National Laboratory of the Rockies

U.S. Distribution Transformer Demand Phase III – Key Drivers and Managing Demand

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June 2026

Photo from Killian McKenna, NLR

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Context and Challenge

- Distribution transformer supply delays and escalating prices remain a major industry challenge
- NLR issued two reports, published in **February 2024**, and **November 2024**, widely picked up by trade journals and media outlets, thanks to **Office of Electricity** for funding this research
- NLR has been continuing work to further **refine and expand forecasts** and establish **how utility practices may impact demand**

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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 elec

[1] DOE is committed to working with the power sector, manufacturers, and appropriate federal partners to identify actions that can t transformers. This had included using the convening power of the U.S. Government to help identify solutions in the public and pri distribution transformers to meet current needs and the expected demand in the future. The distribution transformer demand stu collaborative discussion.

Photo from Getty Images: 1421775423

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.

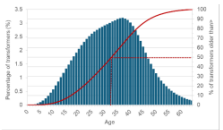


Figure 1. Age distribution of in-service transformers

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.

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 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].

Over **13k downloads**

Distribution Transformers

- Distribution transformers step-down voltage for electrical service and represent the last transformation of electrical power, defined as high-side voltage of <34.5 kV and rating of less than 5,000 kVA
- Almost every kWh of customer energy consumption goes through a distribution transformer, and there are an estimated 60-80 million of them in the U.S.

Note: Throughout this presentation, the term "transformer" refers to distribution step-down transformers. The demand for step-up transformers is also addressed in a separate analysis.

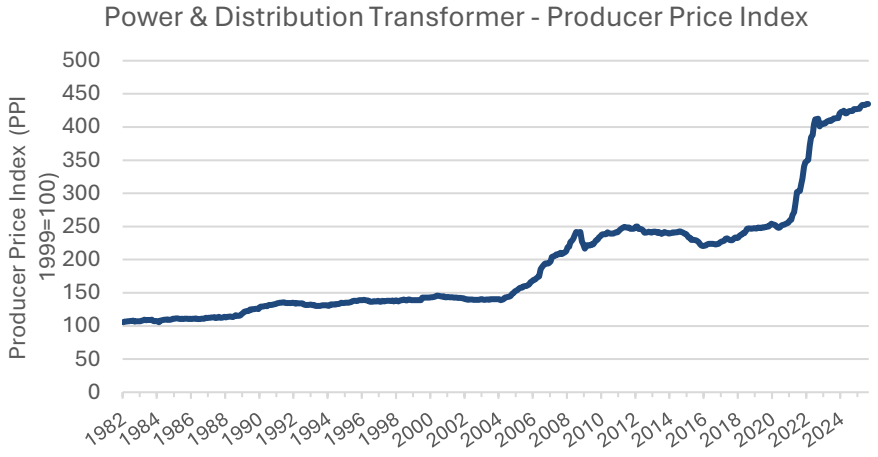
Split-phase pole-mount distribution transformer

Split-phase pad-mount distribution transformer

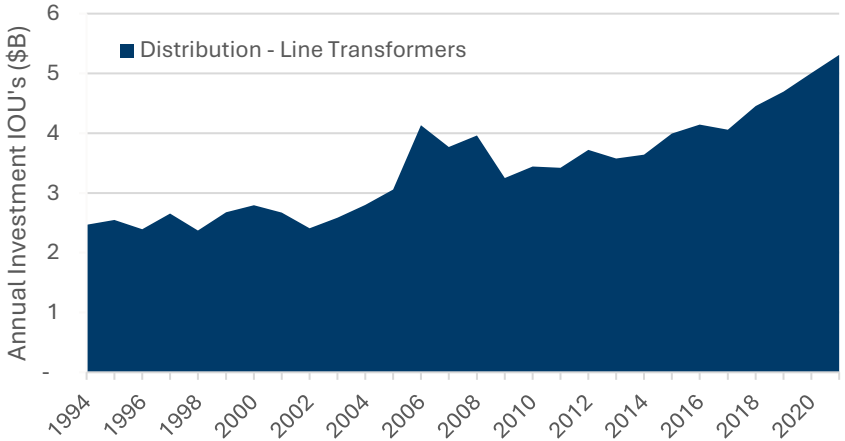
Three-phase pad-mount distribution transformer

Distribution Transformers – The Challenge

- PPA data on transformer costs
- The U.S. has seen continued shortages for distribution transformers, starting during the COVID-19 pandemic
- 2025 lead times for distribution transformers have been reported in the order of months to over a year, and reported average price increases of 78-95%



Source: St. Louis Federal Reserve Bank Transformer Price Index

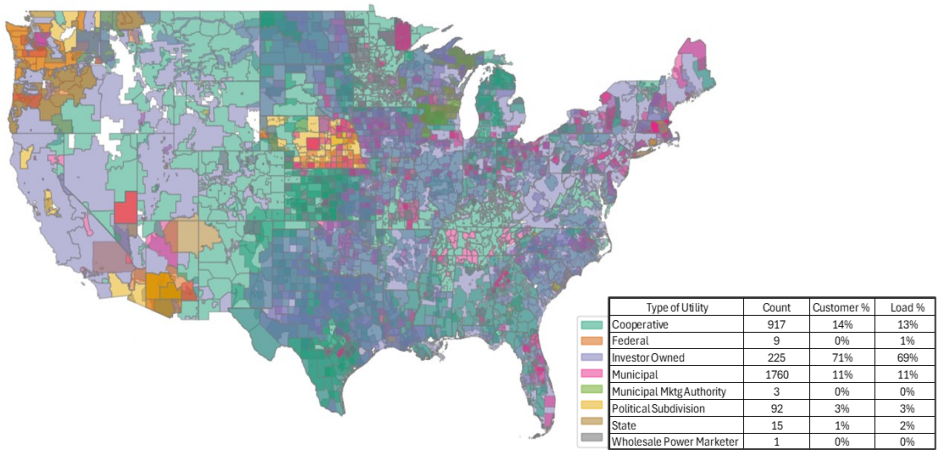


Source: FERC Form 1 Annual Service Transformer Investment Adjusted for GDP

Our Approach – Characterizing the Stock

- There is **no national inventory of distribution transformers**, and distribution transformers are owned by over **3,000 utilities across the U.S.,** and by large commercial and industrial customers
- The age and loading of the current inventory is critical to understanding future demand, in addition to load growth projections

U.S. utility landscape



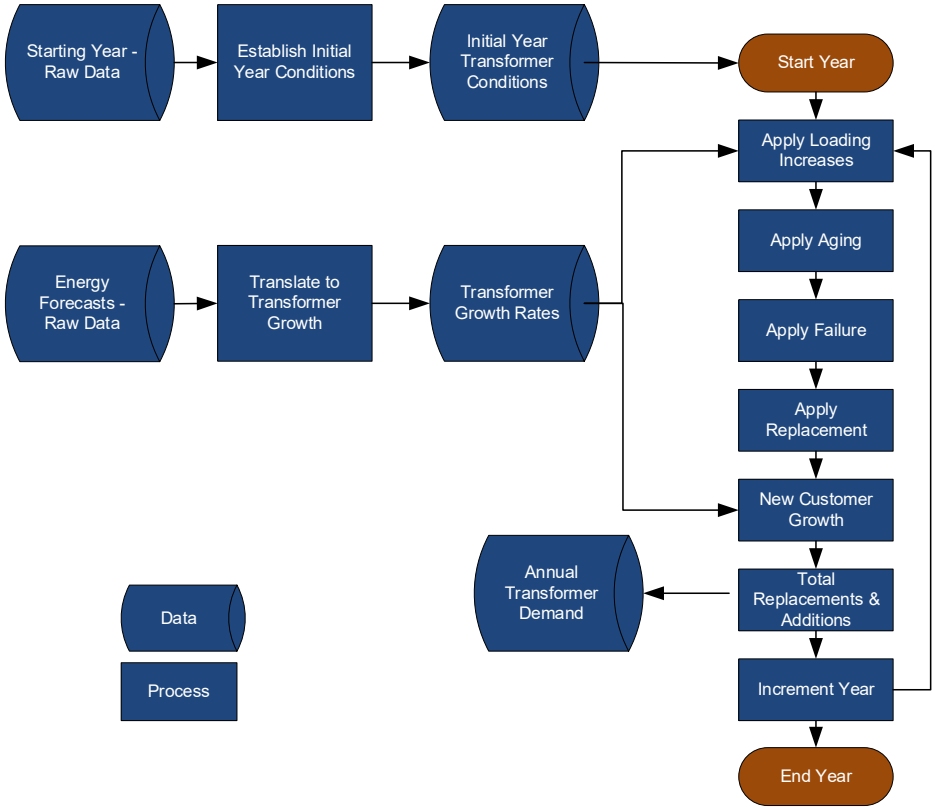
Type of Utility	Count	Customer %	Load %
Cooperative	917	14%	13%
Federal	9	0%	1%
Investor Owned	225	71%	69%
Municipal	1760	11%	11%
Municipal Mktg Authority	3	0%	0%
Political Subdivision	92	3%	3%
State	15	1%	2%
Wholesale Power Marketer	1	0%	0%

NLR Analysis, EIA Form 861

NLR estimates **60–80 million** distribution transformers, with between **2.5 and 3.5 TVA** of capacity

