Informing Transmission Supply Chain Needs from National Transmission Studies

Amy Rose, Becca Fuchs, Lina Ramirez, and Ram Mohan Pandian

National Laboratory of the Rockies

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Technical Report
NLR/TP-6A40-97167
January 2026

NATIONAL LABORATORY OF THE ROCKIES

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Suggested Citation
Rose, Amy, Becca Fuchs, Lina Ramirez, and Ram Mohan Pandian. 2026. *Informing Transmission Supply Chain Needs from National Transmission Studies*. Golden, CO: National Laboratory of the Rockies. NLR/TP-6A40-97167. https://www.nlr.gov/docs/fy26osti/97167.pdf.

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Golden, CO 80401
303-275-3000 • www.nlr.gov

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Acknowledgments

We would like to thank several colleagues for their technical input to this report. Jarrad Wright from the National Laboratory of the Rockies (NLR) assisted with the nodal transmission expansion scenarios and, alongside Patrick Brown and Sebastian de Jesus Machado (NLR), provided technical guidance. Micah Webb (NLR) assisted with the geospatial analysis. Sarah Inskeep, Margaret Mann, Justin Bracci, Annika Eberle, and Vicky Putsche (NLR) assisted with data and methods to determine material concentrations for transmission components. We received valuable input from members of the National Electric Manufacturers Association (NEMA) on existing transmission supply chain constraints to help focus our analysis.

The authors are also greatly indebted to several individuals for their thoughtful feedback and guidance on this report, including Jarrad Wright, Sebastian de Jesus Mechado, Sarah Inskeep, Ilya Chernyakhovskiy, Kate Anderson, Jaquelin Cochran, and Mark Ruth (NLR) and Alissa Baker from the U.S. Department of Energy's Grid Deployment Office. Jennifer Korte (NLR) provided editing and design support.

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List of Acronyms

AC	alternating current
ACSR	aluminum conductor steel reinforced
ACSS	aluminum conductor steel supported
CEM	capacity expansion model
DC	direct current
GOES	grain-oriented electrical steel
GSU	generator step-up transformer
GW	gigawatt
HVDC	high-voltage direct current
hydro	hydropower
kV	kilovolt
LCC	line-commutated converter
MT	multiterminal
MVA	megavolt-amperes
MW	megawatt
NTP	National Transmission Planning Study
VSC	voltage source converter

Executive Summary

Recent national studies indicate inter-regional transmission expansion can provide low-cost options to maintain grid reliability while meeting growing demand (IEA, 2025; Rohrer, 2024; U.S. Department of Energy, 2022; U.S. Department of Energy, 2024; Wood Mackenzie, 2024). However, constraints in domestic supply chains may limit grid expansion across the United States, with higher costs and longer delays for required transmission equipment. This challenge impacts the economy at every level that requires electricity—from new generation resources needed to meet growing energy demand to requests for the construction of new homes and businesses. Prices and procurement lead times for essential components, including large power transformers, circuit breakers, and cables have almost doubled since 2021 (IEA*,* 2025). Despite growing evidence of supply chain constraints for transmission components (Rohrer, 2024; U.S. Department of Energy, 2022; Wood Mackenzie, 2024), transmission planning studies often assume transmission equipment is readily available for deployment, or they analyze future demand for raw materials inputs, refined products and electrical components using historical trade and manufacturing data that may not capture evolving grid and supply chain needs.

This report aims to address this gap by demonstrating methods to quantify future demand for critical transmission components and input materials from national-scale planning models. A subsequent report that evaluates the ability of U.S. supply chains to meet anticipated component and material demand for transmission expansion is planned. These components include large power transformers, generator step-up transformers, converter transformers, transmission lines, circuit breakers, and transmission towers. The materials include aluminum, steel, grain-oriented electrical steel, and copper. The analytical approach is applied to two nodal transmission expansion scenarios from the National Transmission Planning Study to illustrate the methods (U.S. Department of Energy, Grid Deployment Office, 2024). These scenarios represent different transmission expansion strategies for the contiguous United States to the year 2035: the Alternating Current (AC) scenario includes AC transmission expansion across transmission planning areas but within each interconnection, and the Multiterminal (MT) scenario includes interregional transmission expansion across the country using both AC and multiterminal HVDC options between neighboring zones and across interconnects.

Figure ES-1 compares the annual investment requirements for transmission components across the two scenarios. Interregional transmission expansion to 2035 would require roughly 5,000 and 7,000 circuit miles per year for the AC and MT scenarios, respectively. Further, in either scenario, about 1,500 large power transformers and 1,300 high-voltage circuit breakers are needed per year. Investments in longer transmission lines across regions and interconnections result in more than 10,000 additional (or approximately 45% more) towers required in the MT scenario than in the AC scenario.

Transmission expansion under either future scenario would require an average annual supply of more than 174–208 thousand tons of aluminum, 595–693 thousand tons of steel, 94–114 thousand tons of grain-oriented electrical steel, and 61–74 thousand tons of copper (Figure ES-2), equivalent to less than 4% of average annual apparent consumption for aluminum, steel, and copper over the 2019–2023 period and more than 45% average annual apparent consumption for grain-oriented electrical steel (U.S. International Trade Commission, n.d.; USGS, 2024).

Transmission towers have the largest input material requirement followed by transformers and transmission lines. The MT scenario requires more aluminum and steel because of longer lines and greater demand for transmission towers. However, the AC scenario requires more grain-oriented electrical steel and copper to meet increased demand for power transformers. These findings demonstrate how the analytical approach can be used to quantify supply chain needs based on national-scale studies. As the generation resource mix and anticipated demand growth continue to evolve, the results can be updated to reflect changing system conditions.

We also explore potential heuristics to derive transmission component demand from zonal capacity expansion models (CEMs) with coarse representation of the transmission grid. Estimating transmission component demand from CEM scenarios can provide an early assessment of the feasibility of the planned system and highlight potential areas of risk to long-term resource adequacy given the existing and anticipated capability of component supply chains to meet this demand. Another use case would be to use known supply chain constraints in early years of capacity expansion model scenarios. While the heuristics presented in this report are preliminary, they provide an initial indication that can be refined through additional scenarios and capacity expansion modeling.

