Technical Appendix

Distribution Transformers

1. Introduction

This appendix offers a detailed explanation of the specific assumptions used in the distribution transformer module of Mepsy. For information on outputs and data sources for the parameters, please refer to the comprehensive Mepsy Methodology document.

CLASP developed a model to quantify energy and CO_2 emission impacts of **Distribution Transformers (DT)**, covering three main categories, namely:

- Three-phase Liquid-Immersed DTs (3P-Oil)
- Three-phase Dry-Type DTs (3P-Dry)
- Single-phase Liquid-Immersed DTs (1P-Oil)

2. Shipments and Stock

CLASP developed country-level estimates of new and total DT installations for 162 countries using an existing stock model shared by industry stakeholders. The existing model is a stock accounting model, covering 200 countries and territories between 1950 and 2040. The model takes the unit sales of distribution transformers from ABB's sales estimates from 2008 to 2018 and compares this information with actual and projected electricity consumption for the same period.[1] National electricity consumption data was obtained from the US Department of Energy's Energy Information Administration (EIA) and projected electricity consumption is based on the International Energy Agency's World Energy Outlook 2014 which covers national and regional data.[1,2]

ABB's primary sales dataset provides annual data on new and existing installations in Mega Volt-Amperes (MVA) and unit counts for 58 countries in Asia, Africa, America, Europe, and Oceania.[3] Data is available for the three DT categories from 2008 to 2018. The representative unit capacity

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[1] "Electric Power Monthly - U.S. Energy Information Administration (EIA)," accessed January 7, 2025, https://www.eia.gov/electricity/monthly/index.php.

[2] "World Energy Outlook 2014," 2014.

[3] This data used in stock model was provided by ABB for internal use and is not publicly available.

values in the Kilo Volt-Amperes (kVA) rating for each category were obtained from the ratio of capacity and number of units in installation.

To fill gaps for countries not included in ABB's sales dataset, CLASP uses data from the 58 countries covered by ABB and applies adjustments based on factors such as the countries' geographic location, language, and economic development level. For countries with missing data, these adjustments help to estimate the new and total DT installations. The model computes national-level projections by comparing ABB's sales data with electricity consumption in each country. For back-casting to 1950, a 5-year average growth rate (2008–2012) was used, while for forecasting to 2040, a 5-year average growth rate (2014–2018) was applied. These projections were calculated separately for each country and for each of the three DT categories.

The model then calculates an average kVA rating for three product types for each country and calculates the energy consumption of the transformer based on an assumed loading and efficiency scenarios. The model assumes 50% of loading failure on all types of transformers in the model.

Annual capacity of new and total DT installations in MVA is used as the basis to estimate savings from efficiency improvements. The assigned lifetime assumptions for the turnover calculation are provided in Table 1.

TABLE 1. DT LIFETIME & AVERAGE LOAD ASSUMPTIONS

		LIFETIME		
	Stock failure/ year	3P-Oil	3P-Dry	1P-Oil
Country 1 (Non-Industrial)	10% per year	25	20	20
Country 2 (Normal)	7.5% per year	30	25	25
Country 3 (Industrialized)	5% per year	35	30	30
		AVERAGE LOADING ASSUMPTION		
		3P-Oil	3P-Dry	1P-Oil
Country 1 (Non-Industrial)		0.45	0.60	0.30
Country 2 (Normal)		0.40	0.55	0.25
Country 3 (Industrialized)		0.35	0.50	0.20

To assign survival probability over the defined lifetime, CLASP utilizes the S-shape (sigmoid) function with "Shape" index of 0.11.

$$S - shape\ distribution\ function$$

$$= 1 - \frac{1}{1 + e^{-Shape \times (Age - Lifetime)}}$$

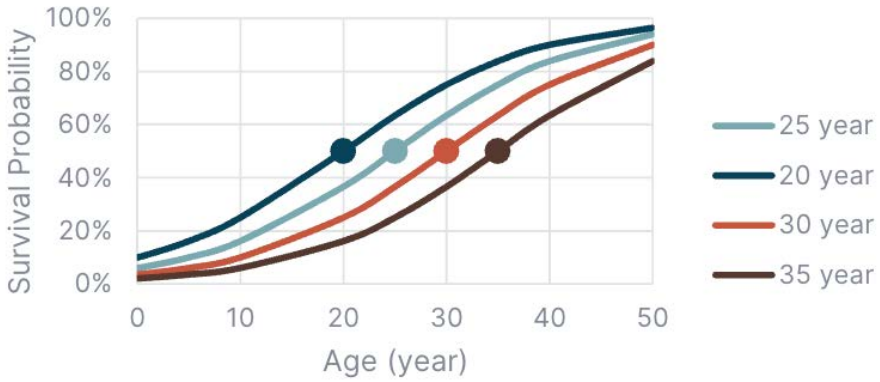
Where:

