Accurate operational carbon emission of transformers using condition monitoring

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ABSTRACT

Operational carbon emissions from electrical power systems serve as essential metrics for sustainability assessment and regulatory compliance. Emission reporting is traditionally based on energy use and nameplate loss values, assuming a constant reference winding temperature of 75°C. However, these methods often result in under- or over-estimations due to their inability to capture real-time operating conditions. This paper explores a more accurate methodology for carbon emission reporting through the integration of temperature-based monitoring in transformers. By accounting for dynamic temperature variations and their effect on resistive losses and auxiliary energy consumption, end users can significantly improve the accuracy of reported emissions and better align with international reporting standards. The broader role of condition monitoring is discussed.

KEYWORDS:

operational carbon emissions, GHG protocol, life cycle analysis, grid emission factor

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1. Introduction

Carbon emissions (CO_{2e}) from power systems are under increasing scrutiny as nations strive to meet net-zero targets under frameworks like the Paris Agreement. In power transmission and distribution networks, electrical losses—primarily in transformers—contribute indirectly to greenhouse gas (GHG) emissions. Conventional carbon reporting techniques do not account for real-time system behaviour, leading to potential misrepresentation of the transformer’s environmental impact.

Multiple studies [1] - [4] show that the operational (use) phase dominates the transformer’s life cycle CO_{2e} emissions, often exceeding 90% of the total. As of today, it is estimated based on an assumed load factor, rated load losses, which are based on a reference winding temperature of 75°C. However, we know that transformer losses depend on the winding temperature, which is affected by load, ambient temperature, and cooling. It has also been shown that even at low loads, the CO_{2e} emissions associated with the use phase exceed those generated during the entire production process [2].

During operation, the winding temperature not only depends on the transformer’s loading, but also on the ambient temperature and cooling type, i.e., ONAN, ONAF, ODAF, etc. ONAN transformers will experience little difference in cooling, but for ONAF or ODAF, the temperatures can be greatly influenced by whether the fans/pumps are turned on or off. There are cases where the windings may be less thermally loaded, resulting in lower load-losses in service as compared to the standard method of recalculating losses on the reference temperature of 75°C.

These dynamics are seldom reflected in standard reporting practices, resulting in estimation errors. Winding temperature changes during operation, affecting the resistance of conductors and losses. This directly affects the value of cumulative energy loss, based on which the traditional operational carbon footprint of the transformer is estimated.

In addition, condition monitoring plays a pivotal role in enhancing the fidelity and responsiveness of carbon emission reporting in power systems. While temperature measurements provide a direct indicator of thermal behavior, broader condition monitoring enables continuous tracking of a transformer’s health, performance, and auxiliary system efficiency. By integrating condition-based data, end users can develop more granular and accurate CO_{2e} emissions reporting.

This paper proposes a temperature-driven operational CO_{2e} emissions calculation method that captures these variations, allowing for more accurate and transparent reporting. By incorporating online temperature measurements, emission estimates can better reflect the actual operating conditions, enabling:

- Enhanced granularity in reporting,
- Improved asset management decisions,
- Regulatory compliance with ISO 14064 and GHG Protocol standards.

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2. Brief background

Electrical infrastructure, while crucial to the modern way of life and economic development, contributes significantly to carbon emissions, especially where fossil fuels dominate the energy mix. Carbon emissions are typically categorized into three scopes:

- **Scope 1:** Direct emissions from owned sources (e.g., on-site diesel generators),
- **Scope 2:** Indirect emissions from purchased electricity used by utility assets,
- **Scope 3:** All other indirect emissions, including those from supply chains.

In transformer operations, energy losses contribute to Scope 2 emissions. These include:

- **No-load losses (core losses):** Constant and independent of load, influenced by voltage and temperature.
- **Load-losses (copper losses):** Vary with the square of load current and temperature.

The losses in a transformer are temperature-dependent, and understanding this relationship is crucial for efficient design, operation, and carbon footprint reporting. Typically, the net effect of temperature on total loss can be:

- In lightly-load conditions: No Load losses dominate → total losses may slightly decrease with temperature.
- In high-load conditions: Load losses dominate → total losses increase with temperature.

[5] gives the relationship between losses and the impact of temperature as listed in Table 1.

Additionally, ambient and oil temperatures affect the efficiency of cooling systems, which in turn affects auxiliary load. The traditional life cycle analysis (LCA) method fails to integrate these dependencies in real-time.