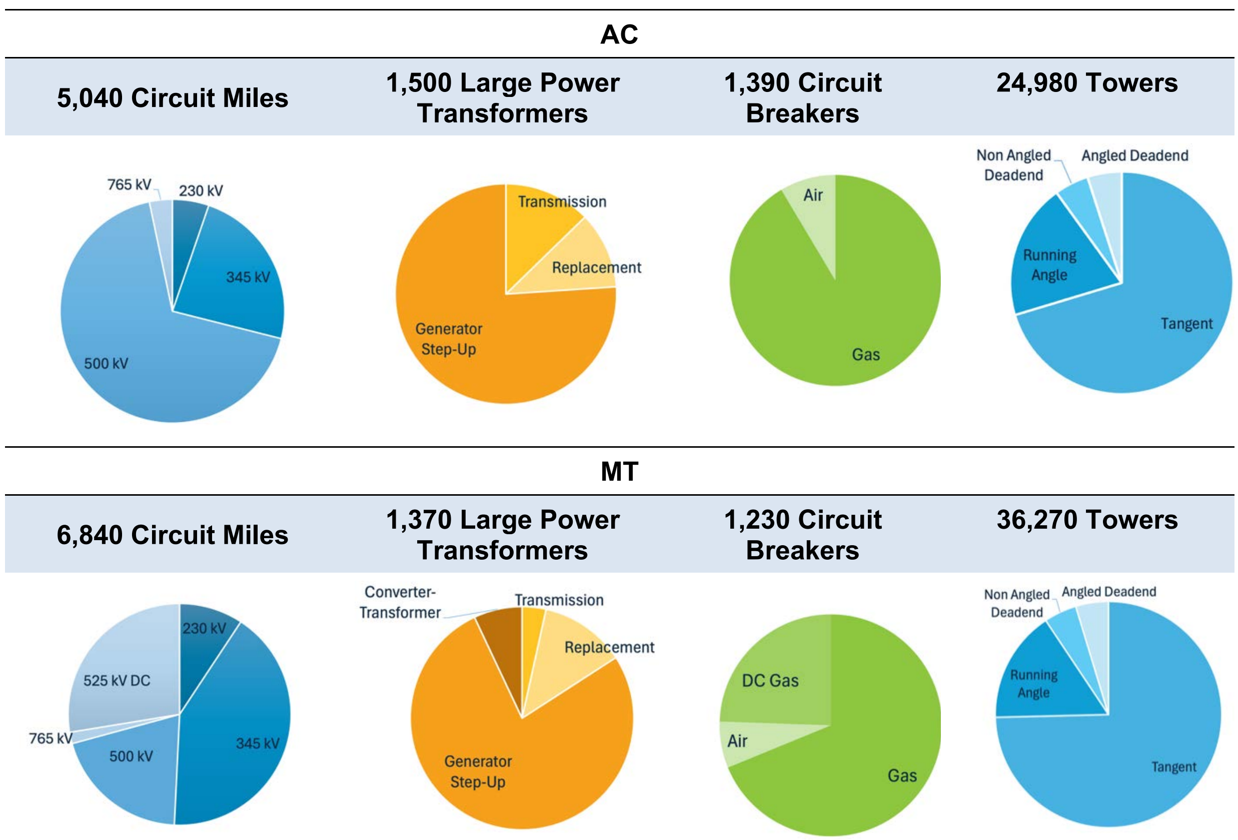

Figure ES-1. Summary of annual transmission component requirements by scenario.

DC = direct current; kV = kilovolt.

This report includes several key assumptions and areas for improvement and further work. As securing materials and manufactured components becomes more difficult, developing methods to link power sector planning and supply chain analysis can inform planning, manufacturing, and procurement strategies to reliably meet power system needs at lower cost.

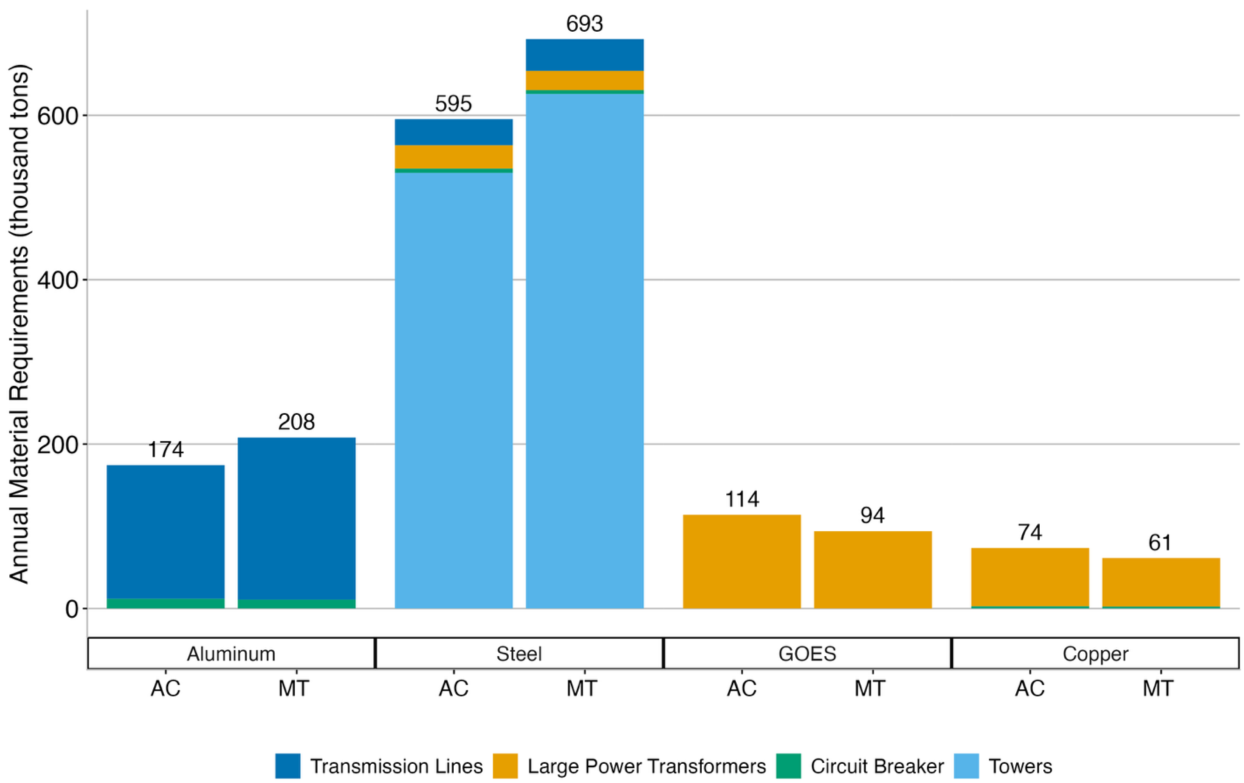

Figure ES-2. Annual material requirements by scenario across all component categories

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1 Introduction

Expanding electric transmission infrastructure can facilitate generator interconnection and improve grid reliability. Recent national studies published by federal government agencies, national laboratories, and research organizations demonstrate significant transmission expansion is the lowest-cost option to meet growing demand and maintain grid reliability (EPRI, 2025; IEA, 2025; Phadke et al., n.d.; Rohrer, 2024; U.S. Department of Energy, 2022).

However, constraints in domestic supply chains for critical grid components may limit grid expansion across the United States (U.S. Department of Energy, 2022). A recent survey of industry leaders found that prices and procurement lead times for essential components, including large power transformers, circuit breakers, and cables have almost doubled since 2021 (IEA*,* 2025). Procurement in 2025 takes 2 to 3 years for cables and up to 4 years for large power transformers. For circuit breakers or specialized components for HVDC systems such as specialized converter-transformers and high-voltage direct current (HVDC) cables, procurement can extend beyond 5 years (Rohrer, 2024).

