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Major Drivers of Long-Term Distribution Transformer Demand

Context

Distribution transformers, used to step-down medium-level voltage to service-level voltage for end-use electrical consumption, are currently experiencing an unprecedented imbalance between supply and demand. Utilities are experiencing extended lead times for transformers of up to 2 years (a fourfold increase on pre-2022 lead times), and reporting price increases by as much as 4–9 times in the past 3 years [1-3]. Current shortages have been attributed to pent-up post-pandemic demand; difficulty recruiting, training, and retaining a skilled workforce; component supply chain challenges; and materials shortages (grain-oriented electrical steel, aluminum, and copper). The supply of transformers is critical for the reliability and growth of the power system. Additionally, supply chain issues, if not resolved, may also impact climate goals with respect to the electrification of demand and the growth of renewable energy. This report summarizes the initial analysis conducted by the National Renewable Energy Laboratory (NREL), supported by the U.S. Department of Energy's (DOE) Office of Electricity and Office of Policy, to assess the long-term drivers of demand for distribution transformers.[1] Expected demand increases are due not only to a confluence of electrification and renewable energy growth, but also to aging electric infrastructure, increased frequency and severity of extreme weather events, and utility-driven investments to improve the reliability and resiliency of the electricity distribution system.

Introduction

The majority of distribution transformers are owned by the more than 3,000 municipal, cooperative, and investor-owned utilities across the United States. Some transformer capacity is privately owned by large commercial and industrial customers (approximately 20% of the total number of transformers, according to historical estimates [4]) and is used for on-site electrical distribution. The Code of Federal Regulations defines distribution transformers as those that have an input voltage of 34.5 kV or less, an output voltage of 600 V or less, and a capacity of 10–2,500 kVA [5]. For consideration here, we examine transformers up to 5,000 kVA, given the trend of increasing capacities due to electrification and revised definitions in proposed rules [6]. We also loosely interpret input and output voltages, given the trend of bidirectional power flow due to distributed energy resources (in particular, solar photovoltaics). In our analysis we consider step-up transformers, used for renewable energy resources and most battery energy storage applications, because these transformers share many of the same properties, supply

[1] DOE is committed to working with the power sector, manufacturers, and appropriate federal partners to identify actions that can help ease the supply-demand mismatch in distribution transformers. This had included using the convening power of the U.S. Government to help identify solutions in the public and private sector that can create a more reliable supply chain for distribution transformers to meet current needs and the expected demand in the future. The distribution transformer demand study is the one of the recommendations that resulted from this collaborative discussion.

chains, and manufacturers as distribution transformers. The insights from this report are a result of initial NREL analysis and extensive interviews with major U.S. transformer manufacturers and utility representative organizations—Edison Electric Institute, American Public Power Association, the National Rural Electric Cooperative Association—and their members.

Current Characteristics of Stock

An accurate understanding of the current stock of distribution transformers is critical to understanding drivers of future demand. This involves understanding the quantity of transformers currently deployed, the capacity of these assets, asset aging, and loading profiles. There is a lack of quantitative data on the number and capacity of distribution transformer stock currently deployed in the country. Data collection is challenging because it involves understanding the assets of more than 3,000 distribution utilities and privately owned transformers. Reports from the last major study of national inventory in 1994 estimated the stock at more than 50 million transformers (for both utility and privately owned transformers) with more than 2.3 TW of utility-owned installed capacity [4]. Initial NREL estimates for current stock range from 60 to 80 million transformers with upwards of 3 TW of installed capacity. The high-level analysis in this report includes a number of assumptions about the volume and capacity of the existing stock by leveraging U.S. Energy Information Administration Form 861 datasets, Federal Energy Regulatory Commission Form 1 data, and specific data from individual utilities [7], [8]. We anticipate further analysis will revise the number and capacity of the current stock.