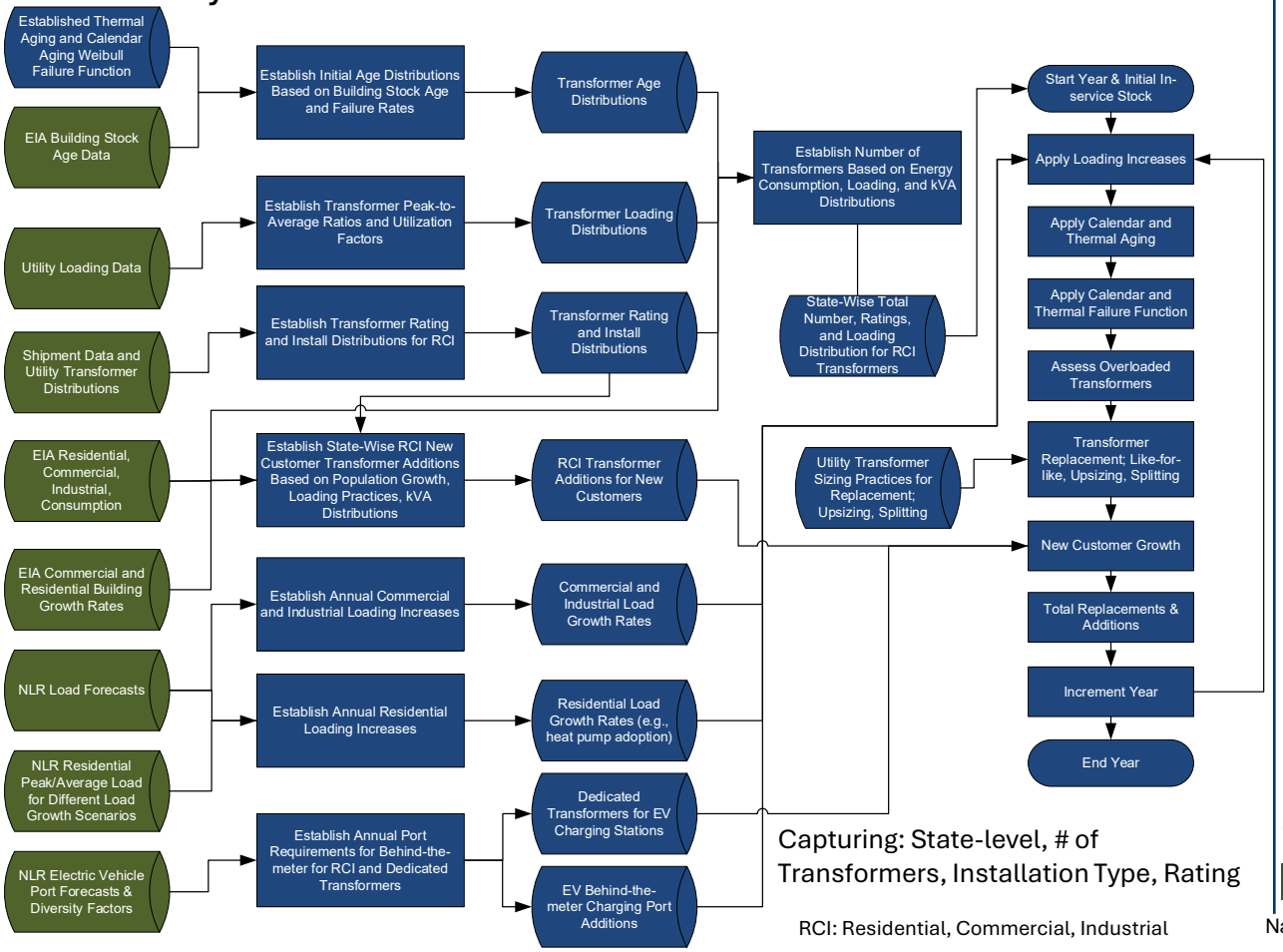
Our Approach – Modeling Future Demand

- Basic overview of modeling approach:
  - Modeling **new customers** and **increase in loading annually**
  - Capturing **transformer rating** (kVA), **loading**, and **installation type** (pole-mount, pad-mount)
  - Capturing demand for **each state**, and **residential**, **commercial**, **industrial**, and **transportation** demand
  - Separate analysis for **step-up** transformers and **data center** transformer demand
  - We model **unconstrained demand** for distribution transformers



Our Approach – The Forecasting Asset Demand for Distribution Systems Model (FC-ADDS)

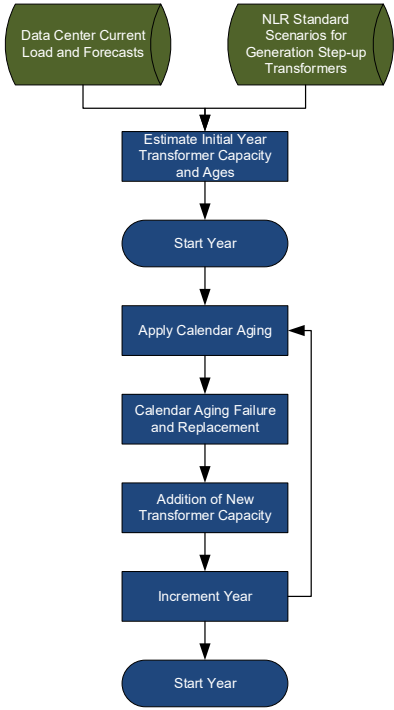
Residential, Commercial, Industrial, and Transportation Utility-Owned Distribution Transformer Demand



Capturing: State-level, # of Transformers, Installation Type, Rating

RCI: Residential, Commercial, Industrial

Data Center & Step-up Transformer Demand



Database | Source Data | Process | FC-ADDS

Key Aspects Driving Sensitivities

Distribution and Average Size of Existing Transformers

# of Transformers
Average transformer size (e.g., kVA) impacts the number of transformers, with low average kVA increasing the # of transformers

Utility Transformer Loading

Capacity of Stock
Low loading scenarios *increase* capacity of existing stock
High-loading scenarios *decrease* capacity of existing stock

Utility Age Distributions and Failure Rates

Age and % Replacements
Transformer failure functions have *very* high impact on age distributions and annual failure rates

Utility Decision Making Process

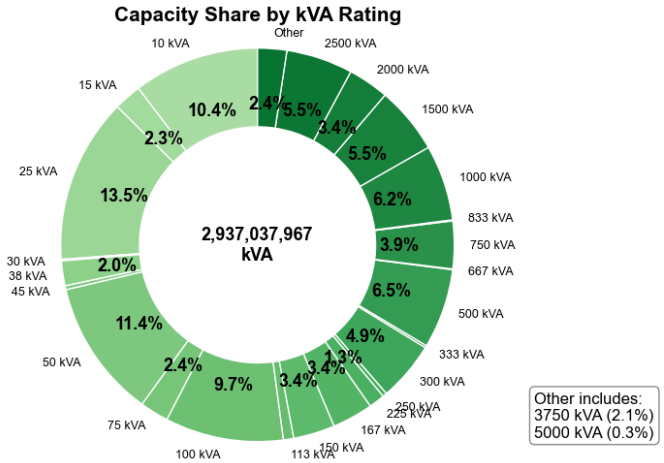
Replacement Scenarios
Run-to-fail vs. active replacement, redeployment vs. load splitting, and preemptive upsizing anticipating growth vs. high utilization have significant impacts on demand required

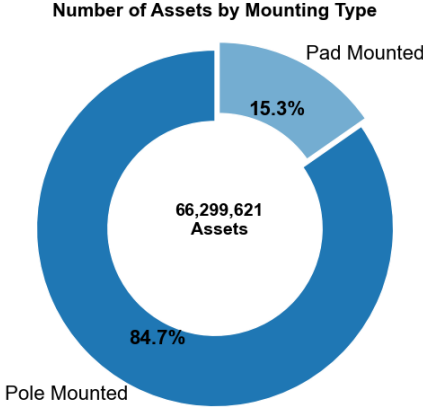
Demand Scenarios

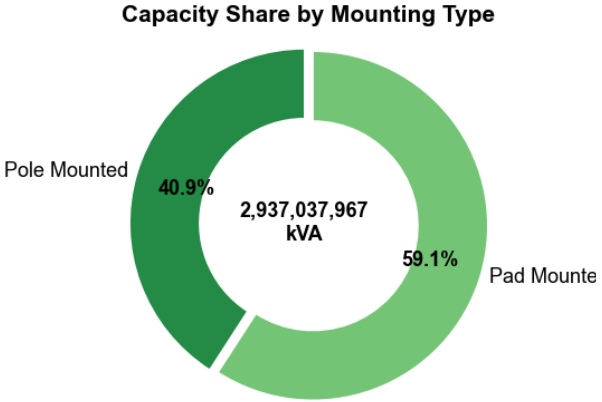
Capacity of Stock
Diversity factors for EV charging and charging stations, demand factors for heat pumps, significantly impact capacity required