3. Proposed methodology

The proposed method to accurately capture operational CO_{2e} emissions consists of data acquisition and instrumentation, dynamic loss calculation, and carbon emission estimation.

3.1 Data acquisition and instrumentation

Implementing accurate temperature-based reporting requires integration of:

- Winding Temperature Indicators (WTI): For estimating hot-spot temperatures,
- Top and Bottom Oil Temperature Sensors: For identifying thermal gradients,
- Ambient Temperature Sensors: Installed externally for the environmental context,
- Load Monitoring Equipment: Real-time current and voltage measurements,
- Cooling System Auxiliary: Operational status and energy consumption of fans/pumps.

The preferred solution is to use fully electronic devices, such as Electronic Temperature Monitors (ETMs), which continuously calculate the hottest temperature on up to three windings based on the measured values of top oil temperature (via existing PT100 RTD sensors) and load current measurements from the CTs. ETMs enable automated cooling control of fans and pumps, using real-time thermal and loading data to reduce auxiliary energy use. The operation status and energy consumed by cooling system auxiliary devices are now available in real time.

Using an ETM will significantly reduce installation and maintenance requirements. Manufacturers of traditional Winding Temperature Indicators (WTI) recommend calibration verification at regular intervals. With the ETM, the sensors are continuously checked, and the system has a fail-safe watchdog function to ensure proper operation of all components. The further benefit of the ETM is its capability to do real-time calculations, such as IEC or IEEE thermal aging, and be connected to SCADA and communicate its data and alarms to the operating and maintenance staff.

Key benefits of ETM will include:

1. Improved accuracy in loss calculations - more accurate CO_2 quantification.
2. Granular emissions profiling - allow emissions tracking hour-by-hour, identify carbon peaks.
3. Enhanced cooling system optimization - trigger cooling only when thermal thresholds are reached, directly lowering Scope 2 emissions.
4. Alignment with digital reporting standards - data can be exported and integrated with carbon accounting software.
5. Predictive maintenance and emission prevention - early intervention prevents elevated losses and carbon "spikes".
6. Facilitates asset-level carbon intensity tracking - carbon footprinting at the individual transformer level, precision planning and decarbonization of critical nodes.

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Table 1. Impact of temperature on transformer losses

Loss Type	Depends On	Temperature Impact
No-load loss	Voltage, frequency, core material	Slightly decreases with temp
Load loss	Load current, winding resistance	Increases with temp (↑ R)
Stray losses	Leakage flux, tank heating	Decreases with temp (↓ R)

3.2 Dynamic loss calculation

Typically, quantification of losses during the use phase is calculated by applying the following equation -

$$E_L(kWh) = (NLL + k^2 \times LL) \times t_{year} \times RSL \quad (1)$$

Where NLL = No load loss, LL = Load loss at 75°C reference temperature, k = average load factor, tyear = total amount of hours during a year (8760 hours), and RSL = Reference Service Life (typically 25(for distribution)- 40 (for power) years).

Using the copper (or aluminum) resistance temperature correction formula, the winding temperature correction for copper windings can be calculated as:

$$LL_{\theta_{wdg}} = LL_{75} \times \frac{(235 + \theta_{wdg})}{235 + 75} \quad (2)$$

The corrected quantification of losses during the use phase can now be calculated by applying the following equation:

$$E_{dynamic}(t) = \left(NLL + k^2 \times LL_{\theta_{wdg}}\right) \times \Delta t + (Auxiliary\ Loss) \times \Delta t \quad (3)$$

Where Auxiliary Loss depends on cooling type (ONAN, ONAF, ODAF, etc.) and its status (fans/pumps on or off). Figure 1 shows a measured profile for an

