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Distribution Transformer Demand: Understanding Demand Segmentation, Drivers, and Management Through 2050

The National Renewable Energy Laboratory (NREL) has been working closely with the U.S. Department of Energy's Office of Electricity (OE) to understand the critical drivers and potential means of managing distribution transformer demand through 2050. Throughout this effort, the project team has consulted with utility representative organizations and transformer manufacturers to understand the problem, characterized the in-service units, and modeled future demand. Distribution transformers (service transformers) range from 10 to 5,000 kilovolt-amperes (kVA), have a high-side voltage of less than 34.5 kilovolts, and step-down power delivery for customer end use [1]. This report provides new research highlights, including estimates of the age of the in-service units and segmentation analysis of demand for different types of distribution transformers. This research will help the manufacturing sector understand production capacity needed and better inform utility strategies for managing their demand.

In-Service Transformer Models and Demand Estimates

NREL has established granular models for in-service distribution transformers and annual demand requirements. NREL estimates the number of in-service units as approximately 60–80 million transformers, with between 2.5 and 3.5 teravolt-amperes (TVA) of combined capacity [2]. Table 1 shows the distribution of transformer types (i.e., three-phase and single-phase, pad- and pole-mount) and sizes [3]. NREL estimates most assets (~80% of number of assets) are between 10 and 50 kVA, whereas most of the capacity (~76% of installed capacity) is between 50 and 5,000 kVA. From estimates, the majority of the number of

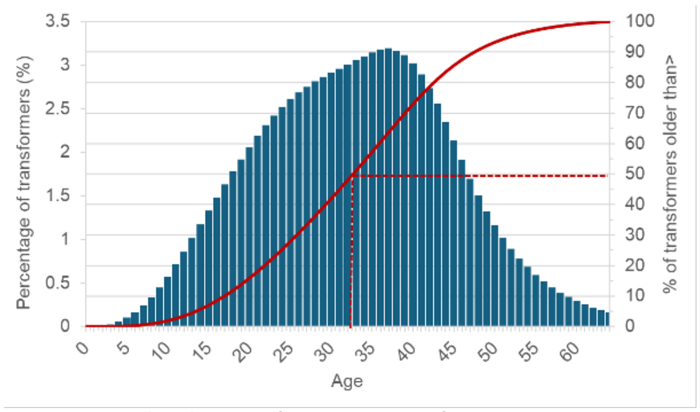

Figure 1. Age distribution of in-service transformers

> NREL estimates 60–80 million distribution transformers, with between 2.5 and 3.5 TVA of capacity, and that ~55% of in-service units are more than 33 years old and approaching end of life.

transformer assets are pole-mount (~76%), whereas pad-mount transformers account for the majority of capacity ~65%. This is a result of many small-scale single-phase transformers (10–100 kVA), compared to relatively fewer but larger-capacity three-phase pad-mount transformers (100–250 kVA). A conservative estimate, based on the modeling workflow established in [2], is that ~50% of the in-service units are older than 33 years and approaching end of life, as shown in Figure 1. This estimate uses the U.S. building stock as a proxy for initial deployment of electric infrastructure and uses transformer failure functions to forward-simulate the expected age profile of the current stock [4], [5], [6].

Table 1. Percentage Distribution in Number of Transformers and Capacity by Unit and Phase Type [3]

Transformer Type			% Number of Assets	% of Capacity
Single-Phase	Pole	10–100 kVA	72.1	27.6
		>100–250 kVA	0.6	1.3
		>250–1000 kVA	0.1	0.6
	Pad	10–100 kVA	19.5	13.6
		>100–250 kVA	0.8	1.6
		>250–1000 kVA	0.0	0.1
Three-Phase	Pole	30–100 kVA	0.1	0.1
		100–250 kVA	0.1	0.2
	Pad	30–100 kVA	0.7	0.6
		100–250 kVA	1.6	3.2
		250–1000 kVA	3.2	21.5
		1,000–5,000 kVA	1.1	27.7
	Other	>500 kVA	0.1	1.7

Assessing the loading of the stock remains challenging and is a focus of future work, with one member organization representing rural electric cooperatives reporting average loading of 80% for distribution transformers and other utilities reporting the mode of their peak loading for distribution transformers of between 45% and 55% [7], [8].