$Shape$ is the parameter controls the steepness of the curve. It defines how quickly the survival probability decreases as the equipment ages past its expected lifetime;

Age refers to the actual age of the transformer or equipment. It is the number of years that have passed since the equipment was installed or put into service;

$Lifetime$ refers to the expected service life of the transformer, or the point at which the probability of retirement reaches 50%.

FIGURE 1. SURVIVAL PROBABILITY OVER TIME FOR FOUR TRANSFORMER TYPES WITH DIFFERENT AVERAGE SERVICE YEARS



3. Unit Energy Consumption, Usage, and Standards Scenarios

CLASP refers to the IEC defined Efficiency Index at 50% Load at 50 Hz (EIA50 in %) to estimate the energy losses attributed to the DT installations. The index was developed through the Super-Efficient Equipment and Deployment (SEAD) Standards & Labelling Working Group Distribution Transformers Collaboration which represents higher efficiency levels with higher tier numbers.[4] The SEAD Tier curves were normalized from mandatory efficiency standards of DTs enforced in a number of major economies—Australia, Brazil, Canada, China, Europe, India, Israel, Japan, Korea, Mexico, New Zealand, and the United States.[5] The average efficiency level of countries with no efficiency policy present is represented as "Non-evaluation" in Figure 2, Figure 3, Figure

[4] "19-Distribution-Transformers-Internationally-Comparable-Test-Methods-and-Efficiency-Class-Definitions-Part-3-Energy-Efficiency-Class-Definitions.Pdf," accessed December 11, 2024, https://www.cleanenergyministerial.org/content/uploads/2022/05/19-distribution-transformers-internationally-comparable-test-methods-and-efficiency-class-definitions-part-3-energy-efficiency-class-definitions.pdf.

[5] U4E. Model Regulation Guidelines for Energy Performance Requirements for Distribution Transformers. https://united4efficiency.org/resources/model-regulation-guidelines-for-energy-performance-requirements-for-distribution-transformers/

4. Table 2 shos the relevant formula and the constants assigned to the SEAD Tiers, along with the best fit indices for the U4E Levels.

TABLE 2. SUMMARY OF DT EFFICIENCY METRIC ASSUMPTIONS

SEAD Tier	$SEAD\ Tier\ X = 1 - \frac{A}{Capacity\ in\ kVA^B}$					
Non-evaluation (Non_eval)	$Non - evaluation = SEAD\ Tier\ 1\ -\ \left(2.5 \times (SEAD\ Tier\ 2 - SEAD\ Tier\ 1)\right)$					
	3P-Oil		3P-Dry		1P-Oil	
SEAD Tier X	A	B	A	B	A	B
SEAD Tier 1	0.037	0.22	0.0628	0.26	0.0355	0.22
SEAD Tier 2	0.0311	0.22	0.0514	0.26	0.0295	0.22
SEAD Tier 3	0.027	0.22	0.0425	0.26	0.0254	0.22
SEAD Tier 4	0.0226	0.22	0.0355	0.26	0.021	0.22
SEAD Tier 5	0.0193	0.22	0.0292	0.26	0.0169	0.22
U4E-Level 1	0.036	0.24	0.0425	0.26	0.036	0.24
U4E-Level 2	0.018	0.172	0.0292	0.26	0.018	0.172