Increased costs and delays in transmission equipment availability impact all aspects of the economy that require a grid connection, from new generation resources needed to meet growing demand to requests for new home and business construction. Global estimates suggest long wait times to obtain a transformer may delay a quarter of the world's renewable energy projects (Wood Mackenzie, 2024). Although demand for data centers across the United States is growing, long procurement times for grid infrastructure present a barrier for interconnecting and powering these loads (Green et al., 2024) and power and grid capacity constraints are considered the number one challenge in meeting load growth caused by data centers, according to a recent survey of 120 US-based power company and data center executives (Stansbury et al., 2025). In addition to new builds, delays in equipment replacements and emergency repairs may reduce system reliability, while increased equipment costs could increase power costs to customers (Rohrer, 2024).

Despite growing evidence of supply chain constraints for transmission components, transmission and generation planning studies—including the ones cited previously—often assume transmission equipment is readily available for deployment. This simplification may undermine the credibility of the planned system and compromise long-term resource adequacy in cases in which infrastructure expansion is time-sensitive (Yao et al., 2025). Previous work to incorporate supply chain considerations in power sector planning has largely focused on supply chain constraints for generation and storage technologies (Yao et al., 2025) or critical materials used to make those technologies (Zhang et al., 2022) and did not consider potential constraints or delays for transmission components. For example, Deetman et al. (2021) estimate material requirements for steel and aluminum from the transmission sector to 2050 based on long-term generation expansion scenarios, assuming the transmission grid would grow proportionally with generation capacity.

On the other hand, analysis of future demand for transmission components is often based on historic trade and manufacturing data (*BloombergNEF*, n.d.; Global Market Insights, 2025; U.S. Department of Energy, 2022) rather than modeled scenarios of grid expansion. However, recent historical data may underestimate market demand due to latent demand not being met by existing supply chains. In addition, recent electrification of transportation and industry, alongside growth in data centers, is increasing demand for electricity and electrical components at a higher rate than previously experienced (Shehabi et al., 2024; Zhou & Mai, 2021).

This report aims to address this gap by demonstrating methods to quantify future demand for transmission components from national-scale planning models. As securing materials and manufactured components becomes more difficult, developing linkages between power sector planning and transmission supply chain analysis can inform planning, manufacturing, and procurement strategies to reliably meet power system needs at lower cost.

1.1 Analysis Scope and Approach

This report outlines an analytical approach to quantify demand for critical transmission components and input materials from large-scale planning and operational grid studies. These components include large power transformers, generator step-up transformers (GSUs), converter transformers, transmission lines, circuit breakers, and transmission towers. We do not assess demand for transformers sized less than 100 MVA or the equipment required to make AC feasible in operation, such as reactive compensation components (reactors and capacitor banks) or synchronous condensers. Figure 1 illustrates the components included in this analysis and their relation to the rest of the electric power system.

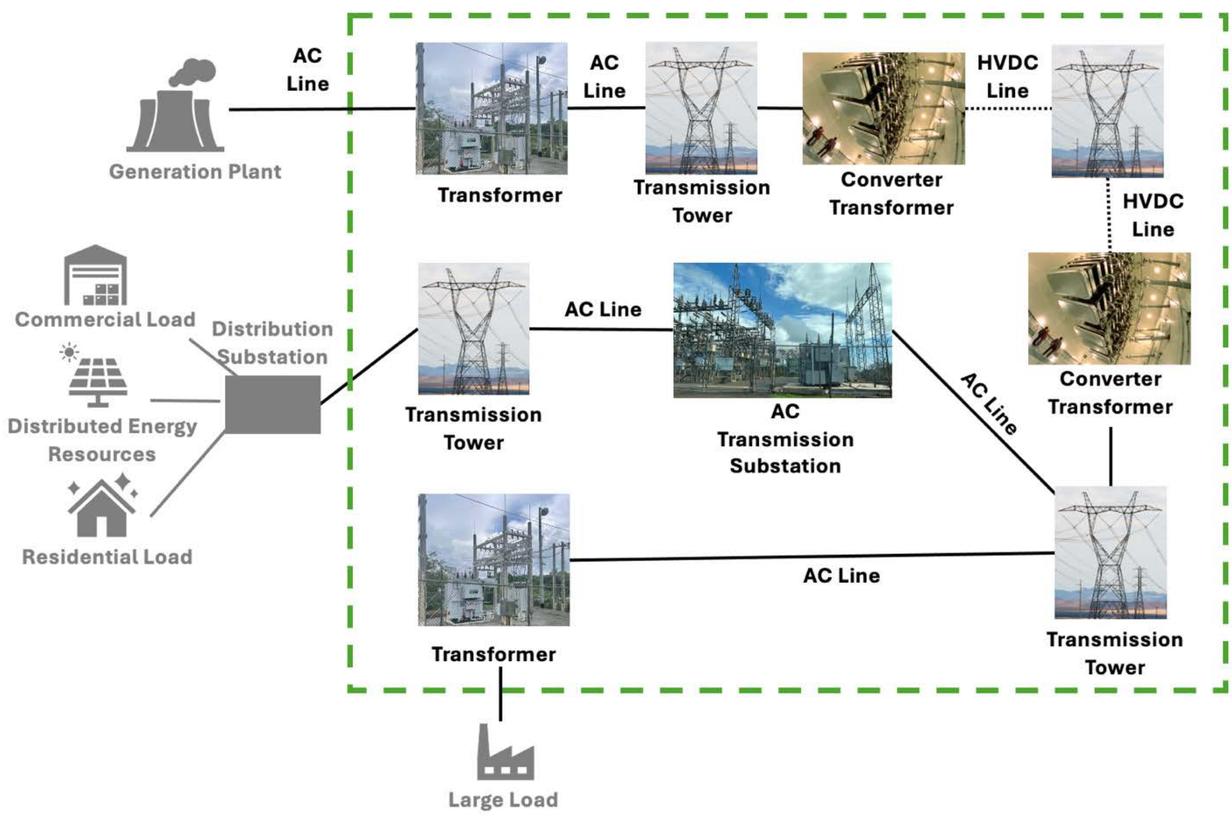

Figure 1. Transmission components included in this analysis

For each component, we present an approach to translate nodal transmission expansion results to demand for individual components and input materials. We also explore potential heuristics to derive transmission component demand from zonal capacity expansion models (CEMs) with coarse representation of the transmission grid.

The analytical approach is applied to two nodal transmission expansion and CEM scenarios from the National Transmission Planning Study (NTP) to illustrate the methods. These scenarios represent different transmission expansion strategies for the contiguous United States to the year 2035 (U.S. Department of Energy, Grid Deployment Office, 2024). The Alternating Current (AC) scenario includes AC transmission expansion within each interconnection. The Multiterminal (MT) scenario includes interregional transmission expansion across the country using both AC and multiterminal HVDC options between neighboring zones. These scenarios represent anticipated changes in the generation resource mix and demand growth at the time of the study and do not capture recent changes such as anticipated investment needs to accommodate increased demand from large loads. As the generation resource mix and anticipated demand growth continue to evolve, the analytical approach can be applied to new scenarios to reflect changing system conditions.