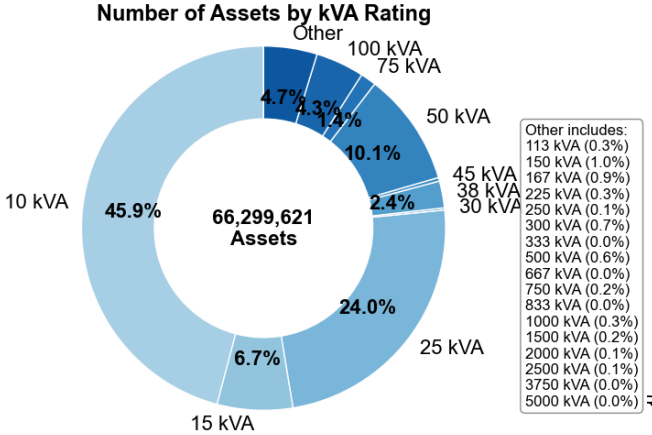
Characterizing the Existing Stock – Pole-Mount Transformers and Lower Sizes Dominate Number of Deployed Assets

- We are capturing the distribution in **transformer rating**, and **installation type**, through a combination of shipment data and utility datasets
  - The majority of transformer **installations** are **pole-mounted** and **ratings < 100 kVA**
  - The majority of transformer **capacity** is **pad-mounted** and **ratings >100 kVA**



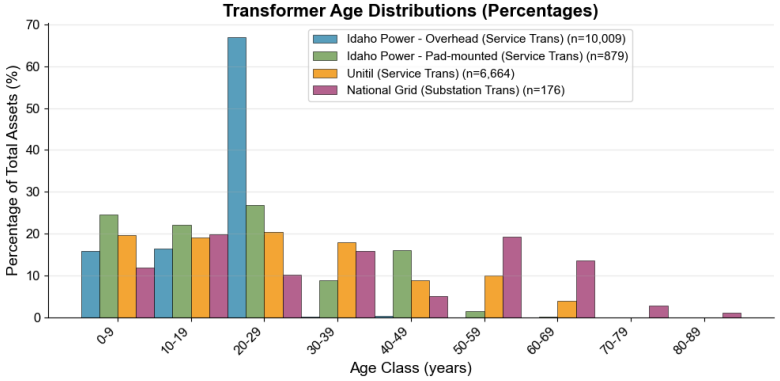




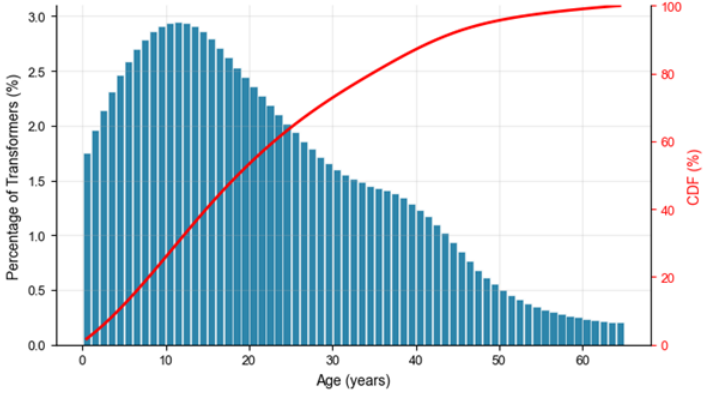


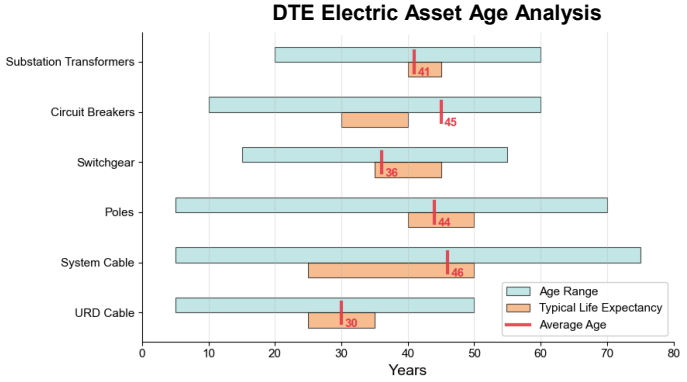
Characterizing the Existing Stock – A Significant Portion of Assets Are Beyond Expected Lifetimes

- Utility reporting shows aging infrastructure at or exceeding life expectations. Through modeling the age of the building stock and transformer failure rates we estimate that:
  - **17.5 million distribution transformers are beyond their expected designed life**



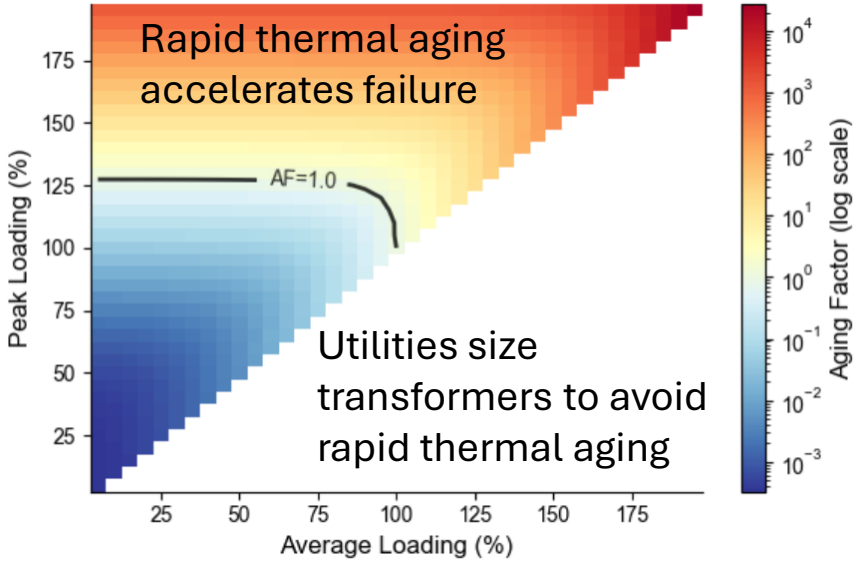
Many transformers are beyond expected life





Characterizing the Existing Stock – Loading Primarily Impacts Insulation and Utilities Size Conservatively To Avoid Thermal Aging

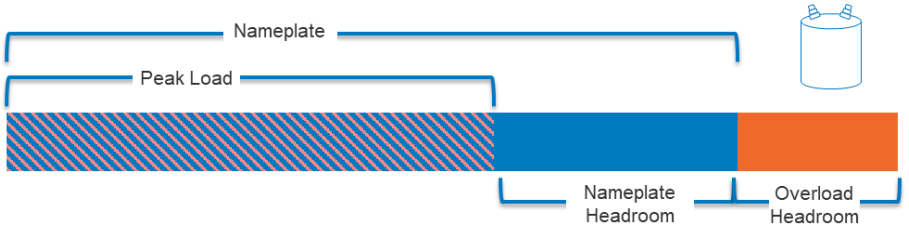
- Transformer loading will impact the rate of insulation paper degradation
- Transformer **hot-spot temperature (HST)** is designed for normal aging at (110°C/230°F)
- Transformer **thermal aging** is determined by insulation lifetime, normal life of a transformer operated at **HST 110°C is 180,000 hours, or 20.55 years**
- NLR developed thermal aging estimation code based on IEEE std C57.91-2011 as function of peak and average loading

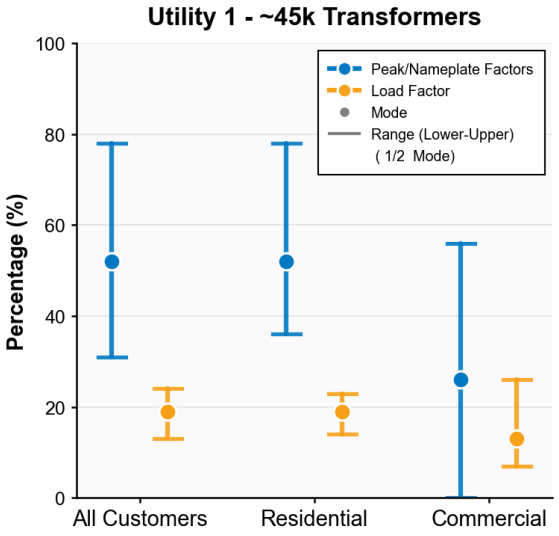


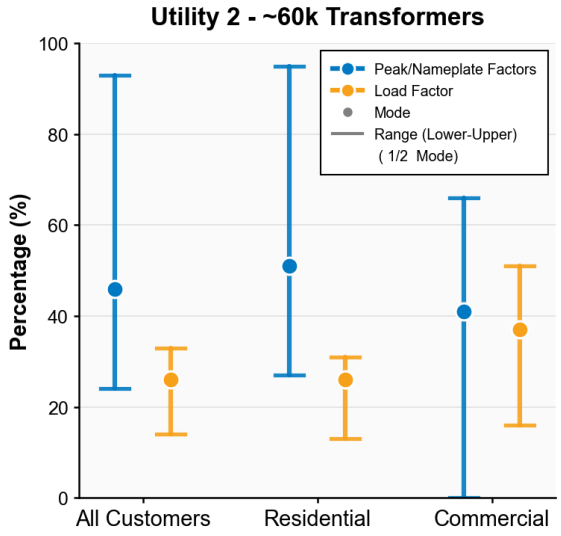
Aging factor of *1* equates to 1 year of normal aging, which would result in a life expectation of 20.55 years