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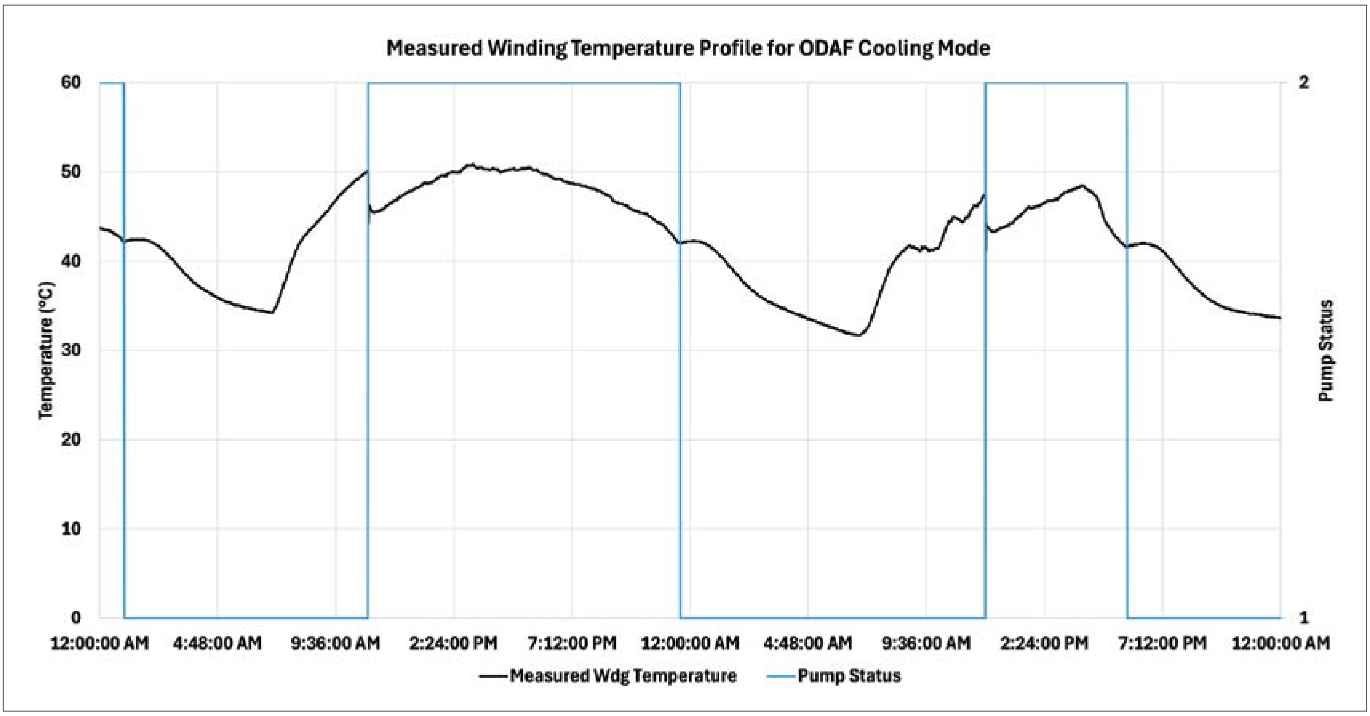

Figure 1. Measured temperature profile for ODAF cooling mode

ODAF transformer, the status and duration of pump operation can be easily computed by the ETM, and the corresponding auxiliary energy loss can be added to the dynamic loss calculation.

3.3 Carbon emission estimation

Total operational CO_{2e} emissions are calculated as:

$$tCO2_e = E_{dynamic}(t) \times t \times GEF_t$$

Where: t = Time duration (hours, can be computed for a day/month/year/lifetime) and GEF = Grid emission factor (tCO_2/MWh) as a function of time, which allows us to integrate the transition in electricity generation from fossil-based to renewable sources.

4. Case study

A simple case study using a 1 MVA, 11/0.415 kV, MEPS efficiency compliant [6] ONAN transformer is used here to illustrate the difference with conventional LCA calculation outcome. For this transformer, NLL = 1.8 kW, LL = 7 kW at 75°C and GEF = 0.669 kg CO_{2e}/kWh.

This transformer operated at varying load levels with an ETM installed to monitor different temperatures. A 24-hour profile is shown in Figure 2.

4.1 Operational CO_{2e} emissions - conventional

At 50% load as per MEPS recommendation, the conventional operational CO_{2e} emissions (use phase) can be calculated as follows, as listed in Table 2.