This report is focused on methods to derive demand for transmission components and input materials from large-scale planning models to inform supply chain analysis. As such, it does not address other important transmission supply chain issues, including workforce needs or component needs for distribution networks. We also do not investigate the causes of current transmission supply chain constraints nor seek to develop recommendations to address these constraints. In a subsequent report, we will identify competing demand from other energy sectors for input materials and the ability of domestic supply chains to meet anticipated demand for transmission components and input materials.

2 Methods and Assumptions

Nodal transmission expansion models, such as those developed in NTP, are designed to identify interregional transmission portfolios that can reliably meet demand under a range of network and operational constraints. These models primarily represent transmission expansion of individual transmission corridors including some estimate of new large power transformer capacity required at substations.[1] Other components, including GSUs, converter transformers, and circuit breakers, are not explicitly modeled. This section presents methods to translate the outputs from nodal transmission expansion scenarios—namely, circuit/transmission corridor additions, large power transformer capacity, and generator and storage capacity additions—to demand for transmission infrastructure components and input materials.

2.1 Transmission Lines

Transmission lines are the high-voltage cables that carry electricity over long distances. These cables are typically made of aluminum because of its high conductivity, low weight, and low cost; this aluminum is reinforced with steel for strength and support (INL, 2023).

Demand for new transmission lines and material requirements can be derived from model outputs on line voltage and nodal coordinates at each endpoint. The line length can be estimated based on the straight-line distance between nodal coordinates plus an adder to account for routing and line sag.[2] For AC and HVDC lines, Table 1 presents line type and material assumptions based on aluminum conductor steel reinforced (ACSR) type transmission lines. For advanced conductors, such as aluminum conductor steel supported (ACSS), we found the material requirements for aluminum and steel were less than 0.5% different than those required for ACSR type conductors.[3] However, an important caveat in these assumptions is that material requirements will be different for high-temperature low-sag transmission lines, or other lines that require different materials for differing mechanical strength needs. A thorough analysis of material requirements for more types of transmission lines is beyond the scope of this study.

[1] For more information on nodal transmission expansion in NTP, see Chapter 3 of (U.S. Department of Energy, Grid Deployment Office, 2024).

[2] The 2024 Midcontinent Independent System Operator *Transmission Cost Estimation Guide for MTEP24* (MISO, 2024) assumes a 30% adder for routing and 4% for line sag.

[3] We did not attempt to quantify any potential reduction in total conductor capacity required if ACSR conductors are replaced by advanced conductors.

Total aluminum and steel required for transmission lines can be calculated from modeled line type, bundling, and line length combined with material assumptions in Table 1.

Table 1. Line Type and Material Assumptions by Voltage

Voltage (kilovolts, kV)	Option	Line Type/Bundle	Weight per Bundle (pound [lb] per mile)	
			Aluminum	Steel
230	Standard	2 x Grosbeak	6,330	2,910
	High capacity	2 x Bluejay	11,130	2,160
345	Standard	2 x Bluejay	11,130	2,160
	High capacity	3 x Bluejay	16,690	3,240
500	Standard	4 x Grosbeak	12,660	5,820
	High capacity	6 x Bluejay	33,380	6,470
525 (HVDC)	High capacity	2x (bipole) 5 x Bluejay	55,650	10,800
765	Standard	6 x Bluejay	33,380	6,470

Sources: (CIGRE WG B4.72, 2020; De Angeli Prodotti, 2020; EPE, 2022).

2.2 Transformers

Transformers are used to efficiently step up voltage from generation sites for long-distance transmission and step down voltage for safe distribution to end users. Within the transmission network, transformer types consist of large power transformers, generator step-up transformers (GSUs), and converter transformers for HVDC applications. The key components are grain-oriented electrical steel (GOES), continuously transposed conductor (CTC) copper wire, insulating materials, and tap changers. Based on our review of materials with potential supply chain constraints, this analysis will focus on demand for GOES, steel, and copper for transformers.

2.2.1 Large Power Transformers

The demand for large power transformers is derived from estimates of transformer additions in the nodal expansion plan. In some cases, including NTP, transformer additions are added in terms of required megavolt-amperes (MVA) capacity at each substation rather than individual units available on the market.[4] High MVA requirements may require multiple transformers configured in parallel to achieve the required capacity. For higher-voltage applications, large power transformers available on the market are often single phase, requiring three appropriately arranged transformers for three-phase power. Table 2 presents assumptions for transformer sizes

[4] For example, NTP (U.S. Department of Energy, Grid Deployment Office, 2024) added transformer capacity in increments of 2,000 or 2,400 MVA.

available on the market and an example of how many transformers would be required to meet a 2,000-MVA capacity requirement.

In 2022, the U.S. Department of Energy estimates there are at least 170 large power transformers reaching end of life every year in the United States that may require replacement (U.S. Department of Energy, 2022). This could also be added to the demand estimate using a standard sizing assumption for transformers deployed in the past, such as 240 MVA.

Transformer capacity additions (in MVA) can be translated to demand for large power transformers using sizing assumptions for units available on the market, such as those in Table 2.

Table 2. Large Power Transformer Capacity Assumptions

Voltage (High/Low kV)	Phase	Capacity (MVA)	Number of Units Required for 2,000 MVA
345/138	3	700	3
345/230	3	700	3
500/230[a]	1	667	9
500/345[b]	1	667	9
765/500	1	667	9

[a]Assumed design from 765/230 kV units; [b]Assumed design from 765/345 kV units.

Source: (*HICO America*, n.d.)

2.2.2 HVDC Converter Transformers

The two dominant technologies for HVDC transmission are voltage source converter (VSC) and line-commutated converter (LCC) (Oni et al., 2016). In HVDC systems, an HVDC converter transformer serves two purposes. The first is to serve as an interface between the AC grid and the converters, adjusting to the required voltage at each end. The second purpose (for LCC HVDC systems) is to generate the 6-phase system required for the converter, decreasing the injection of harmonic currents into the grid, thereby enhancing power quality. In VSC systems, typically used in underground lines, short distances or offshore wind (Korompili et al., 2016), active and reactive power control happens independently. The size of the required converter transformers will depend on the HVDC technology. The apparent power capacity rating (MVA) is typically 1.05 to 1.15 times the active power (MW) capacity for VSC and 1.5 to 1.7 times the megawatt capacity for LCC to account for the reactive power requirements of the converters and associated compensation equipment. For example, a 1,000 MW HVDC line would require a 1,005- to 1,015-MVA converter using VSC or a 1,500- to 1,700-MVA converter using LCC. While HVDC expansion may include some combination of VSC and LCC technology, we use a conservative assumption that all converter-transformers are LCC type for this analysis.

Similar to large power transformers, the capacity added in a nodal transmission expansion scenario may not align with unit sizes available on the market and must be converted. Some companies offer single-phase converter transformers of approximately 600 MVA (China XD, n.d.; GE Grid Solutions, 2019; Rahimo & Klaka, n.d.). Figure 2 shows a simplified converter transformer configuration for a potential 4,000-MW LCC HVDC bipole.