Characterizing the Existing Stock – Utility Reporting Shows Low Thermal Loading of Transformers

- Utility reported and analyzed **loading is low**, with average loading <30%, and peak loading < 60% in many cases
- This results in **headroom for load growth**, **low thermal aging**, and likely is a contributing factor to much of the **stock lasting well beyond expected lifetime**

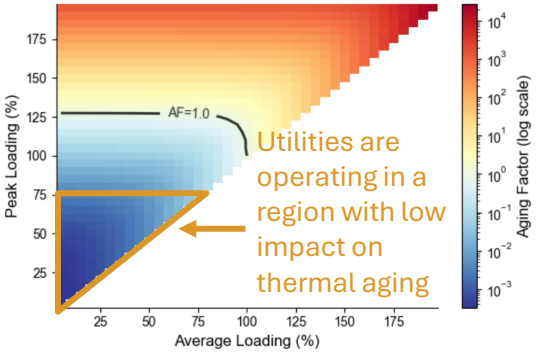


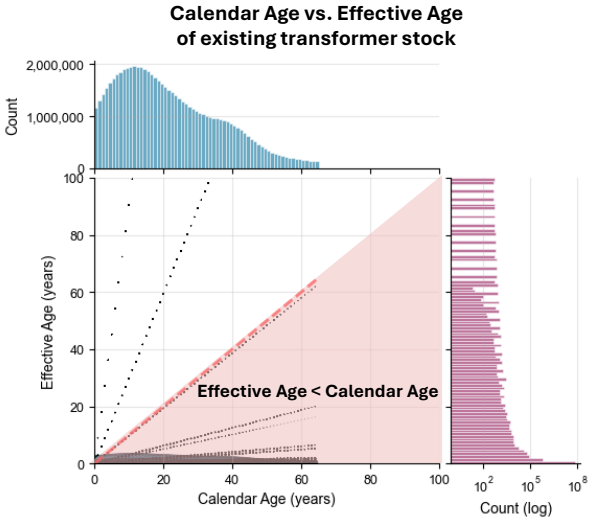


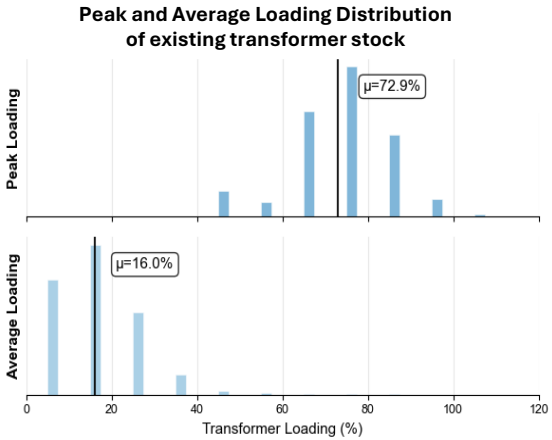


Characterizing the Existing Stock – Thermal Loading Remains Low, Resulting in Low Effective Age

- With low thermal loading, the **effective thermal age of transformers is expected to be much lower than calendar age**
- We calculated both initial calendar age and thermal age for the base year







NLR is estimating initial calendar age and initial thermal age to determine future transformer failure rates

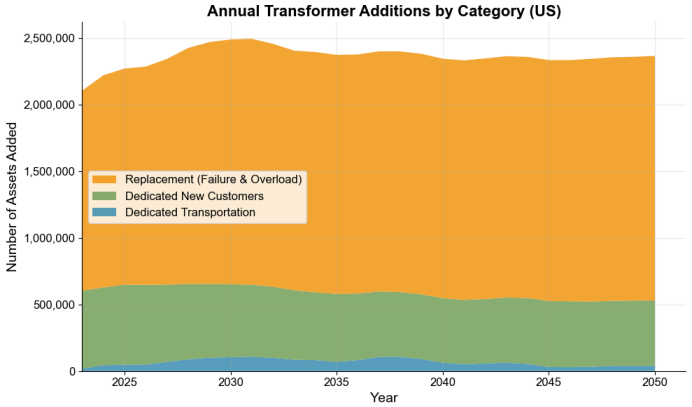
Future Growth – There Are Many Sources of Future Growth for Distribution Transformers, Including Emerging Sectors

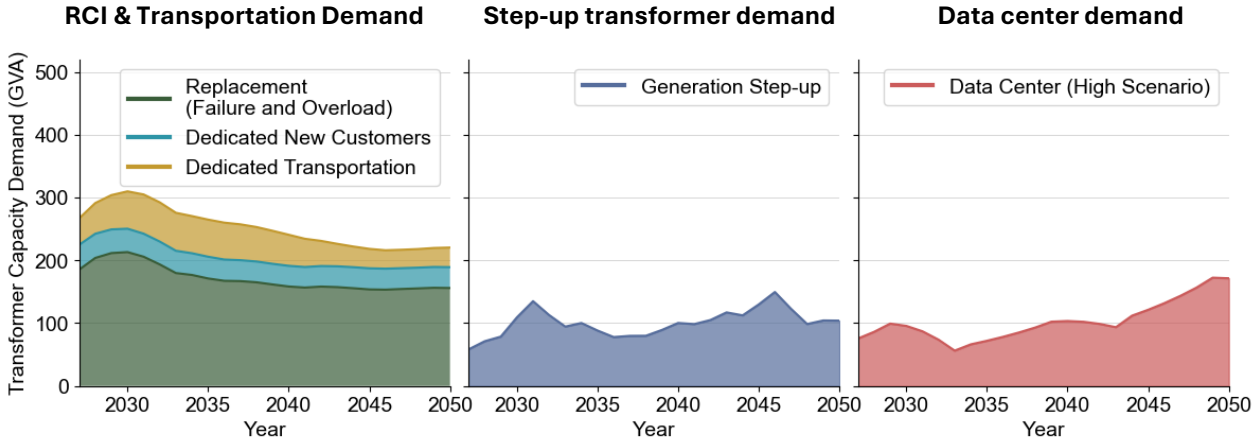
Future growth will be driven by multiple current and emerging sectors of demand, with noticeable drivers from transportation, data centers, and step-up transformers

	Residential	Commercial	Industrial	Transportation	Data Center	Step-up Transformers
Drivers	New customers, Replacement, Per capita load growth	New customers, Replacement, Per capita load growth	New customers, Replacement, Per capita load growth	Primarily new customers	Primarily new customers	Primarily new customers
Phasing	Split-phase, Some three-phase in dense urban	Split-phase, and three-phase	Mostly three-phase	Three-phase	Three-phase	Three-phase
Installation type	Primarily pole-mount, increasing pad-mount	Mix of pole-mount and pad-mount	Pad-mount	Pad-mount	Pad-mount	Pad-mount
Cooling	Oil-filled	Oil-filled, some dry type	Oil-filled, some dry type	Oil-filled	Oil-filled (power transformer), Dry type (PDUs)	Oil-filled

Future Growth – Emerging Sectors Are Significant When Compared to Current RCI Demand

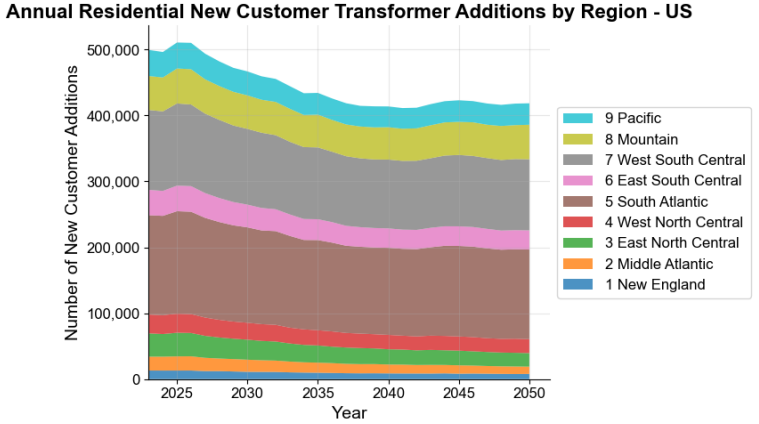
- **Residential, commercial, and industrial** (RCI) transformer demand will be driven by **new customers** and replacement due to **aging infrastructure** and increased **loading**
- **Transportation**, **data centers**, and **step-up** transformer demand will primarily be driven by **new customer growth**, and **could close to match that of RCI demand**

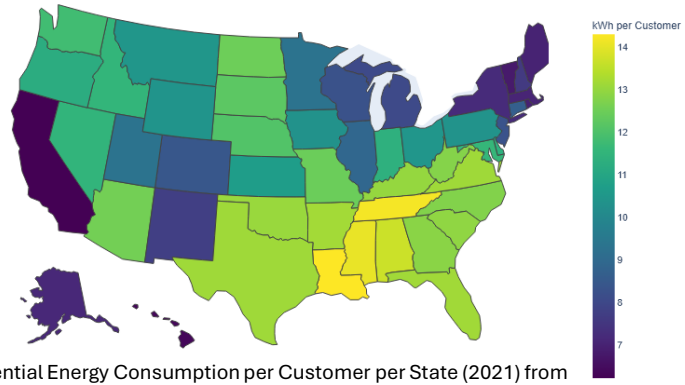




Future Growth – Residential Sector Transformer Growth Will Be Driven by New Customers and per Capita Load Growth