Annual addition and replacement rates are estimated to be between 2.5% and 3% of in-service units (i.e., 1.5–2.4 million units a year, or between 62.5 and 105 gigawatts (GW) of demand annually); that is, depending on growth rates, most of the stock will have been new additions or entirely replaced by 2050 [6], [9]. With expected load growth from electrification of buildings and transportation, utility strategies for ongoing replacement (e.g., like-for-like or active upsizing) will impact future demand needs.

Aging Assets and Load Growth Impact

We expect both aging assets and increases in loading to accelerate asset failure rates, particularly after 2030. This is primarily because of a combination of in-service assets reaching end of life, accelerated growth rates and corresponding increased thermal loading impacts from electrification. NREL has developed thermal models to assess load growth impacts on thermal aging based on established industry standards [10], [11]. We also expect the growth rate in annual required transformer capacity will outpace the growth rate in the number of transformers required as average transformer sizes increase. For replacement because of load growth, utilities are more likely to upsize smaller transformers and reserve load splitting (i.e., splitting existing transformer load across two assets) for larger transformers (e.g., >75 kVA) [12]. An important focus for future work is the potential decrease in transformer core temperature that distributed solar photovoltaics, installed on the low-voltage side of distribution transformers, can achieve. This can reduce peak and midday net load, impacting net demand and demand management [13].

Large growth areas for demand include step-up transformers, electrification of transportation, and data center demand. A potential of ~2 terawatts (TW) of step-up transformers for wind and solar, which share many similar characteristics to distribution transformers, is needed by 2050 [14]. The alternating current (AC) capacity of electric vehicle (EV) service equipment (i.e., charge port capacity that plug into EVs) is expected to reach up to 1.2 TW by 2050, with most of the port capacity that will be added on existing residential service transformers for behind-the-meter charging [15].

An increasing number of extreme weather events and resulting resilience investments are expected to heighten demand for pad-mount relative to pole-mount transformers over time, including higher demand for more resilient transformer design for more specific applications such as submersible and dry-type transformers [2].

> Modeling suggests annual capacity requirements will far outpace increases in the number of units required each year; that is, the average transformer size is set to increase.

Breakdown of Transformer In-Service Units and Demand Trends

Shown in Table 1 is our examination of the breakdown of transformer in-service units, estimated on shipment data. We estimate the majority of the number of transformer assets are single-phase (~93%), whereas more than ~53% of the capacity of transformer assets are three-phase. Several trends are driving demand for different transformer assets:

- The average size of single-phase transformers is set to increase with many utilities now offering 25 kVA as their minimum size [16], [17]. Single-phase pole-mount transformers dominate annual demand for units of transformers, and although that is expected to continue, pad-mount transformer demand is expected to increase because of 1) utilities increasingly building new secondary service as underground and 2) utilities proactively undergrounding primary and secondary distribution for resilience and aesthetics. Single-phase transformers are highly unlikely to migrate to three-phase because of the nature of split-phase service in the United States, except for highly urban centers that use three-phase distribution (e.g., highly urban areas and apartment blocks). Current NREL scenario analysis sees the average residential transformer size increasing by more than 150% and 120% for the residential and commercial sector by 2050, respectively.
- The average size of three-phase transformers is also likely to increase and will see new demand from dedicated

Table 2. Drivers of Different Distribution Transformer Types

Drivers of Specific Transformer Growth		
Single-Phase	Pole	Single-phase represents more than ~73% of the current number of installed transformers and ~30% of the capacity and primarily constitutes service transformers for residential and commercial customers. Pole-mount transformers can expect growth from electrification, new customers, increased failures from aging infrastructure, accelerated thermal aging from increased loading, and extreme weather event failures. We expect the average size of transformers to increase because of electrification growth and the replacement rate to accelerate from increased thermal aging.
Single-Phase	Pad	Single-phase pad-mount transformers represent ~20% of the current number of installed transformers and ~15% of capacity and constitute service transformers for both residential and industrial customers. From NREL and Office of Electricity discussions, utilities are typically developing new service requests with underground electrical infrastructure and pad-mount transformers—a function of planning practices and state and local regulation for new construction [20]. That combined with utility resilience programs will see an increase in pad-mount transformer sales relative to pole-mount.
Three-Phase	Pole	Three-phase pole-mount transformers are an uncommon type of transformer, principally because of weight restrictions of placing typically larger three-phase transformers on electric poles.
Three-Phase	Pad	Three-phase pad-mount transformers will see growth from renewable step-up transformers, EV charging stations, and data center load. Although small Level-1 and Level-2 EV charging stations may use single-phase transformers, larger charging stations with multiple Level-2, high-capacity Level-2, or direct current (DC) fast-charging will typically use three-phase transformers. An estimated up to 477 GW of AC EV charging station port capacity will be required by 2050, for which number of ports per charging station, diversity factors, and transformer sizing will be required to translate into equivalent transformer required capacity [21]. Three-phase pad-mount step-up transformers—i.e., those used for solar, wind, and battery arrays, which have similar characteristics to distribution transformers—could see close to 2 TW of additional demand by 2050. NREL's 2023 Standard Scenario representing 'Mid-Case, Current Policies' which represents the central scenario, sees the addition of more than 1.7 TW of generation capacity that would require step-up transformers [14]. Dry-type three-phase transformers will see demand from data centers, with recent studies producing growth scenarios for 3.71%–15%, on an estimated 150–200 TWh of annual demand. With uncertainty in growth rates, and based on annual energy consumption, this could result in annual power delivery transformer capacity demand between 1–6.5 GW in 2024, increasing to 1.3–15 GW by 2030. Cumulatively, data center demand may add between 12.6 and 72 GW of transformer capacity (for power delivery units) from now until 2030. This is separate from the oil-immersed three-phase transformers for data centers to step-down from utility supply to commercial service [19], [22].