FIGURE 1. EFFICIENCY LEVELS FOR THE THREE-PHASE LIQUID-IMMERSED DTS

FIGURE 2. EFFICIENCY LEVELS FOR THE THREE-PHASE DRY-TYPE DTS

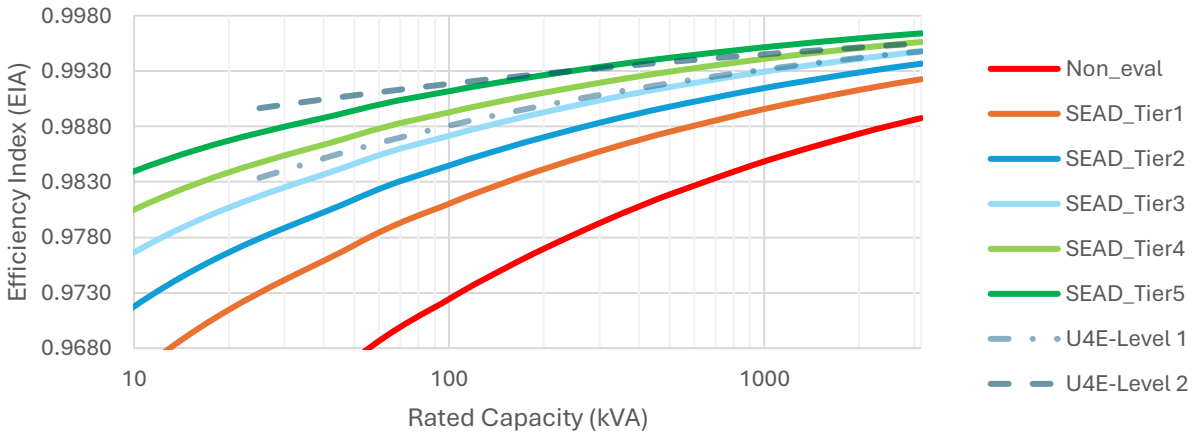
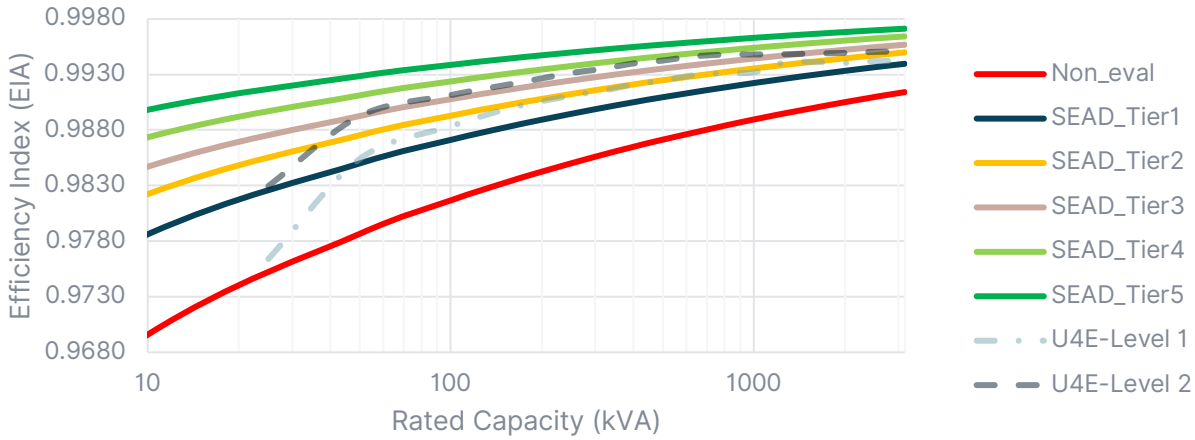


FIGURE 4. EFFICIENCY LEVELS FOR THE SINGLE-PHASED LIQUID-IMMERSED DTS



Unit Energy Consumption (UEC) is defined as the amount of energy losses attributed to each year's DT installations. The values in kWh/kVA are calculated for the Non-evaluation and the SEAD tiers for each category's representative average rated capacity in kVA of each country. The formula is defined as follows:

$$UEC = \frac{Load\ Losses + No\ Load\ Losses}{Average\ Capacity}$$

$$Load\ Losses = 2 \times (Average\ Capacity \times 0.5 \times (1 - EIA50) \times Operating\ Hours) \times RMSload^2 \times Substation\ Ratio$$

$$No\ Load\ UEC = 0.5 \times (Average\ Capacity \times 0.5 \times (1 - EIA50) \times Operating\ Hours)$$

With,

UEC (kWh/kVA), load and no-load losses of per kVA of DT installed Load Losses (kWh), dynamic losses from operation, dependent on operating condition

No Load Losses (kWh), continuous losses from core losses, roughly constant for the lifetime of the unit

Average Capacity (kVA), the representative rated capacity of DTs per category for each country

RMSload (%), Root Mean Square load, as defined per category for each country

Operating Hours at 8760 hours, 365 days per year, 24 hours per day

Substation Ratio at 1.3, set ratio of DT count per substation

EIA50 (%), the efficiency index percentage at 50% load, 50 Hz as defined for Non-evaluation and the SEAD Tiers.