- Transformer demand for residential customers will be driven by continued **population growth** and **replacement of aging infrastructure**
- **Load growth** (i.e., adoption of heat pumps, electric water heaters, electric vehicles) will **accelerate transformer replacement in certain states** – with larger impacts on loading for states with little existing electric load

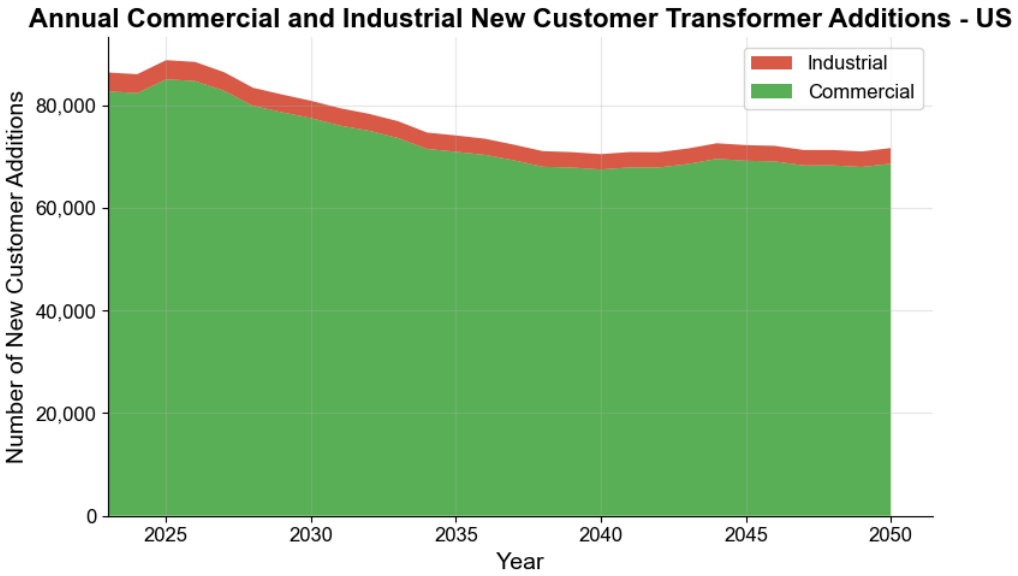




Residential Energy Consumption per Customer per State (2021) from NLR EIA 861 Analysis

Future Growth – Commercial and Industrial Sector Transformer Growth Will Be Driven by New Customers and per Capita Load Growth

- Commercial and industrial sector load growth is challenging to forecast and in our models is principally driven by **new customers** and **replacement of aging infrastructure**
- Data center demand is modeled separately given the anticipated scale of growth

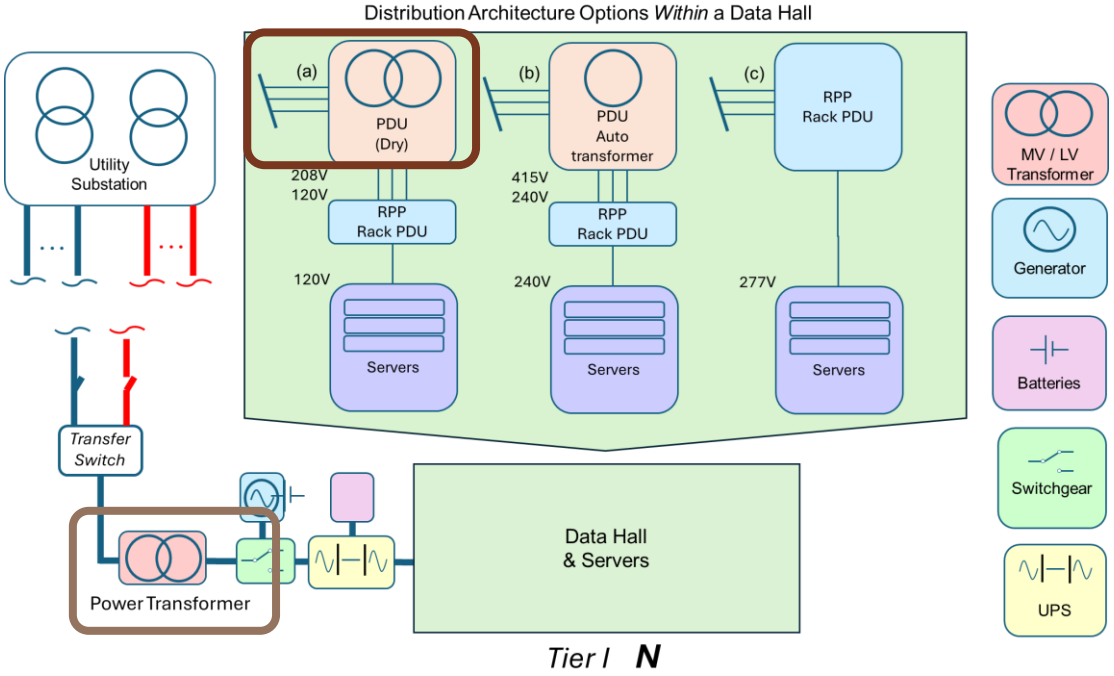


Future Growth – Data Centers Are Emerging As a Large Potential Area of Growth for Distribution Transformers

- **Medium voltage transformers/power transformers** step down from a substation supplied primary voltage (e.g., ranging from 13-34.5 kV)
  - Often oil-filled but can be dry-type
  - Must serve site loads apart from server load

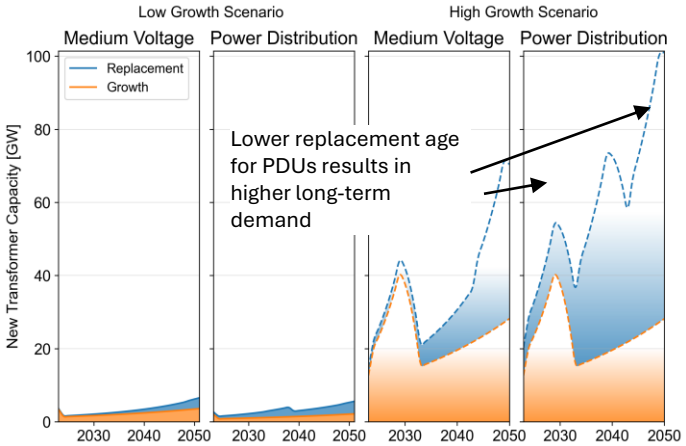
- **Power Distributions Units (PDU)** provide further reduction to the operating voltage of the servers
  - Inside the data center and dry-type, see (a)
  - Alternative data center architectures avoid the use of PDUs via higher service voltage or DC service, see (b) and (c)

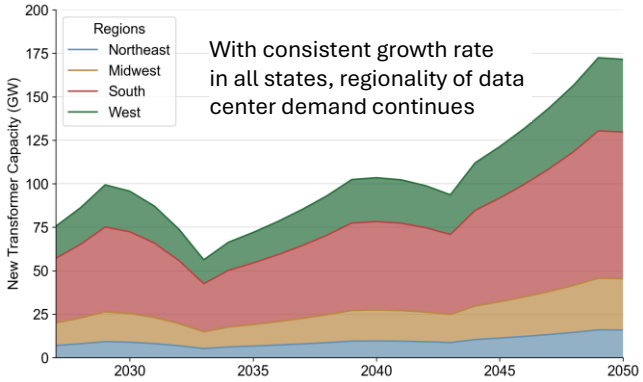
Data centers have a number of transformer requirements



Future Growth – There Is Large Uncertainty in Data Center Growth Forecasts, But High Potential Growth

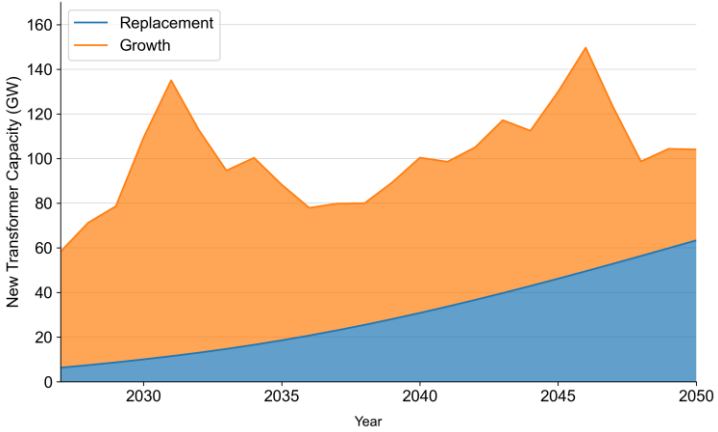
- Forecasts for data center demand show high uncertainty, taking EPRI's low and high demand growth scenarios reflect **3.71% through 15% compounded annual growth rates** (EPRI, 2024)
- Scenarios also differ in assumptions of retirement age, utilization levels, and data center efficiency
- Without forecasts post-2030, we analyze a period of high growth until 2030, and return to 3.71% CAGR thereafter, meaning
  - **Up to 2030**, growth is dominated **by new load**
  - **After 2030**, growth is dominated by **replacements**