EV charging stations (e.g., public and private charging stations) and from data center demand where three-phase commercial service is used to supply data center servers. For data centers, demand is highly regional, with demand centers in California, Texas, and Virginia (e.g., PJM is forecasting almost 25 GW of demand by 2030) [18]. From International Energy Agency (IEA) forecasts, data center demand is expected to grow from 200 TWh in 2022 to more than 260 TWh by 2026 [19], which, estimating a load factor of 80%, would represent an increase in transformer demand (for both site-level and service-level, i.e., two stages of transformer step-down) from 57 GW in 2022 to 74 GW in 2026 of installed of dedicated transformer capacity. Approximately half of that demand would be stepping down distribution primary voltages to data center commercial distribution voltage and then stepping down to distribution service voltages (likely three-phase dry-type transformers for directly feeding server load). A study by EPRI estimates lower data center total energy consumption demand than that estimated by IEA, at 152 TWh for 2023, and the study produces compounded annual growth rate scenarios for data center demand increasing between 3.71 and 15% out to 2030. For transportation demand, NREL estimates up to 477 GW of AC EV charging station port capacity will require dedicated transformers by 2050 (i.e., public and private charging stations, not behind-the-meter demand); the required transformer capacity will be lower than this value if charging stations can take advantage of diversity in charging patterns when sizing transformers [21]. The majority of these charging stations would require three-phase transformers.

Projected Transformer Capacity Demand by 2050

Overall, NREL expects the in-service distribution transformer capacity requirement in 2050 to be between 160% and 260% of 2021 levels, with annual transformer capacity demand (not number of units) increasing between 140% and more than 250% depending on the scenario. Overall, demand drivers will heterogeneously impact demand for different types of assets, e.g., for single-phase vs. three-phase transformers (see Table 2).

- Demand is highly regional, with electrification seeing the largest relative increase in demand in regions where electric heat is transitioning from fossil-fired space and water heating to electric heat pumps. For example, states in the Northeast, which currently have some of the lowest per customer annual electricity consumption in the United States, are set to have the highest relative increase in demand from electrification and subsequently are likely to see strong requirements for upsizing of residential and commercial service transformers.

NREL analysis shows required in-service transformer capacity in 2050 will be between 160% and 260% of 2021 levels, with annual transformer capacity demand increasing between 140% to more than 250% depending on the scenario. NREL is refining scenarios with input from utilities and industry to bring more certainty. Utility planning practices—i.e., like-for-like replacement vs. proactive upsizing—are expected to have major impacts on national demand.

Collaboration with Industry Partners

NREL has collaborated with utility and industry partners to further the understanding of future transformer demand. NREL will continue to establish transformer demand scenarios, focusing on utility planning scenarios and demand management. Challenges remain regarding the diversity of production requirements requested of manufacturers; that is, production is constrained by customization requirements (based on diversity of requests around asset sizes, voltage levels, weight requirements, insulation, mounting, and so on). Although large power transformer manufacturing is primarily imported, the majority of distribution transformer manufacturing is domestic—with the remainder imported from Canada and Mexico [23]. In future work, NREL will further engage utilities and manufacturers to refine data inputs and scenarios and establish planning practices that can help manage future demand and provide more certainty for the industry.

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