A key aspect of assessing the current stock is the age of the assets. There is a broad consensus among utility engineers that the majority of the transformer stock is reaching the end of designed life. However, little data are available on actual transformer age. The age of the current stock is estimated from building stock age (from both the Residential Energy Consumption Survey and Commercial Building Energy Consumption Survey) [9], [10]. The 1990s and early 2000s saw major building growth in the United States, but there has been relatively less construction since the economic downturn of the late 2000s, likely resulting in less stock that is younger than 10–15 years old. However, individual utility stock is highly heterogeneous. Whereas some utilities will have older stock (e.g., DTE Energy in Detroit estimate the average age of their substation transformers at 41 years, with a typical life expectancy of 40–45 years), major investments in storm recovery have led to other utilities having a relatively modern fleet (e.g., ConEdison in New York City lost more than 900 distribution transformers in Hurricane Sandy in 2012 and have invested $1 billion in grid resilience since the disaster [11]). A recent estimate by a utility in Massachusetts estimated that 35% of their stock was more than 30 years old [12]. Transformers are expected to last more than 20 years at nameplate loading [13], but in practice, transformers with low loading conditions and mild temperatures can last for more than 50 years [14].

The loading capability of transformers is another critical element in understanding how much load growth these assets can accommodate. Transformer rating is dynamic and a function of their thermal loading (temperature), which is a function of the current flow through them, the duration of high current flow, ambient temperatures, and solar insolation gain. The transformers loaded at nameplate capacity are said to be loaded at 100%, but these assets can facilitate loading of up to 200% for brief periods with little impact on life expectancy or insulation degradation [4]. The overloading (i.e., loading above 100%) that a transformer can absorb is a function of ambient temperature conditions, loading profile, and the duration and magnitude of the overload. Repeated and long-duration overloading (>125%–150%) will ultimately reduce the life of a transformer and raise the probability of the device failing.

Demand Drivers and Key Trends

Transformer demand is driven by several elements that can be broadly categorized as replacement of existing stock and demand growth. Replacement is driven by a range of mechanisms, including aging and overheating, short-circuiting, random failure mechanisms, and extreme weather events. Demand growth can result in the need for active replacement of deployed assets (i.e., due to loading increases) or new assets dedicated for new customers.

NREL is developing analysis capabilities to examine future transformer demand, which will be the subject of future analysis and reporting. We are examining multiple trends that will raise both the current rate of transformer stock replacement and new customer growth. We are building a demand model to examine how device failure, proactive replacement, and new growth will impact annual transformer stock growth. An overview of the model is provided in Figure 1, which was used for limited analysis in this report, and will be the focus of future work.

The current modeling effort is being expanded to provide refined non-coincident peak demand analysis, examine climate impacts and extreme weather events on transformers, and build out thermal life models. To date, the work has focused on characterizing the major drivers of transformer demands, for which preliminary findings are itemized below.