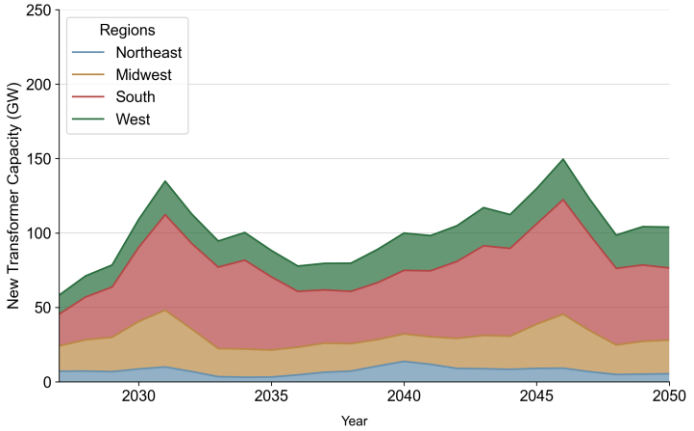


Future Growth – Step-Up Transformers Are Set To Grow as a Result of Wind, Solar, and Battery Deployment

- Wind, solar, and batteries all require **step-up transformers** to transform generator terminal voltage to medium-voltage, these transformers voltage (e.g., input <1,000V, high side < 34.5 kV) and capacity characteristics (e.g., <5,000 kVA) are similar to distribution transformers
- **Early demand dominated by new growth**, with **replacement picking up after 2040** - assumptions around existing stock age could change the nature of replacement

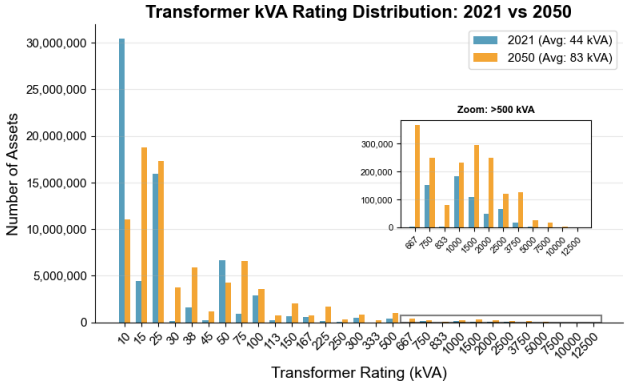


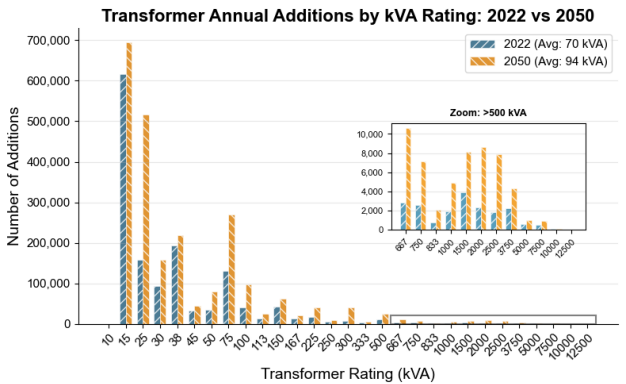
Demand becomes dominated by replacement of existing capacity (441 GW in 2026)



Future Growth – The Types of Transformer Being Requested by Utilities and Customers Will Evolve Over Time

- Transformer ratings are expected to change over time, with upsizing due to **increases in residential customer electric load**, and **additions of more three-phase transformers**
- Comparing 2021 and 2050 transformer size ratings we see a **large drop in 10 kVA transformers**, reflective of **ongoing utility sizing practices to use larger kVA transformers**



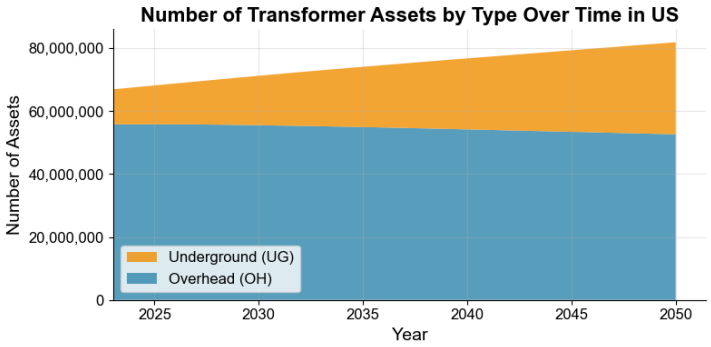


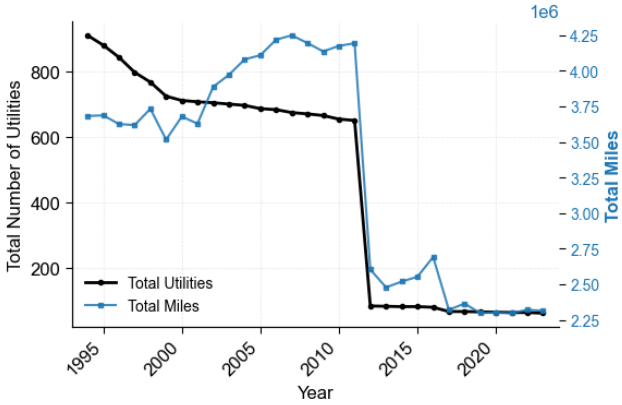
Many utilities are using 25 kVA as the new minimum transformer size

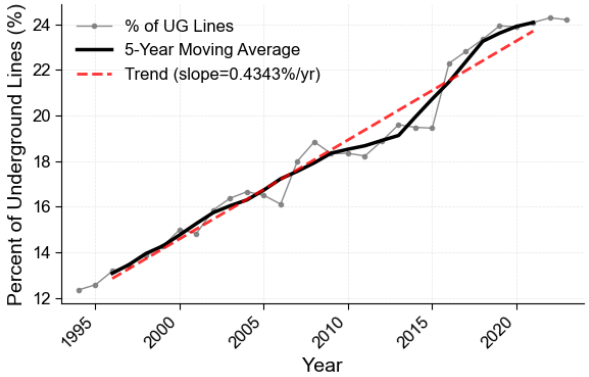
Three-phase transformers for EV charging stations are set to increase

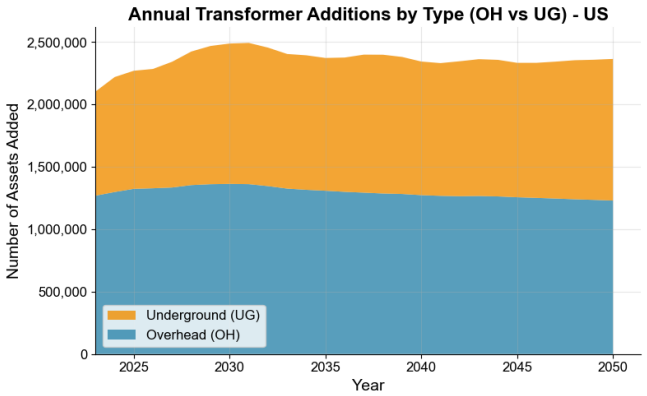
Future Growth – Pad-Mount Transformers Are Set To Continue To Grow as Utility Hardening and Undergrounding Continue

- We examine historical rates of undergrounding which will reflect uptake of pad-mount transformers, **establishing a U.S. undergrounding rate of 0.43%/year**
- Overall, we see an **increase in the rate of pad-moun additions out to 2050**



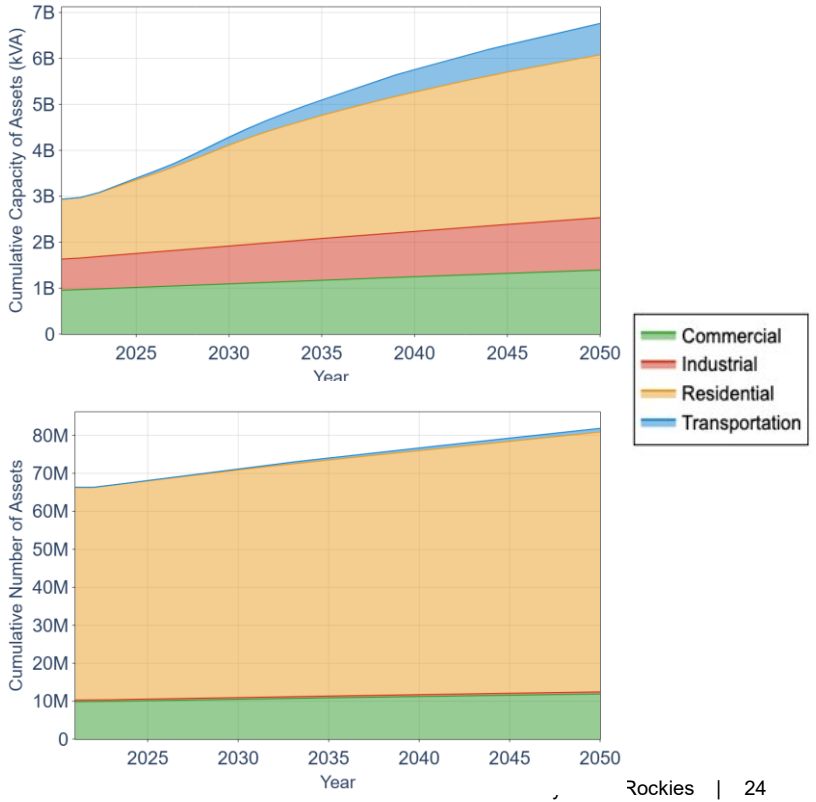






Future Growth – Overall, the Total Demand for Increased Transformer Capacity (MVA) Will Outpace Demand for a Number of Transformers