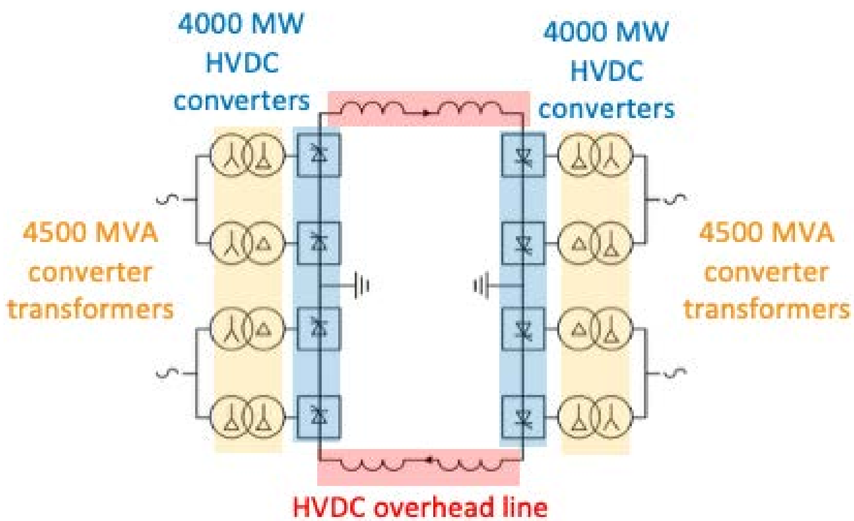

Figure 2. Proposed configuration for HVDC converter transformer for 4,000-MW HVDC bipole

In the example in Figure 2, twelve 400-MVA single-phase transformers would be required on each end of the HVDC line, or 24 converter transformers in total, to meet the required capacity for a 4,000-MW HVDC bipole. This assumes a 525-kV HVDC line.

Converter transformer requirements (in MVA) can be derived from the HVDC transmission line carrying capacity (MW) and technology type (VSC vs. LCC). The number of units can be calculated from unit sizes currently on the market.

2.2.3 Generator Step-Up Transformers

GSUs increase the low-voltage output from a generator to a higher voltage required for power transmission. Unlike other power transformers, GSU additions are not typically modeled explicitly in nodal transmission expansion models. Instead, the number and size of GSUs can be derived from model outputs on the number of generating units and MVA ratings for these additions.

For new generating stations, the GSU transformer size must meet the MVA rating of the generating units, and the number of GSUs is based on the number of generating units. For example, a new generating station with five units, each with an MVA rating of 195, would require five 200-MVA GSUs. In other words, **demand for GSUs can be derived from the number of generating units and MVA ratings for each unit. Standard sizes for transmission applications range from 100 MVA to 1,000 MVA.**

Using detailed industry planning cases for the Western Electricity Reliability Council (Western Electricity Coordinating Council, 2022) and Eastern Interconnection Reliability Assessment

Group,[5] we assume new GSUs are available in seven ratings (MVA): 100, 200, 400, 600, 800, 1,000, and 1,500.[6]

2.2.4 Material Requirements for Transformers

The transformer size, and the underlying material requirements, can vary significantly based on the rating of the transformer. In transmission applications, large power transformers can range from 100 MVA to more than 1,000 MVA. To estimate how transformer weight changes with MVA rating, we reviewed life cycle assessments for 18 power transformers with sizes ranging from 1 MVA to 750 MVA (Guo et al., 2022, 2022; Krishnan & Nair, 2019; Liu et al., 2025; U.S. Department of Energy, 2022). Figure 3 shows the trends in transformer weight, in kilograms (kg), as a function of MVA rating.

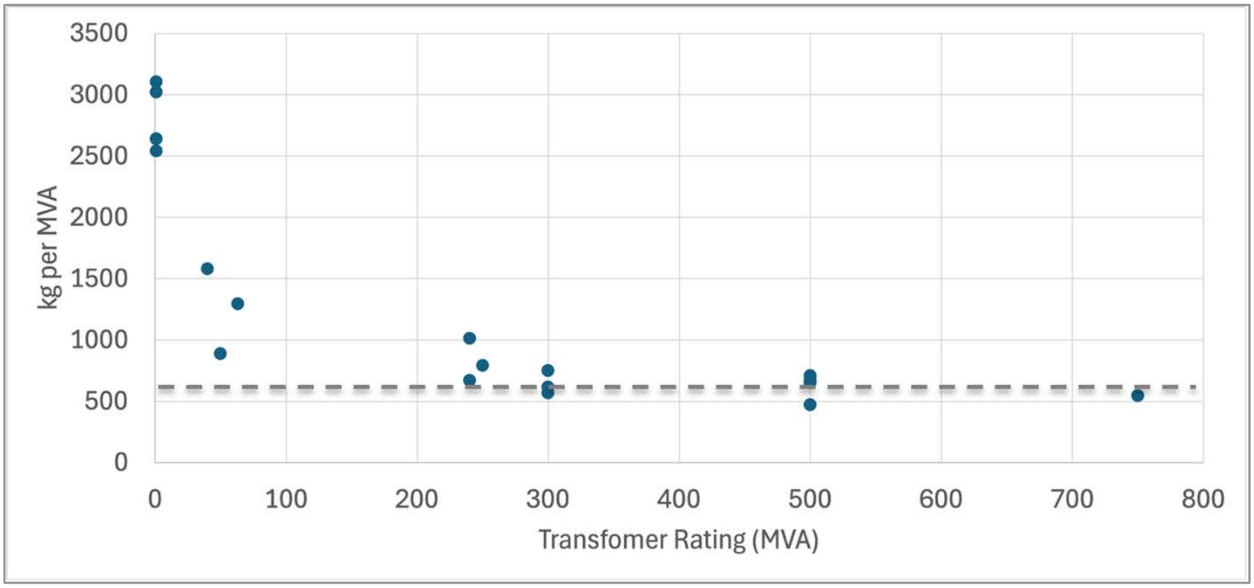

Figure 3. Trends in transformer weight per MVA rating.

Dashed line indicates the average weight per capacity for transformers between 100 and 1,000 MVA.

The life cycle assessments reveal that transformer weight per MVA rating decreases as the rating increases. However, for large power transformers above 100 MVA—the focus of this analysis—the size per MVA begins to stabilize, around 600 kg (1,323 lb) per MVA.

Although each transformer may have a slightly different design, the transformer core, comprising GOES, non-GOES steel, and thin insulating material, typically accounts for 60% to 70% of the unit's weight (U.S. Department of Energy, 2014, 2022). Windings account for 20% to 30% of the weight (U.S. Department of Energy, 2014, 2022), with large power transformers typically

[5] The Eastern Interconnection Reliability Assessment Group oversees the Multiregional Modeling Working Group, which is responsible for assembling nodal network models for the Eastern Interconnection (among other responsibilities).