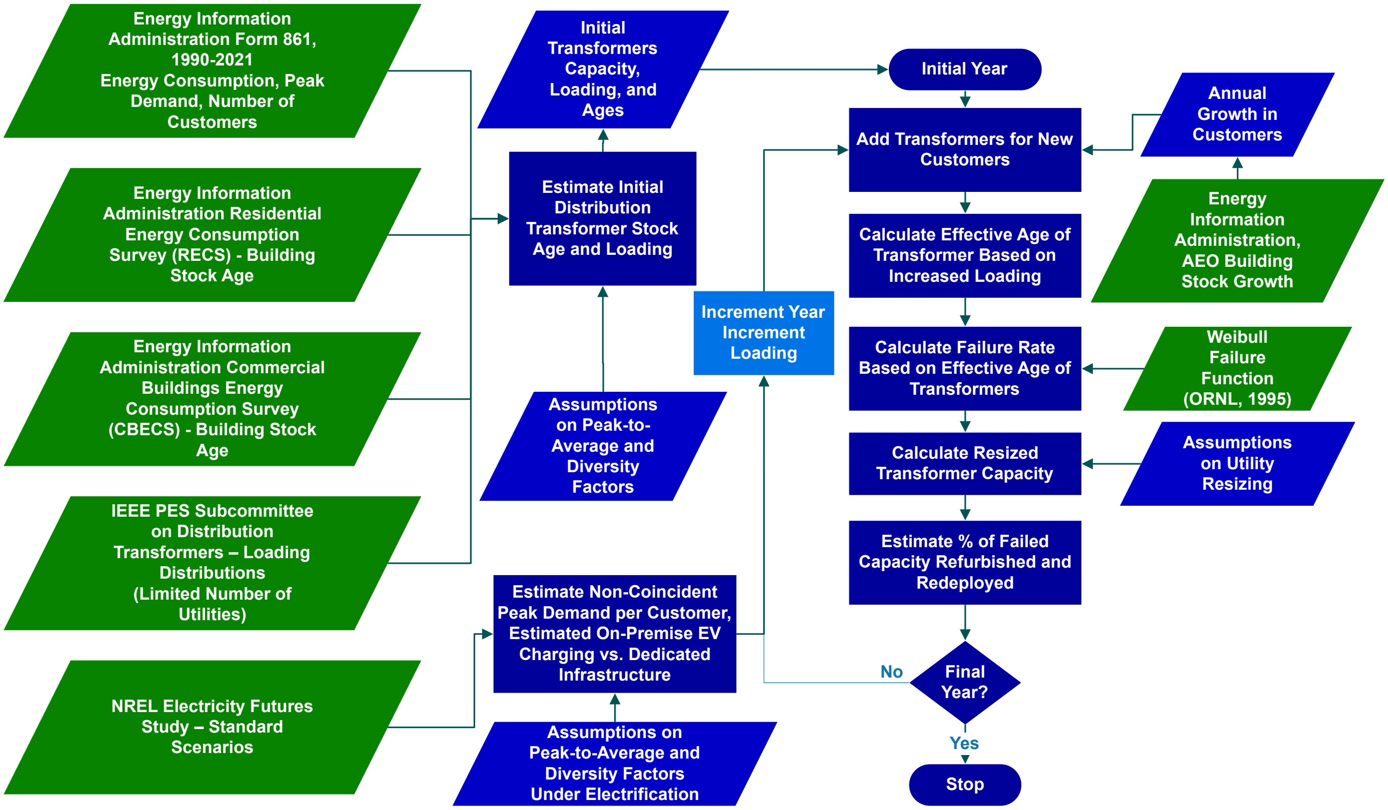

Figure 1: Overview of a preliminary transformer demand model developed at NREL. The model uses data from the U.S. Energy Information Administration [7]-[10], NREL's Standard Scenarios [15], Weibull failure functions [4], and IEEE Power and Energy Society Subcommittee on Distribution Transformer loading estimates [16] to examine annual transformer demand by state and by sector (e.g., residential, commercial, industrial, and transportation). The analysis is being refined to include transformer thermal life models, extreme weather impacts, refined demand analysis, and climate data to examine temperature impacts.

Increasing Capacity Needed for Electrification

- Our preliminary estimates for the overall capacity of distribution transformers that will be needed to serve economywide demand (i.e., residential, commercial, industrial, and transportation) indicate an expected 160%–260% increase compared to 2021 levels due to electrification (driven in part by the Inflation Reduction Act). These estimates are based on initial analysis of the potential non-coincident peak demand that would need to be served by distribution transformers, considering economywide electrification demand from the Electricity Futures Study Moderate electrification scenario [15]. More work will be required to refine these analyses to estimate demand based on diversity factors, weather-driven peak demand, and nameplate of electrification loads. Critical uncertainties include charging rates and management of EVSE in the future. Utility investment plans and state demand forecasts are also highly regional and heterogeneous. Large variations are evident in utility system peak load forecasts, even within the same state, for example the three major investor-owned utilities in Massachusetts with forecast 2050 peak demand increases of up to 230%, 193%, and over 400% [12], [17], [18]. Additional insights into demand drivers from electrification include:
  - Increased load due to electrification is a result of increased electric vehicles, heat pumps, and electric cooking, among other drivers. Demand growth for the residential sector across states is highly heterogenous; the largest increases in demand are expected in cold-climate states where both electric vehicle adoption and adoption of heat pumps will likely significantly drive demand.
  - Trends in growth due to commercial and industrial sectors warrant more examination. Utilities are realizing growth in data center loads, and an expected increase in U.S. manufacturing driven by domestic national security policies related to semiconductor (i.e., the CHIPS Act) and electric vehicle manufacturing will also drive privately owned transformer demand.
  - Recent NREL work analyzing the need for charging ports estimates 26.8 million privately accessible Level 1 and Level 2 charging points would be required at single-family homes, multifamily properties, and workplaces by 2030 [19]. Charging capacity depends on the installed capacity of Level 2 charging points

Demand for transformers for EV charging stations is set to increase. *Photo from Getty Images 1421282386*

(e.g., 6, 12, and 18 kW have been used), but considering sole adoption of 6-kW Level 2 chargers, an estimated 125 GW of charging port capacity is required. Much of this load will likely be connected to existing transformers and will require a combination of transformer replacement and the splitting of load across new transformer capacity. An estimated 182,000 publicly accessible fast-charging ports along highway corridors and in local communities will require dedicated transformers (estimated 45 GW of direct-current fast charging port capacity). Additionally, 1 million publicly accessible Level 2 charging ports (estimated 6 GW of charging port capacity) will likely require dedicated transformers.