- Number of distribution transformers rises gradually out to 2050, driven by **new customers**, **residential expansion**, and **transportation additions**
- An important implication for manufacturing is the **growth in capacity** relative to the **growth in number of new transformers** – the demand for larger transformers results in much **greater demand for capacity** than **an increase in the number of transformers**



Utility Sizing Practices and Decision-Making Have Trade-Offs and Will Impact Demand

Our Scenarios

Utilities have assets with **low utilization** and **existing headroom** for load growth

Utilities may **anticipate** load-growth and **upsize** during standard replacement

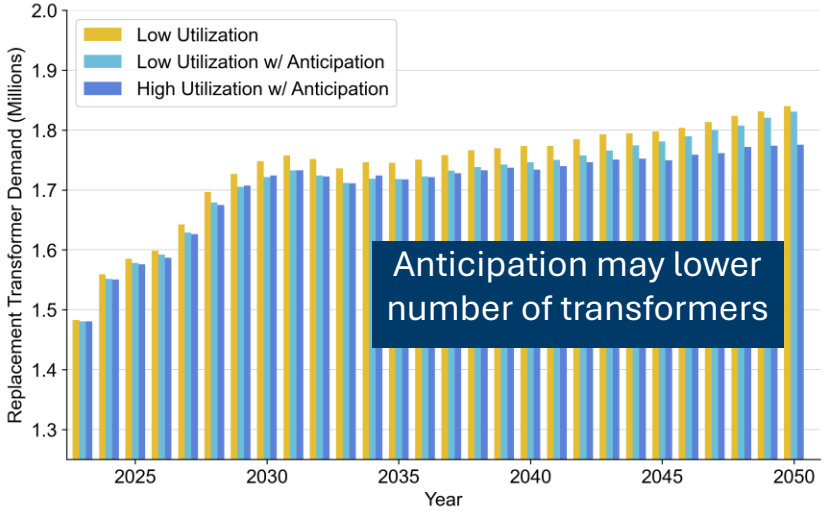
Utilities may **increase asset utilization** when upsizing for load growth

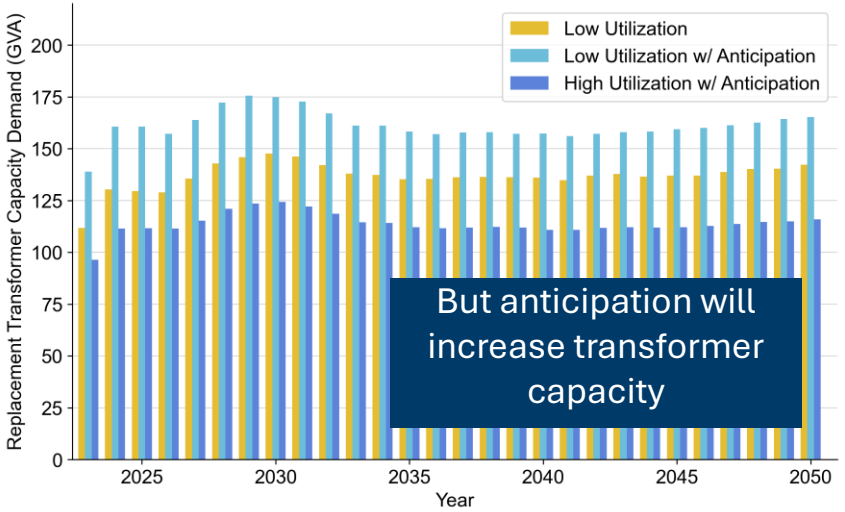
Or, they may continue to size assets to **keep low utilization** and **headroom**

Asset utilization
Headroom

Replacement Growth – Utility Decision-Making on Preemptive Upsizing and Utilization Will Heavily Impact Demand

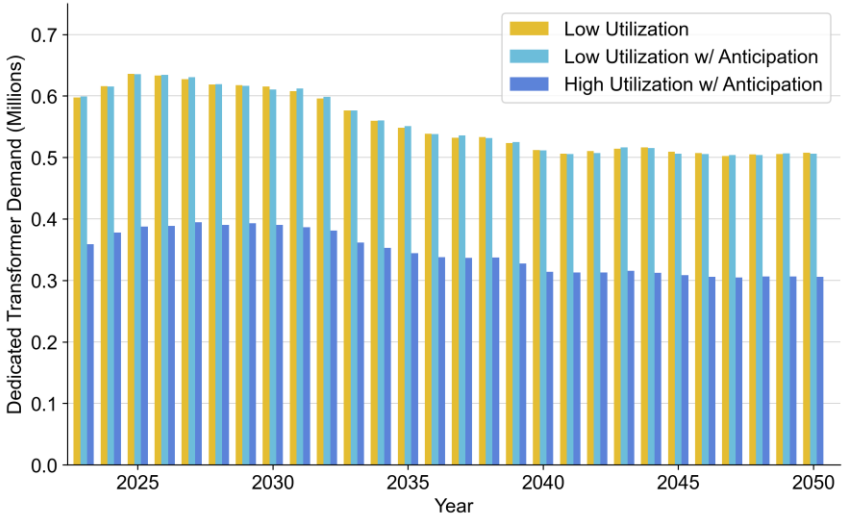
- In all scenarios, utility sizing practices have a **larger impact** on capacity demand than the **number of transformers**, with tradeoffs for utilities on these sizing practices
- In all scenarios, **transformer demand grows out to 2030** and **starts to level-off**, with **high utilization** having the largest impact on reducing demand

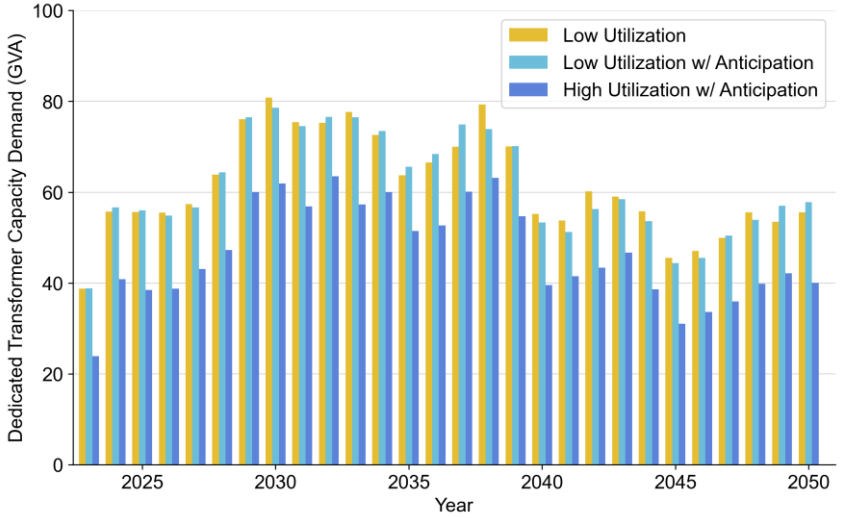




Additions Growth – Utility Decision-Making on Preemptive Upsizing and Utilization Will Heavily Impact Demand

- Similar decision making has a larger proportional effect on **transformers dedicated to new customer growth**
- **Higher utilization[1] directly lowers number of transformers and capacity demand**, with anticipation impact likely to be seen in long term replacement impact





[1]Open questions remain whether utilities could achieve this due to load density

There Are Trade-Offs Between Increasing the Loading of Transformers in Sizing Decisions, Versus Leaving More Headroom

Utilities have a choice between **increasing transformer utilization** or **oversizing assets**, of which those choices can have a large impact on transformer capacity demand, while there are considerable trade-offs

	High Utilization	Low Utilization
Thermal aging	Shorter Life	Longer life
Load Growth Accommodation	Lower potential	Higher potential
Losses per Unit Power Delivered	Increased Delivery Efficiency	Decrease Delivery Efficiency
Labor Costs	Increased labor (If resulting in increased replacements)	Decreased labor (If resulting in decreased replacements)
Labor Costs per kVA	Higher	Lower
Upfront Capital Costs	Lower upfront	Higher upfront

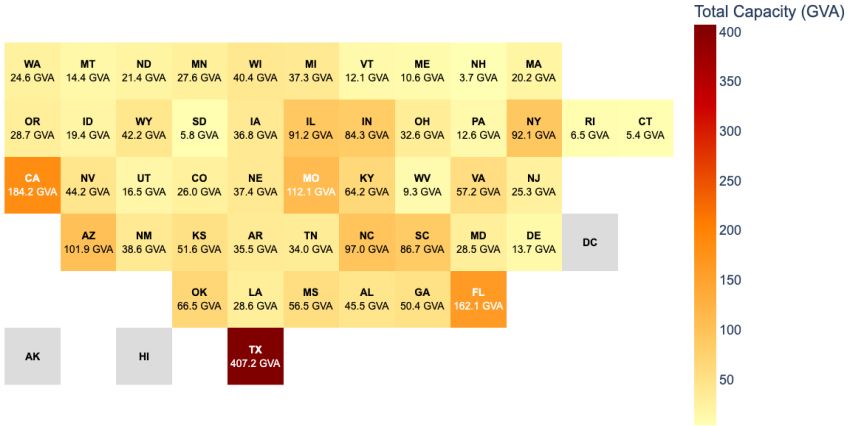
There Is Widespread Regionality in Anticipated Load Growth and Its Impact on Transformer Demand