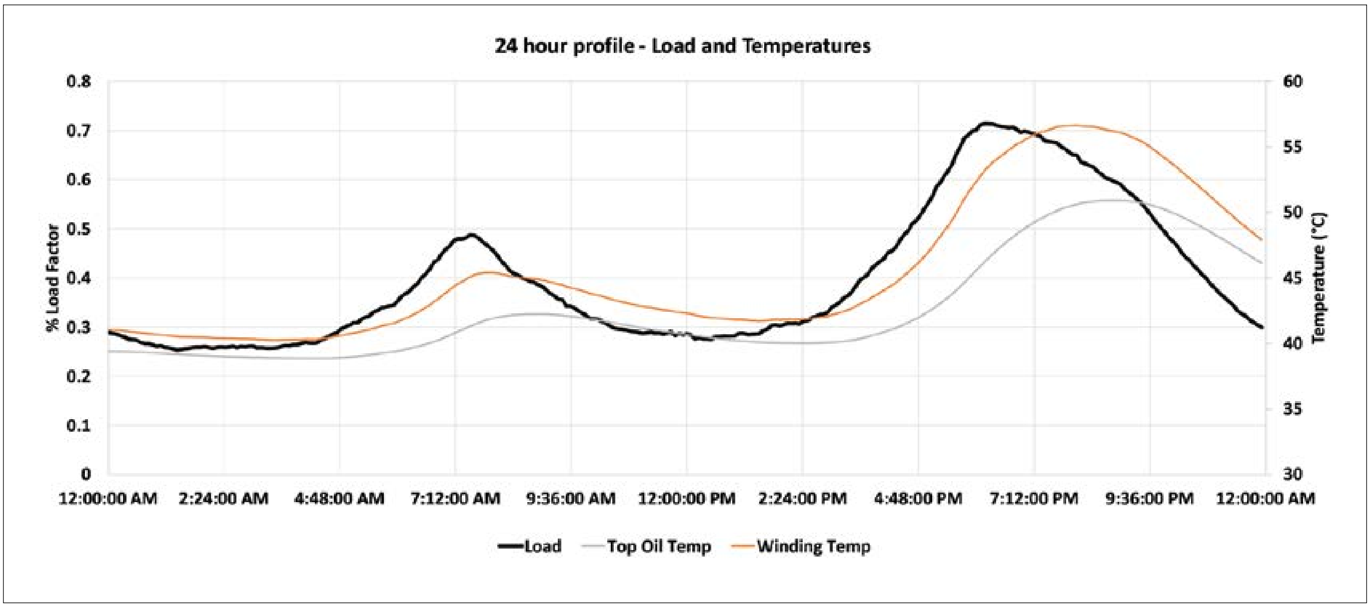

Figure 2. Measured outputs from ETM for a 1 MVA ONAN transformer

4.2 Operational CO_{2e} emissions - proposed

Using Eq. (2), the corrected load loss for different winding temperatures can be calculated as listed in Table 3.

For a 24-hour period, there is a 17% overestimation if using the conventional static data, as shown in Table 4.

Assuming a similar daily load pattern, extrapolating the values for a 25-year lifetime of this 1 MVA transformer, instead of 432 tCO_{2e} tons (use phase), the conventional method would yield 520 tCO_{2e}. If using the ETM, real data time would yield reporting accuracy within ±5%. Temperature-based carbon emission reporting introduces a critical layer of precision and accountability to operational sustainability assessments in the power sector and should be implemented in a much wider context.

4.3 Advantages of temperature-based carbon reporting

There are several advantages to the proposed approach -

- Higher Accuracy: Real-time data yields reporting accuracy when compared to static values.

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Table 2. Operational CO_{2e} emissions based on MEPS

Global Warming Potential due to Operation	CO_{2e} from operation (use phase)	Values
	NLL (kW)	1.8
	LL (kW)	7.0
	Load factor	0.5 (50%)
	Daily energy loss (kWh)	85.2
	Total energy loss per year (kWh)	31,098
	Total losses for lifetime (kWh) – 25 years	777,450
	tCO_{2e} tonnes (use phase) only	520

Table 3. Correction of load losses based on temperature

Winding Temp	Corrected Load Loss (W)	Comment
10°C	5,532	
20°C	5,758	
30°C	5,984	
40°C	6,210	
50°C	6,435	
60°C	6,661	
70°C	6,887	
75°C	7,000	Nameplate Value
80°C	7,113	
85°C	7,226	
90°C	7,339	
95°C	7,452	
100°C	7,565	

Table 4. Outcome Comparison: 50% load factor at 75°C vs Measured Temperature

Global Warming Potential due to Operation	CO_{2e} from operation	At 50% load at 75°C	Using Measured Values
	Daily energy loss (kWh)	85.2	70.77
	Total losses for lifetime (kWh)	31,098	25,830
	tCO_{2e} tonnes (use phase) only	520	432
	Difference	Over-reporting by 17%	

The road to net zero runs through a condition monitored transformer!

