This strategy not only meets energy needs but also rejuvenates the environment, which is essential for agriculture and food security (Jones et al., 2022). By integrating the restoration of the ecosystem into renewable energy projects, communities create a sustainable recovery framework that meets immediate and long-term needs.

Tigray's experiences show that integrated recovery approaches can lead to significant progress in the regions affected by the crisis. The restoration of socio-ecological systems is linked to community resilience and access to energy. Conflicts can devastate these systems, but thanks to initiatives led by the community, such as those led by Tigray organizations, the communities began to heal (Gebreslassie & Bahta, 2023).

4.7. Digital technologies for post-conflict energy resilience

Digital technologies are increasingly essential for strengthening post-conflict energy-system resilience and improving the accuracy of future assessments. They enhance decision-making, resource allocation, and transparency in complex energy environments. For example, (Khomenko et al., 2024) show that digitalization accelerates conflict-resolution mechanisms in energy transactions by improving communication among stakeholders. Digital tools also reshape how climate-related damage is assessed; (Bettini et al., 2020) highlight their role in advancing Loss and Damage Assessment (DaLA), enabling more precise quantification of climate impacts.

In conflict-affected regions, digital technologies support real-time monitoring and accountability. (Zieliński, 2025) notes that digital monitoring tools can document environmental harm as it occurs, strengthening evidence-based responses. Remote-sensing platforms such as Landsat, Sentinel-2, and nighttime-light datasets (e.g., NASA Black Marble) provide scalable, near-real-time capabilities for detecting infrastructure destruction and vegetation loss (Li et al., 2020). Their effectiveness is demonstrated in recent studies: (Aimaiti et al., 2022) used Sentinel-1 and Sentinel-2 imagery to assess building damage in Kyiv; (Kaplan et al., 2022) reviewed remote sensing for monitoring war-related environmental security; and (Dietrich et al., 2025) developed an open-source tool using Sentinel-1 time-series data to map destruction in Ukraine.

Geospatial analytics and machine learning further enhance damage assessment, particularly for energy infrastructure. GeoAI has proven effective for post-disaster building-damage evaluation (Taiwo H. Agbaje et al., 2024), while deep learning applied to high-resolution geospatial data can precisely identify conflict-related damage (Risso et al., 2025). Mixed-methods approaches combining machine learning with statistical indicators also improve agricultural-damage assessments (Kussul et al., 2023). Integrating machine learning with remote sensing strengthens disaster-management strategies and supports crisis-time decision-making (Al Shafian & Hu, 2024). Together, these technologies enable faster and more accurate assessments, offering valuable opportunities for future research on post-conflict energy-system recovery.

Although this study did not employ digital technologies directly, these tools represent important avenues for advancing future post-conflict energy assessments.

4.8. International law for the protection of infrastructure in conflict areas

International humanitarian law, as outlined in the Geneva Conventions and Additional Protocols, mandates the protection of civilian infrastructure, including energy installations, during armed conflict (Dinstein, 2004; Greenwood, 2022; Levie, 1907; UNSC, 2017; Elnourani et al., 2024). Infrastructure must only be destroyed if it constitutes a legitimate military target. United Nations Security Council Resolution 2341 (UNSC, 2017) reinforces this obligation by calling for the safeguarding of infrastructure from armed groups and terrorism.

However, compliance in Tigray has been inadequate, evidenced by drone attacks on the Tekeze and Mekelle substations in 2021, causing damage to transmission infrastructure and disrupting electricity supply to civilians (H. Wier D. & Schulte to Bühne, 2022). Similar challenges persist in Ukraine, Syria, and Yemen due to political constraints and a lack of accountability (Dunayev, I., Kuchma, M., Byelova, L., Jatkiewicz, P., Bilichenko, O., & Poberezhets, 2024; Hryhorczuk et al., 2024; Sowers, J. L., Weinthal, E., & Zawahri, 2017; Al-Shammari, 2016). Possible mechanisms to ensure compliance include International Criminal Court prosecutions, UN Security Council sanctions, and rapid-response monitoring missions. Nonetheless, the absence of these mechanisms in Tigray has led to repeated violations.

The lack of accountability in Tigray will have lasting impacts on its recovery, as impunity hampers investment in rebuilding critical energy infrastructure. Legal actions, such as reparations for infrastructure damage and criminal prosecution of perpetrators, could facilitate reconstruction and deter future attacks, drawing from post-conflict accountability experiences. Proposals such as UN-led investigations or ICRC-monitored safe zones, suggested by (Zabyelina, Y., & Kustova, 2015), could enhance adherence to International Humanitarian Laws in similar conflicts. These efforts are crucial for Tigray to rebuild trust in its energy systems and achieve Sustainable Development Goal 7 targets on reliable energy access energy (MoWE, 2024).