- There is widespread regionality in anticipated load growth in residential, commercial, industrial and transportation with:
  - **New customer growth** primarily expected in states TX, FL, CA, NC, GA, VA, AZ
  - **Per capita load growth** expected in states NJ, MI, RI, IN, MN, CT

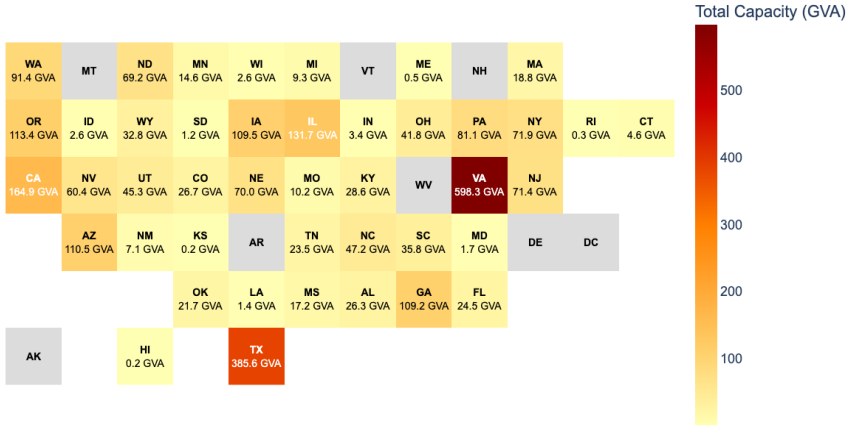
Data Centers and Step-Up Transformer Growth Also Exhibit Regionality

- There is widespread regionality in step-up and data center transformer demand:
  - **Step-up transformer demand** concentrated most heavily in **Texas**, **California**, and **Florida**
  - And **data center load growth** concentrated in **Virginia**, **Texas**, and **California**

Cumulative Step-Up Transformer Addition Capacity by State (2026-2050) (US Tile Map)



Cumulative DC Transformer Addition Capacity by State (2023-2050) (US Tile Map)



States with no data available

Manufacturers Are Challenged Due To Lack of Visibility and Mass Customization

- **80,000 different designs** due to variations in ratings, type, cooling method, phase, winding, voltages, and basic impulse level
- Manufacturers manage **mass customization** and need to wait to receive utility orders to match supply with specific demand

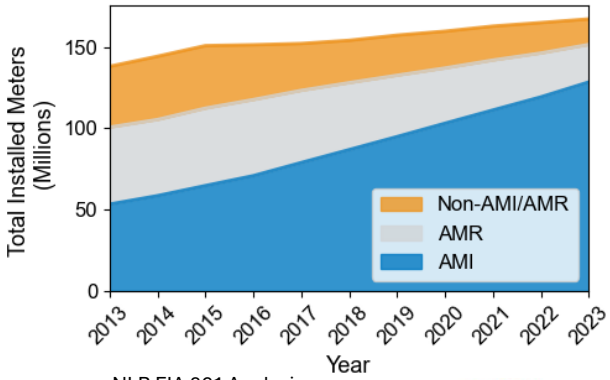
Pole-mount key variations
Oil-filled
High-voltage (2-34.5kV)
Single-phase high-side
Split-phase low-voltage side (120/240 V)
Rating 5 – 150 kVA

Pad-mount key variations
Oil-filled or dry type
High-voltage (2-34.5kV)
Three-phase I/P
Three-phase (208/240 V or 277/280 V)
Rating 50-5,000 kVA

- **Manufacturers have little insight as to drivers behind utility orders** (e.g., failures, active upsizing, new customers, etc.)
  - **Standardization** of design may help manufacturing efficiency
  - **Granular longer-range utility forecasts** may help manufacturers manage supplies

Load Management Schemes and Advanced Transformer Monitoring May Help Manage Demand

- U.S. **Advanced Metering Infrastructure** roll-out can give utilities **advanced loading estimates** if paired with holistic GIS and meter-mapping – helping **wide-scale monitoring of loading conditions**
- **Load management schemes** (e.g., HEMs, smart breakers, etc.) that help modulate demand to either **monitor whole-premise import**, or **monitoring transformer loading**, can help **mitigate the need for upgrades of existing transformers** and hence life utilization



NLR EIA 861 Analysis

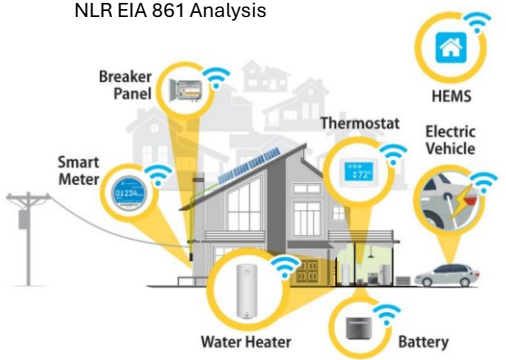


Image from Sparn and Werling (2021): https://www.osti.gov/servlets/purl/1810537

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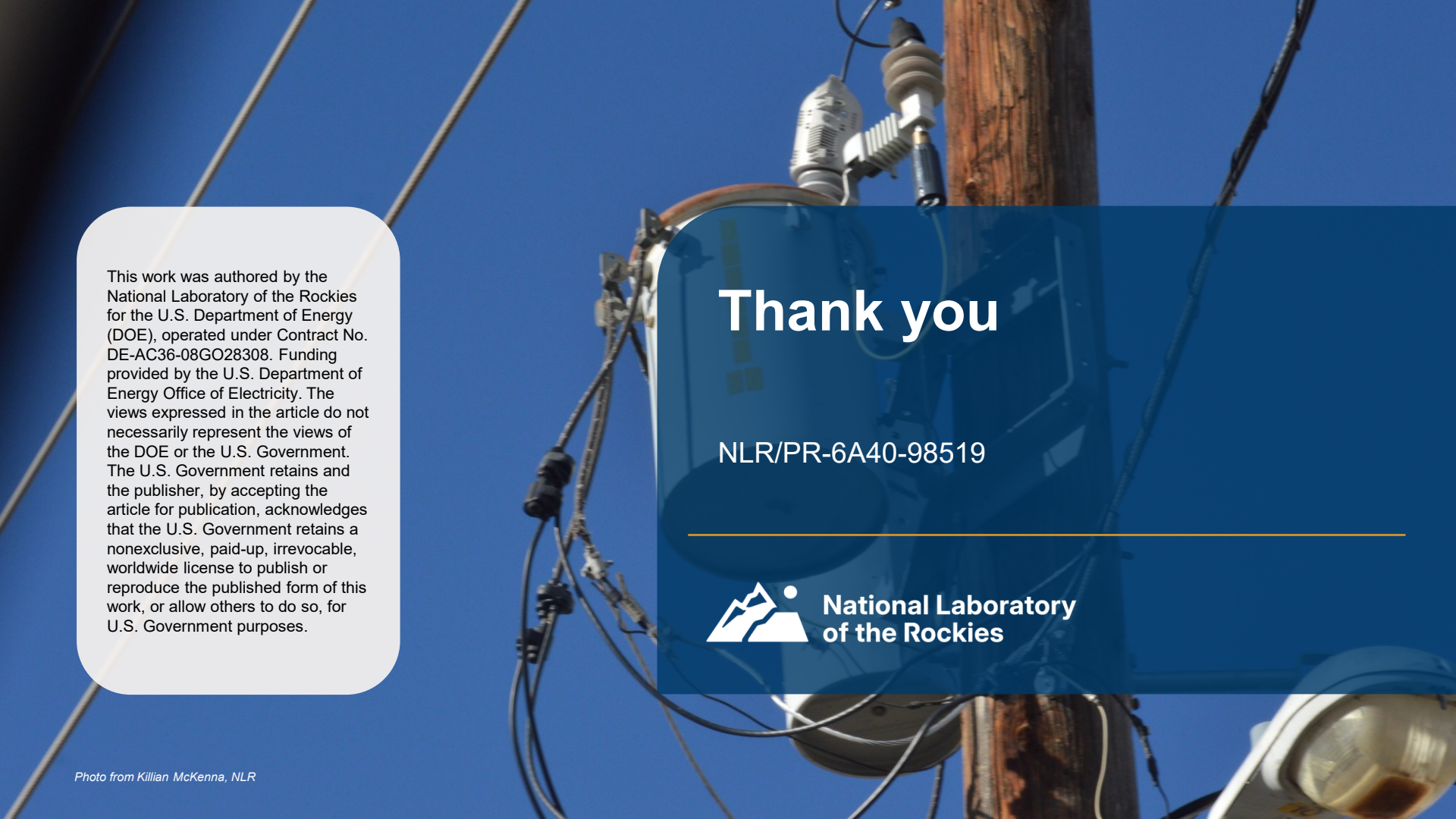

Thank you

NLR/PR-6A40-98519

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