[6] This analysis excludes GSUs <100 MVA in line with the U.S. Department of Energy's definition of a large power transformer (U.S. Department of Energy, 2022).

using more copper instead of aluminum to handle higher currents. Table 3 shows the assumed material concentrations for steel, GOES, and copper used in large power transformers.

Table 3. Material Concentrations for Large Power Transformers

Material	Share of Total Weight (%)
Steel, non-GOES	12%
GOES	48%
Copper	30%
Other[1]	10%

[1]"Other" includes concrete, ferrite, transformer oil, plastic, and epoxy resin.

Sources: U.S. Department of Energy, 2014, 2022.

Material requirements for new large power transformers, converter transformers, and GSUs can be calculated based on an assumed weight of 600 kg per MVA and the material concentrations in Table 3.

2.3 Circuit Breakers

Circuit breakers are used to interrupt electrical circuits to protect critical equipment in case of faults, isolate faulted sections of the power grid, and open or close transmission lines and transformers to place grid components into or out of service. AC circuit breakers use a medium such as compressed air or sulfur hexafluoride (SF6) to extinguish electrical arcs that can occur when contacts are separated in the process of interrupting high-voltage electricity. For DC current, the arc is more difficult to extinguish because DC has no natural zero-crossing point like AC, requiring a separate design to create an artificial zero current. The main DC circuit breaker types are mechanical circuit breakers, solid-state circuit breakers, and hybrid circuit breakers that combine the breaking capability of mechanical circuit breakers with the speed of solid-state circuit breakers (ENTSOE-E, 2025). Although mechanical circuit breakers can use gas or air, solid-state circuit breakers use semiconductor devices and software instead of an arc-quenching media.

Nodal transmission models do not typically explicitly model circuit breakers unless for the purposes of detailed studies when needed (for example, when examining protection or insulation coordination). Instead, the demand for new circuit breakers can be derived from the number of new transmission lines and transformers in the planned scenario. In line with industry planning standards, we assume a breaker-and-a-half configuration for each new transmission line and transformer (PG&E, 2017). Converter transformers are assumed to have a DC circuit breaker on the DC side of the transformer, as well as a sufficient technology readiness level to be operationally utilized when needed on the planning horizon of 10 years. AC circuit breakers are assumed to be gas insulated for high-voltage (500-kV and above) applications and in coastal/urban areas. All other substations are assumed to use air-insulated AC circuit breakers.

Although assembled circuit breakers are identified as a critical supply chain constraint (IEA, 2025), many of the input materials, including aluminum, steel, and copper, may also face supply chain shortages. Table 4 shows estimated material concentrations for gas-insulated and air-insulated switchgear, comprising circuit breakers, fuses, and switches housed inside a metal enclosure, to give an idea of how the material requirements may vary for enclosed switchgear applications (Harrison et al., 2010).

Table 4. Material Concentrations for Gas-Insulated and Air-Insulated Circuit Breakers (tons/breaker)

Material	Gas-Insulated	Air-Insulated
Aluminum	9.3	0.2
Steel	3.9	0.7
Copper	2.0	0.1
Porcelain	-	1.0
Other[1]	minor	2.0

Based on 275-/400-kV circuit breakers; does not include materials for arc suppression mechanism and other design changes required for DC switchgear.

[1]Includes foundations and steel work for busbar supports, gantries, and connectors.

Requirements for circuit breakers can be calculated based on a breaker-and-a-half configuration for each new transmission line and transformers, excluding GSUs, with material weights presented in Table 4. Gas-insulated circuit breakers are appropriate for substations in costal/urban areas or high-voltage (500 kV and above) or DC applications coastal/urban areas. All others may use air-insulated types.

2.4 Transmission Towers

Transmission towers are the structures used to support overhead transmission lines. The tower design will vary, depending on the line type and voltage as well as environmental and site-specific factors such as temperature, wind, and ground clearance requirements. The primary input material is steel. Although we did not find evidence of supply chain constraints to procure transmission towers, we include them in this supply chain analysis because the requirement for steel may be significant and potentially impact the price and availability of procurement.

Transmission towers are not included in nodal expansion models, but demand for new towers can be estimated based on the number, voltage, and estimated length of new transmission lines. Table 5 presents sample data that can be used to calculate the number of structures and steel required per mile for different line types. In this example, MISO (2024) data was used which includes a 500 kV DC tower type, which we assumed to be the same tower to be used for our modelled 525 kV DC lines.

Table 5. Requirements for Transmission Towers by Line Type and Voltage

Voltage (kV)	Line Type	Structure Type	Structures per Mile				Weight per Structure (U.S. ton)			
			Tangent	Running Angle	Non-Angled Deadend	Angled Deadend	Tangent	Running Angle	Non-Angled Deadend	Angled Deadend
230	AC	Double-circuit steel pole	7	1	0.25	0.25	9.3	12.3	13.7	21.4
345	AC	Double-circuit steel pole	6	1	0.25	0.25	18	23.9	27.0	42.3
500	AC	Single-circuit steel pole	3	1	0.25	0.25	17.6	29.9	33.4	40.4
765	AC	Single-circuit steel pole	3.5	0.25	0.125	0.125	26.4	74.5	77.4	77.4
500	DC	Single-circuit steel tower	3.5	0.5	0.25	0.25	13.5	19.9	23.0	29.7

Source: MISO, 2024.

3 Case Studies

To illustrate the approach outlined in Section 2, we estimate demand for transmission components and input materials from two NTP nodal transmission scenarios for the year 2035 (U.S. Department of Energy (DOE), 2024). The AC scenario only allows expansion of AC transmission lines within each interconnection (Figure 4). The MT scenario includes interregional expansion across the contiguous United States, using both AC and multiterminal HVDC options (Figure 5).