- Transformers are designed to accommodate increased loading for limited periods. In some situations, this extra built-in capacity could absorb some of the increase due to electrification. In such cases, the transformers are expected to run until failure. However, using up this "extra capacity" due to loading from electrification is expected to increase the rate of transformer failure in these situations, particularly post-2030. Loading patterns will likely play a critical role in the life of transformer assets. For example, distributed solar photovoltaics could (at medium adoption levels) provide relief to transformers by reducing midday demand. In contrast, EV night charging will erode the thermal relief that these assets typically gain in lighter loading periods. Future work will quantify these benefits in more detail by using loading pattern analysis on thermal life models for transformers.

Routine Replacement and Aging Assets

- Utility routine transformer replacements, both due to failure and active resilience investments, will benefit from future-proofing asset sizing to accommodate electrification load growth and avoiding future overloads. From preliminary NREL analysis, by 2050, 60–80% of service transformers will have been replaced through routine replacement. If utilities upsize capacity rather than practice like-for-like replacement, routine replacement can be used to help gradually accommodate electrification. Proactive transformer load management programs can also be used to extend the life of existing assets by adding transformers (rather than outright replacement) and transferring/splitting load onto new assets to accommodate growth.

Accelerated growth in wind and solar generation will require a corresponding supply of step-up transformers. *Photos from Getty Images, top: 1406020186, bottom: 1284482079*

  - With increased focus on equity-driven programs, customers with historically smaller-amperage connections could see proactive programs to increase their service connection, which may drive proactive upsizing and increases in demand. (This concept of "minimum level of services" is currently being considered at several state utility commissions).

Load Metrics and Utility Programs

- We note a need to develop demand factors and diversity metrics that could be used to inform distribution planning decisions for transformer sizing along with surveying to reduce the uncertainty on the volume of capacity and the loading of existing assets. Electrification load metrics will help distribution planning engineers adequately size assets to avoid replacing them before end of life due to undersizing and to avoid creating unnecessary cost burden on rate-payers from the risk of heavily oversizing assets.
- Proactive utility customer engagement and programs can help utilities understand and manage the increased loading that will be caused due to electrification. Active utility engagement in customer EV charging programs can help manage demand, which can reduce the replacement rate and oversizing of future transformer capacity. Accurate load forecasting can assist in least-regret transformer sizing for load growth to ensure transformers are sized sufficiently for the lifetime of the asset and facilitate load growth from electrification.
- Transformer load management programs can enable utilities to produce more accurate forecasts and active assessments for transformer replacement, split loads onto new assets, and manage transformer maintenance and loading. Utilities can leverage advanced metering infrastructure and geographic information system asset databases to estimate the thermal loading of transformers.

Demand from Extreme Weather Events

- The increasing frequency and severity of extreme weather events and longer-term trends in climate are also expected to increase transformer demand. Historically, hurricanes, storms, wildfires, heat waves, blizzards, and high-wind events have caused significant damage to the transformer stock. In 2005, Hurricanes Katrina and Rita damaged 12,600 transformers in Entergy's Louisianna service territory alone, and Mississippi Power lost around 2,300 transformers [20]-[22]. The need for replacements caused by hurricanes, based on reporting from large utilities, we estimate was more than 1% of the annual transformers shipped [23]. While the demand resulting from these events can seem low in terms of overall transformer demand, it can represent a massive volume of infrastructure for an individual utility. For example, 65% of Mississippi Power's power delivery system was down or damaged after Hurricane Katrina. More recent major events have included Hurricane Laura in 2020 (Entergy identified 4,760 damaged transformers), Hurricane Ida in 2021 (nearly 6,000 transformers damaged in Entergy's service territory), and Hurricane Idalia in 2023 (Suwannee Valley Electric Cooperative in northern Florida identified 354 damaged transformers) [24]-[26]. There is an overall lack of data from non-hurricane events (e.g., lightning strikes, wildfires, winter storms, etc.), and lack of available data from smaller utilities, which challenges efforts to quantify the total volume of equipment damage from weather events.
- Extreme temperatures increase customer demand, which in turn raises the loading stress on transformers and reduces transformer operating efficiency and life expectancy. For instance, as unusually hot days are becoming more common in summer, the air-conditioning