The following scenarios and assumptions were applied to quantify potential country-level savings from DT installations:

- **Business-as-usual**: represents the baseline of the current trajectory without intervention. Efficiency level of **non-evaluation** is assigned for countries where no requirement has been established, while countries with mandatory regulation were assigned with **SEAD Tier 2 or the specific EIA50 value enforced as MEPS** at the respective policy effective year. Representative average rated capacity values in kVA are defined per category for each country.
- **Efficiency Policy (MEPS)**: represents the introduction of mandatory efficiency requirements at levels equivalent to **U4E Level 1**.
- **Best Available Technology (BAT)**: represents the introduction of mandatory efficiency requirements at levels equivalent to the highest efficiency rating, **U4E Level 2**. The SEAD Tier levels were developed through SEAD Standards & Labelling Working Group, and the U4E Levels are defined in the published regulation for distribution transformers.[6,7]

Other assumptions applied across all three scenarios:

- **Usage**: continuous, 8760 hours per year—365 days per year, 24 hours per day
- **Average Lifetime**: 20-35 years, assigned based on category and country grouping (based on industrial activity—less industrialized, normal, and industrialized)

4. Model Outputs and Validation

GLOBAL LOSS

Figure 5 presents a comparison of the global total losses in distribution transformers from Mepsy with two other references: (1) the global distribution losses as calculated from the U.S. Energy Information Administration (EIA) report,[1] and (2) the results derived from the 2019 study by Kristina Sadovskaia et al.[8]

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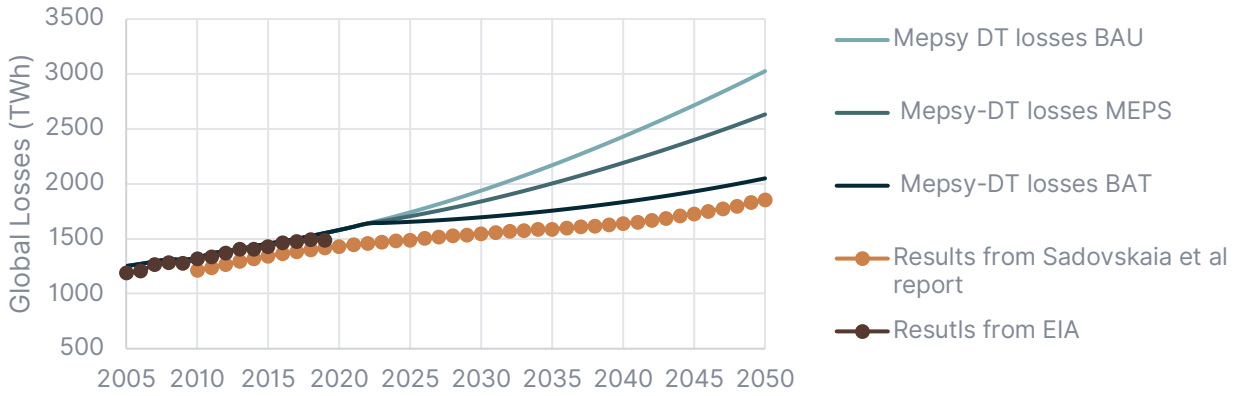
[6] "19-Distribution-Transformers-Internationally-Comparable-Test-Methods-and-Efficiency-Class-Definitions-Part-3-Energy-Efficiency-Class-Definitions.Pdf."

[7] "Transformers-Policy-Brief.Pdf," accessed January 7, 2025, https://united4efficiency.org/wp-content/uploads/2017/11/Transformers-Policy-Brief.pdf.