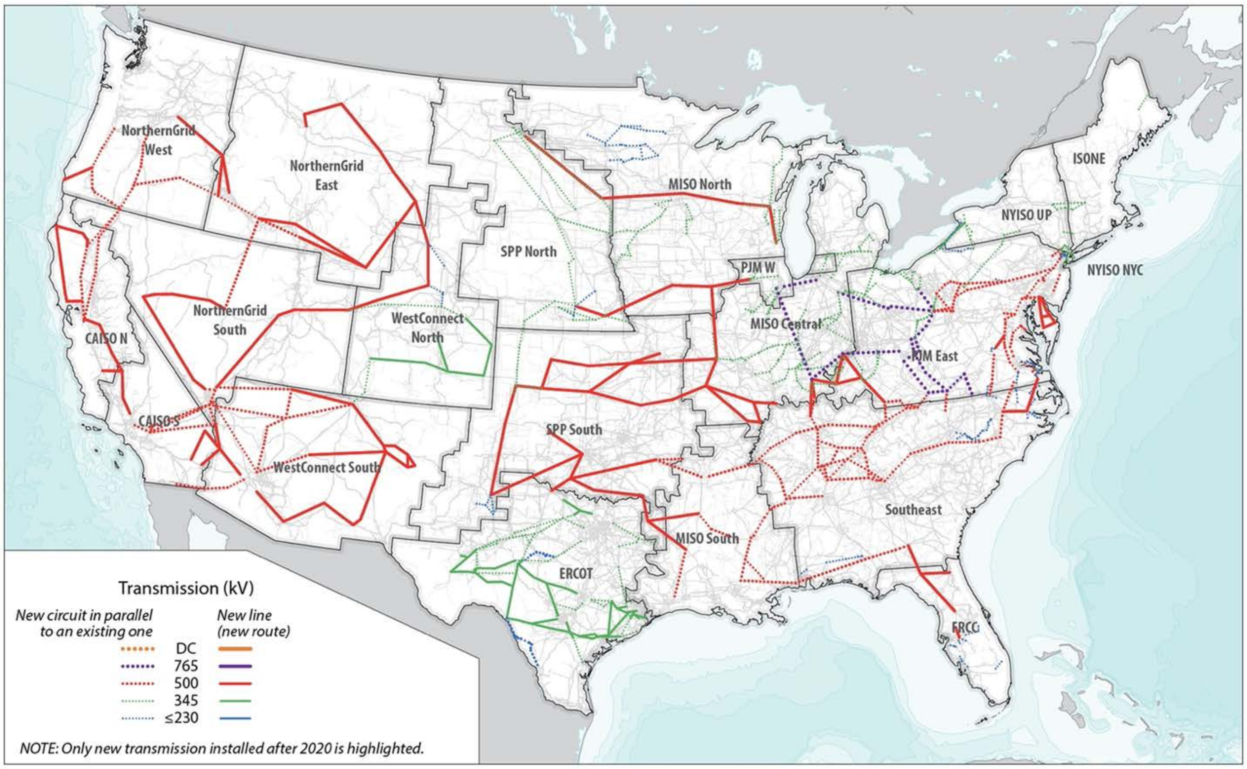

Figure 4. Nodal transmission expansion for the AC scenario for the model period 2025–2035

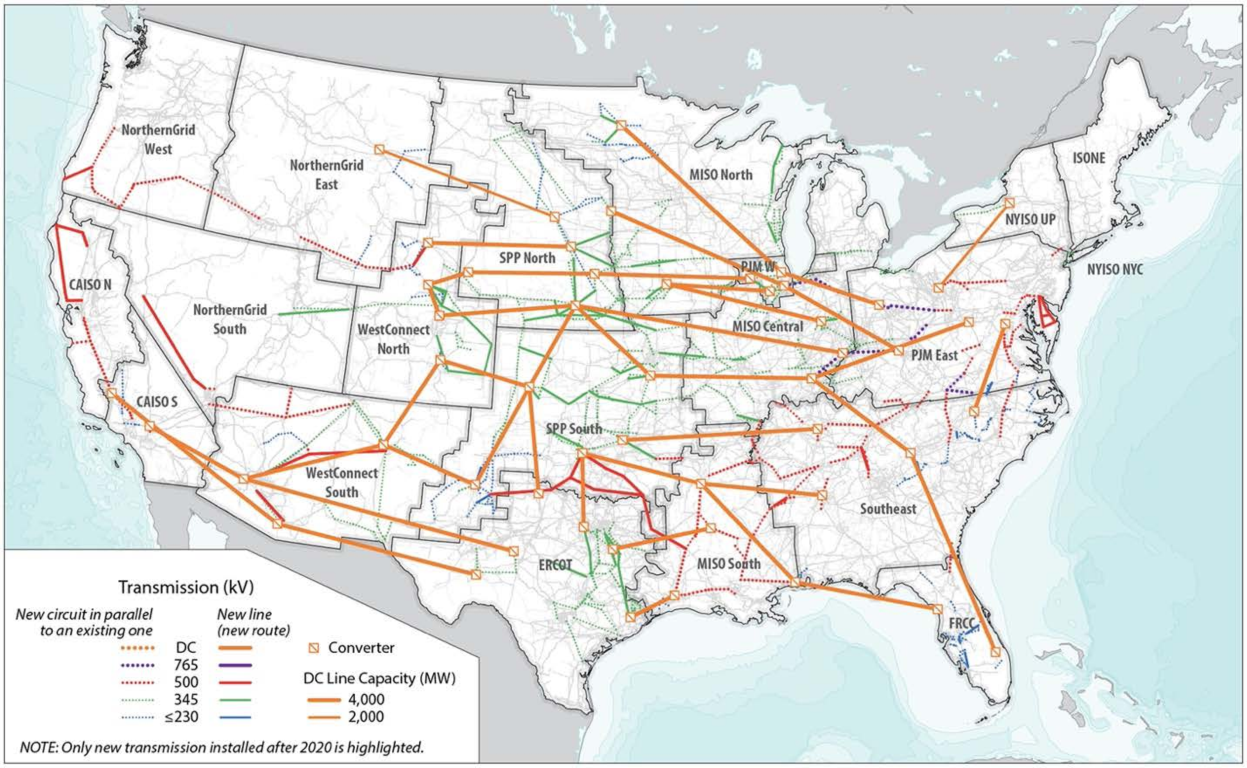

Figure 5. Nodal transmission expansion for the MT scenario for the model period 2025–2035

3.1 Transmission Lines

The NTP outputs include the number and voltage of new transmission lines as well as the coordinates for the transmission line endpoints. AC transmission lines have voltages of 230, 345, 500, or 765 kV; DC transmission lines are assumed to be 525 kV DC. In the AC scenario, 1,019 new transmission lines were added. The MT scenario included 914 new AC and 40 new DC transmission lines.

We calculate the estimated length of each new transmission line as the straight-line distance between nodal coordinates plus a 30% adder to account for routing constraints and a 4% adder for line sag. Figure 6 summarizes the estimated length by voltage and scenario.