demand is driven up. This prolonged heavy loading and high ambient temperature overheat transformers, increasing the risk of failures. In July 2006, a heat wave in California caused widespread outages due to transformer failures. In Northern California, 1,150 PG&E distribution transformers failed, and 860 transformers malfunctioned in LADWP's service territory [27].

While pole-mount transformers account for the most orders of transformers by numbers [23], pad-mount demand is expected to increase as utility investment in undergrounding and resilience programs increases. *Photos from Getty Images, top: 1388647482, bottom: 152264156*

Changing Requirements for Transformers

- Demand for smaller transformers (e.g., 10 or 15 kVA) is expected to decline as electrification increases load growth. For example, in interviews, 25 kVA has been implemented by some utilities as a new default minimum size rather than 10–15 kVA [29], [30].
- Pole-mount transformer demand is expected to decline relative to pad-mount transformers as utilities increase their undergrounding and resilience programs. Many utilities have extensive undergrounding programs for storm resilience, wildfire mitigation, and community aesthetic preferences; some have adopted the practice of undergrounding all new medium-to-high load density service. Estimates from 2012 developed by Edison Electric Institute estimated that roughly 18% of their members' distribution systems were underground [30]. There are pushes to move more of the network underground to improve grid reliability and resilience. PG&E has a major program that plans to invest in undergrounding 10,000 miles of their network (approximately 10% of their system) by 2026 [31].
  - For specific service territories where the risk of utility equipment starting wildfires is expected to increase, we expect increased demand for dry-type transformers as replacement for oil-filled pole-mount transformers [32]. For flood resiliency, demand will increase for submersible transformers, transformers with less corrosive steel, and corrosion-resistant paint.

Step-Up Transformers for Renewables

- Step-up transformers, required for wind and solar generation, share many of the same characteristics of distribution transformers in terms of voltage classes and capacity. These assets are required for both bulk-system connected generation as well as large distributed generation plants (e.g., multi-MW solar farms connected to the distribution primary system). Step-up transformers for interconnecting renewable plants will add significant orders to manufacturers; up to 2 TW of step-up transformer demand of sizes ranging from 0.5 to 5 MVA will be required by 2050.

Summary

An adequate and timely supply of distribution transformers is critical to preserving the reliability of the grid, satisfying utility customer new or enhanced service requests, meeting increased load, helping the nation electrify key load sectors, and providing enhanced resilience to combat the threats of increased extreme weather events. Manufacturers have little visibility on the underlying causes that drive orders from utilities; increased communication and information-sharing of utility plans for achieving electrification and enhanced resiliency will help manufacturers scale their operations appropriately to meet changing and increasing utility demand. This report has outlined the major factors that are expected to result in increasing demand of transformers: aging infrastructure, electrification and massive growth in electricity demand, increased failure due to extreme weather events, and proactive utility resilience replacement programs. NREL preliminary analysis estimates current stock of between 60-80 million distribution transformers with upwards of 3 TW of installed capacity, and estimates the growth in overall stock capacity by 2050 will see up to a 160%–260% increase on 2021 levels. The type of transformers utilities will require is expected to change; demand for larger transformer sizes is expected to increase due to electrification. Enhanced reliability and resilience will increase the demand for pad-mount, dry-type, and submersible transformers. Lastly, step-up transformer demand is expected to substantially grow due to large build-out of renewable power production capacity—this will put increased pressure on transformer manufacturing. Utilities have commented that recent manufacturing supply constraints have meant they are adjusting their orders to take what supply is available rather than what is ideally needed (e.g., in terms of size and type of transformers). Consequently, demand modeling (independent of supply-side constraints) is critical to understand future utility requirements. NREL will continue to work with the Office of Electricity and Office of Policy to refine this preliminary analysis to help the industry come to consensus on projected transformer demand, which will in turn help manufacturers make strategic investment decisions in the supply chain.

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