[8] Kristina Sadovskaia et al., "Power Transmission and Distribution Losses – A Model Based on Available Empirical Data and Future Trends for All Countries Globally," *International Journal of Electrical Power & Energy Systems* 107 (May 2019): 98–109, https://doi.org/10.1016/j.ijepes.2018.11.012.

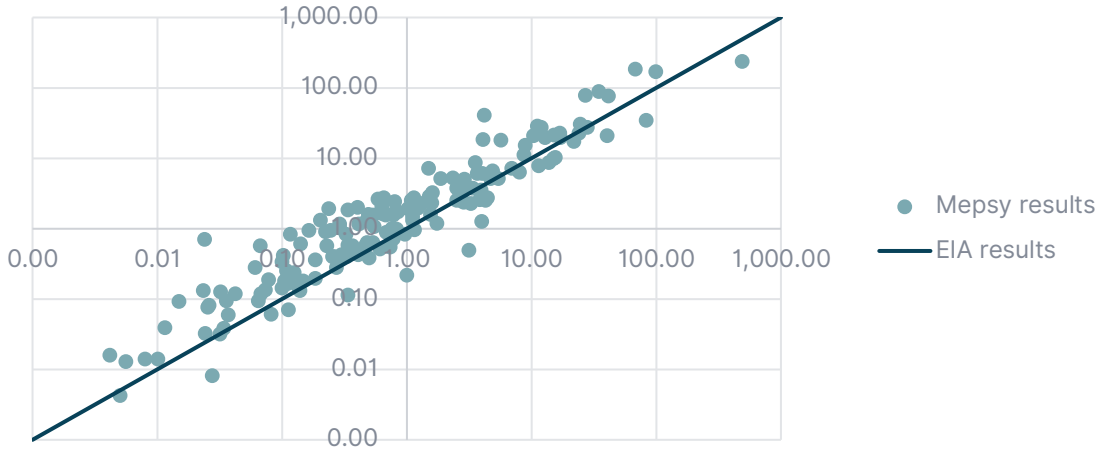
FIGURE 5. COMPARISON OF DISTRIBUTION TRANSFORMER LOSSES (TWH) BETWEEN MEPSY OUTPUT AND T&D LOSS ESTIMATES CALCULATED FROM EIA AND SADOVSKAI'S REPORT



COUNTRY DISTRIBUTION

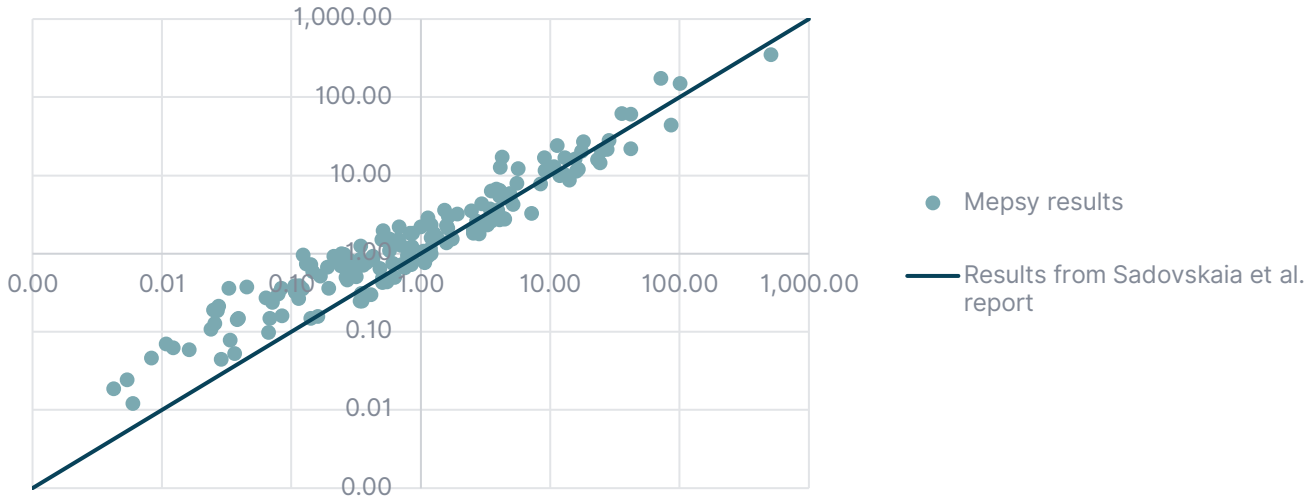
Figure 6 and Figure 7 show individual country results comparisons between Mepsy's output for distribution transformer losses in TWh and the estimated loss value from two references: (1) EIA's international T&D losses[9] (2) results from Kristina Sadovskaia et al. in their 2019 study[8]. Based on these two charts, it is evident that while some countries have values above the line—indicating higher values than the ones from reference—most countries are closely aligned with the reference data.