- Operational Insight: Helps identify peak loss periods and optimize loading.
- Cooling System Optimization: Reduces unnecessary auxiliary energy use.
- Regulatory Compliance: Better alignment with GHG Protocol and ISO 14064.
- Asset Health Monitoring: Thermal data aids in predictive maintenance.

This approach supports and enhances:

- ISO 14064-1: Organization-level GHG emissions quantification and reporting.
- GHG Protocol Scope 2 Guidance: Enhanced tracking of indirect energy emissions.
- CDP, ESG, and other sustainability disclosures: Provides audit-grade accuracy.

5. Challenges and possible mitigation

The main challenges and some mitigation strategies to the proposed method are listed in Table 5.

6. Role of condition monitoring in carbon emission reporting

Condition monitoring plays a pivotal role in enhancing the fidelity and responsiveness of carbon emission reporting in power systems, especially for transformers. While temperature measurements provide a direct indicator of thermal behaviour, broader condition monitoring enables continuous tracking of a transformer's health, performance, and auxiliary system efficiency. By integrating condition-based data, end users can develop more granular and accurate carbon profiles.

Key Contributions of Condition Monitoring:

- Real-Time Asset Performance Tracking: Monitoring of parameters such as oil moisture, dissolved gases (DGA), partial discharge, and vibration can signal abnormal operations that result in increased energy losses. Identifying these conditions early allows timely intervention to prevent prolonged high-loss operation.
- Dynamic Loss Characterization: Traditional models assume ideal or nameplate conditions. Condition monitoring reveals real-world deviations such as winding deformation or increased contact resistance which elevate actual losses and associated emissions. These can be factored into operational emissions dynamically.
- Auxiliary System Efficiency Monitoring: Fans, oil pumps, and load tap changers (LTCs) often run inefficiently due to age or wear. Condition monitoring systems track runtime, energy draw, and switching patterns, allowing precise quantification of auxiliary carbon contributions.
- Predictive Maintenance Reduces Carbon Spikes: Failure or degradation often causes transformers to operate in thermally stressed states, increasing I^2R losses. Predictive diagnostics enabled by monitoring help avoid such scenarios, thus maintaining carbon efficiency.
- Integration with Emissions Dashboards: Modern condition monitoring systems integrate with centralized SCADA or EMS dashboards. These platforms can convert condition indices and measured values into carbon intensity indicators (e.g., kg CO_2/MWh), making emissions visible in real time.

Table 5. Challenges and Mitigation Strategy for temperature-based CO_{2e} quantification.

Challenge	Mitigation Strategy
Sensor accuracy and calibration	Scheduled verification and self-diagnostics
Data synchronization	Time-stamped SCADA integration
Varying emission factors	Use regional emission factor databases
Real-time data processing	Use edge computing and cloud analytics

7. Conclusion

As end users pursue low-carbon operations, the specification and deployment of high-efficiency transformers becomes a strategic consideration. MEPS are being implemented globally (e.g., DOE in the US, EU EcoDesign, Australia/NZ), mandating improved efficiency levels. However, without correctly evaluating the current baseline losses and mandating high-efficiency transformers, a barrier in terms of an initial manufacturing cost increase is encountered. High-efficiency transformers typically require more expensive materials and precision manufacturing. The increased upfront cost can deter utilities and private operators, especially in cost-sensitive procurement environments. Decision-makers often prioritize initial purchase cost over total cost of ownership (TCO), which includes operating losses. This short-term view undermines the long-term savings. Together, real-time carbon reporting and high-efficiency hardware offer a synergistic path toward accurate and lasting decarbonization. If one is mandated without consideration of the other, achieving accurate and lasting carbon reductions will be a challenge.

This proposed method introduces a critical layer of precision and accountability to operational carbon emission values in the power sector, especially transformers. By capturing the thermal dynamics of transformer operation and associated energy losses, end users can better reflect their true carbon footprint and make informed decisions to enhance energy efficiency.

Adoption of this methodology aligns operational data with global climate action goals and paves the way for transparent, data-driven environmental governance, such as MEPS mandates.

ETMs will serve as the digital backbone of accurate, transparent, and actionable carbon footprint reporting in transformers. Their integration not only enhances environmental accountability but also supports broader digital transformation and decarbonization strategies.

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