5. Conclusion

This study provides the first comprehensive, asset-level assessment of conflict-induced energy insecurity in Tigray, quantifying the physical destruction of infrastructure, the resulting economic losses, and the cascading environmental impacts. The findings show that the war caused extensive damage to power plants, substations, transmission lines, and distribution networks, resulting in a region-wide blackout that persisted until the 2022 Pretoria Agreement. The destruction of 1,699 documented assets and the interruption of electricity services generated an estimated US$587.9 million in economic losses, demonstrating the severe vulnerability of energy systems in conflict-affected regions.

The environmental consequences were equally profound. Conflict-driven biomass dependence accelerated deforestation at a scale unprecedented in the region. Remote-sensing evidence indicates approximately 930 km² of woody-vegetation loss, equivalent to 4% of Tigray's total forest cover, while Landsat-based analyses show an additional 403 km² decline in vegetation density between 2020 and 2022. Field-based assessments further reveal a 628.7% increase in fuelwood extraction, resulting in 268–365 hectares of forest loss annually. Together, these findings illustrate how the collapse of electricity services triggered a cascading environmental crisis, underscoring the tightly interlinked relationship between energy insecurity, ecological degradation, and humanitarian vulnerability during armed conflict.

The study's integrated approach combining primary field data, economic valuation, and remote-sensing validation offers a methodological contribution to post-conflict energy assessments in Africa, where empirical evidence remains scarce. The results underscore the need for reconstruction strategies that prioritize resilient energy systems, decentralized renewable technologies, and ecological restoration. Addressing the long-term consequences of the Tigray conflict requires coordinated efforts to rebuild infrastructure, restore degraded landscapes, and reduce dependence on biomass. Promoting off-grid renewable energy, expanding agroforestry, and strengthening community-based natural resource management can support both environmental recovery and social wellbeing. By integrating sustainable energy solutions into post-conflict reconstruction, it is possible to advance SDG 7 while laying the foundation for a more resilient and equitable energy future for the people of Tigray.

6. Managerial implications

The findings of this study provide several important implications for energy-sector managers, reconstruction planners, and government agencies responsible for post-conflict recovery. First, the asset-level destruction data showing 1,699 damaged installations and near-total collapse of transmission and distribution networks offers a clear basis for prioritizing reconstruction investments. Managers should focus on restoring substations and high-voltage corridors in the Central and North-Western zones, where destruction exceeded 95%, to re-establish regional grid stability.

Second, the quantified economic losses of US$587.9 million highlight the need for risk-informed planning and financial protection mechanisms, including infrastructure insurance, contingency funds, and donor-supported reconstruction financing. Energy managers should integrate digital asset-management systems, remote-sensing diagnostics, and automated fault-detection technologies to improve grid visibility and reduce vulnerability to future disruptions. High-level managers must coordinate with environmental agencies to ensure that reconstruction does not exacerbate ecological degradation and that energy planning supports long-term sustainability.

7. Practical implications

The prolonged blackout and destruction of infrastructure underscore the need for diversified and decentralized energy solutions in post-conflict settings. Practical interventions include deploying mini-grids, solar-battery systems, and modular substations to restore essential services while large-scale grid reconstruction is underway. Strengthening supply chains for transformers, conductors, and protection equipment is essential to reducing reconstruction delays. The quantified economic losses presented in this study provide a basis for mobilizing donor financing, insurance mechanisms, and public–private partnerships to support recovery.

8. Social implications

Energy insecurity during the Tigray conflict had profound social consequences, affecting health, education, livelihoods, and community resilience. The collapse of electricity services forced households to rely on biomass, increasing the labor burden on women and girls who are primarily responsible for fuelwood collection. This contributed to heightened exposure to violence and increased time poverty. The destruction of energy infrastructure also disrupted healthcare delivery, limiting the operation of medical equipment, cold-chain systems, and emergency services. Schools faced closures or reduced hours due to a lack of lighting and digital resources, deepening educational inequalities.

Environmental degradation, such as 930 km² of forest loss and biodiversity decline, further threatens long-term food security and rural livelihoods. Social recovery requires not only rebuilding infrastructure but also restoring ecosystems, supporting community-based natural resource management, and ensuring equitable access to modern energy services.

Reconstruction efforts must prioritize inclusive planning, ensuring that women, youth, displaced populations, and rural communities participate in decision-making. Strengthening social institutions and community organizations will be essential for rebuilding trust, restoring livelihoods, and enhancing resilience to future shocks.

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