FIGURE 6. 2019 RESULT COMPARISON OF DISTRIBUTION TRANSFORMER LOSSES (TWH) BETWEEN MEPSY OUTPUT AND T&D LOSS ESTIMATES CALCULATED FROM EIA VALUES (2014 IEA PROJECTION)



[9] US Energy Information Administration (EIA), "International", Data for Electricity Consumption and Distribution losses, 2018 data or earlier. https://www.eia.gov/tools/faqs/faq.php?id=105&t=3

FIGURE 7. 2020 RESULT COMPARISON OF DISTRIBUTION TRANSFORMER LOSSES (TWH) BETWEEN MEPSY AND SADOVSKAI'S REPORT



Glossary

ABB: A multinational company providing power and automation technologies, which shares sales data for distribution transformers (DT) for use in the stock model.

Average Capacity: The representative rated capacity of Distribution Transformers (DTs) per category for each country, measured in Kilo Volt-Amperes (kVA).

Business-as-usual: A scenario representing the baseline, where the current trajectory of DT installations and energy consumption is maintained without any intervention or policy changes.

Capacity: The power rating of a transformer, typically measured in kVA

Distribution Transformer (DT): A type of transformer that steps down voltage for distribution to end-users in electrical grids.

Efficiency Index (EIA50): The energy efficiency rating at 50% load and 50 Hz frequency, as defined by the International Electrotechnical Commission (IEC).

Energy Information Administration (EIA): A U.S. government agency that provides energy data, including national electricity consumption statistics.

Energy Losses: The loss of energy that occurs due to the inefficiencies in the operation of distribution transformers, calculated in terms of load losses and no-load losses.

Global Loss: Total energy losses from distribution transformers at a global level.

IEC (International Electrotechnical Commission): A global organization that sets international standards for electrical, electronic, and related technologies.

Lifetime (Years to 50% failure): The expected operational lifespan of a transformer until it reaches 50% failure, with varying values depending on the country and transformer type.

Load Losses: Dynamic losses that occur from the operation of transformers, dependent on the loading conditions and operating hours.

Non-evaluation Country: A category for countries without any mandatory efficiency policies for distribution transformers, where default energy efficiency levels are used.

Operating Hours: The annual hours that a transformer operates, set at 8760 hours (365 days per year, 24 hours per day).

Root Mean Square (RMS) Load: a measure of the average load applied to a transformer, expressed as a percentage of the transformer's capacity.

S-Shape Distribution Function: A function used to calculate the survival probability of transformers over their lifespan, utilizing a sigmoid curve.

Shipments and Stock: The data on the installation and existing stock of distribution transformers, including annual sales and installed units.

Stock Accounting Model: A model used to estimate the number and capacity of transformers installed over time, based on historical sales data and projected future consumption.

Substation Ratio: A set ratio that defines the number of distribution transformers per substation, used in calculating energy consumption and losses.

T&D Losses: Transmission and distribution losses, including the losses caused by inefficiencies in the transmission and distribution of electricity.

Unit Energy Consumption (UEC): A measure of the energy losses attributed to each year's distribution transformer installations, calculated using the load losses and no-load losses.

U4E-Level: A classification for efficiency levels based on the United for Efficiency (U4E) program, used to define the best available technology for distribution transformers.

World Energy Outlook (WEO): A report by the International Energy Agency (IEA) that provides projections for global energy consumption and trends.

SEAD Tier: A classification of energy efficiency levels developed by the Super-Efficient Equipment and Deployment (SEAD) Standards & Labelling Working Group for distribution transformers.

Shape Index: A parameter used in the S-shape distribution function, with a typical value of 0.11, to define the probability of transformer failure over time.

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