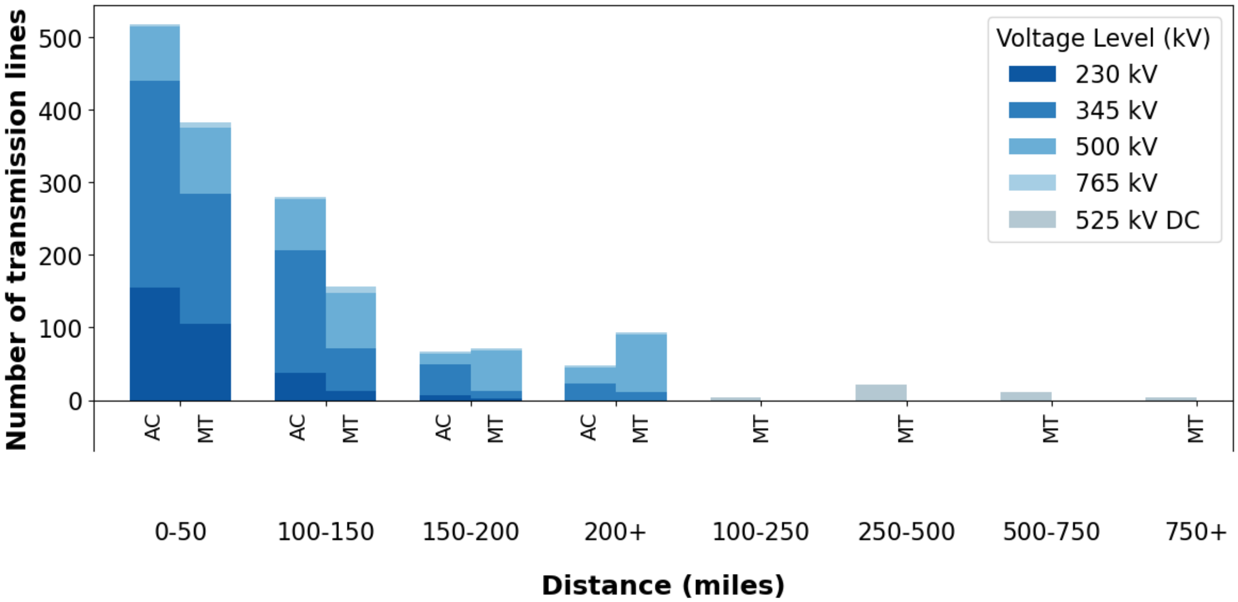

Figure 6. Estimated length of the given number of new transmission lines by voltage for the AC and MT scenarios

In total, 50,350 miles of new transmission lines are added in the AC scenario, and 68,440 miles are added in the MT scenario, including 18,890 miles of HVDC. Although the MT scenario has 6% fewer new transmission lines, it has a higher share of longer-distance lines, resulting in more miles of new transmission overall. Over the 10-year model horizon, this averages to 5,000 and 6,800 miles of new high-voltage transmission per year in the AC and MT scenarios, respectively.

Using the line type and material assumptions in Table 1, the total aluminum and steel requirements for new transmission lines are summarized in Table 6. The requirements for aluminum and steel assume AC transmission lines require three conductors per line for three-phase power while HVDC lines only require two conductors per line.

Table 6. Aluminum and Steel Requirements for New Transmission Lines 2025–2035 (thousand tons)

Scenario	Aluminum	Steel
AC	1626	318
MT	1973	386

3.2 Transformers

The NTP transmission solutions include estimates for new large power transformers at substations but do not explicitly consider converter transformers or GSUs.

Additions for large AC power transformers are reported in terms of high/low voltage and an MVA rating of 2,000 or 2,400. The sizing assumptions for large power transformers in Table 2 are used to convert these additions to standard unit sizes available on the market. Figure 7 compares the transformer additions reported from the NTP study and the number of new transformer units required to meet this demand. We estimate a total of 1,914 and 474 large power transformers are needed by 2035 for the AC and MT scenarios, respectively.

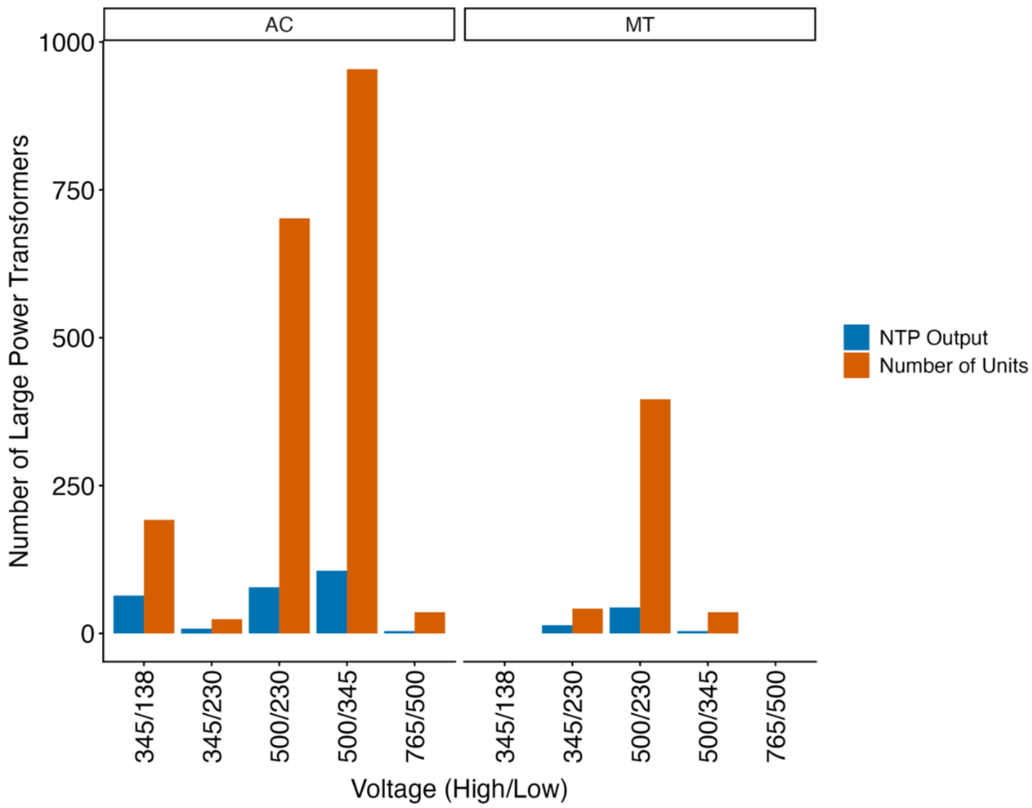

Figure 7. Number of large power transformer units required for the NTP transmission solutions 2025–2035 converted from NTP output for large power transformer capacity

In addition, we assume 170 new large power transformers are required each year, or 1,700 over the 10-year planning period, for end-of-life replacement of existing units. We do not have data on the size of the existing transformer stock and assume the replacement units are 240 MVA.

The MT scenario includes forty new 4,000-MW HVDC bipole circuits. We assume these will require twelve 400-MVA single-phase converter transformers on each end, or twenty-four total for each HVDC line. Similar to AC transformers, we do not include estimates for strategic spare transformers. In total, 960 converter transformers are required over the 2025–2035 planning period.

To estimate demand for GSUs, we use the NTP scenario outputs for the number of generating units and MVA rating of each unit. We exclude units with an MVA rating of less than 50, which may require smaller GSUs outside the scope of this analysis, which is focused on large power transformers. After these exclusions, the AC scenario includes 2,638 new generating plants comprising more than 14,000 individual units. The MT scenario includes 2,445 new generating plants and more than 13,000 new units.

Each new generating plant is assigned GSUs sufficient to cover the total MVA requirement of all units in the plant. We assume GSU size options are 100, 200, 400, 600, 800, 1,000, and 1,500 MVA. We determine the required GSU size for each plant based on the MVA rating of the individual units, rounded up to the next nearest size option. Table 7 summarizes the total GSUs required for each size option and scenario.

In general, most new GSUs are 100 MVA with more than 99% of new GSUs with a capacity of 400 MVA or less. Only nuclear plants require GSUs with capacities above 400 MVA (Figure 8). The GSU requirements average to 1,150 and 1,060 units per year in the AC and MT scenarios, respectively. These quantities align with recent estimates for the U.S. GSU market over the same period of 1,000–1,300 units per year (Wood Mackenzie, 2025).

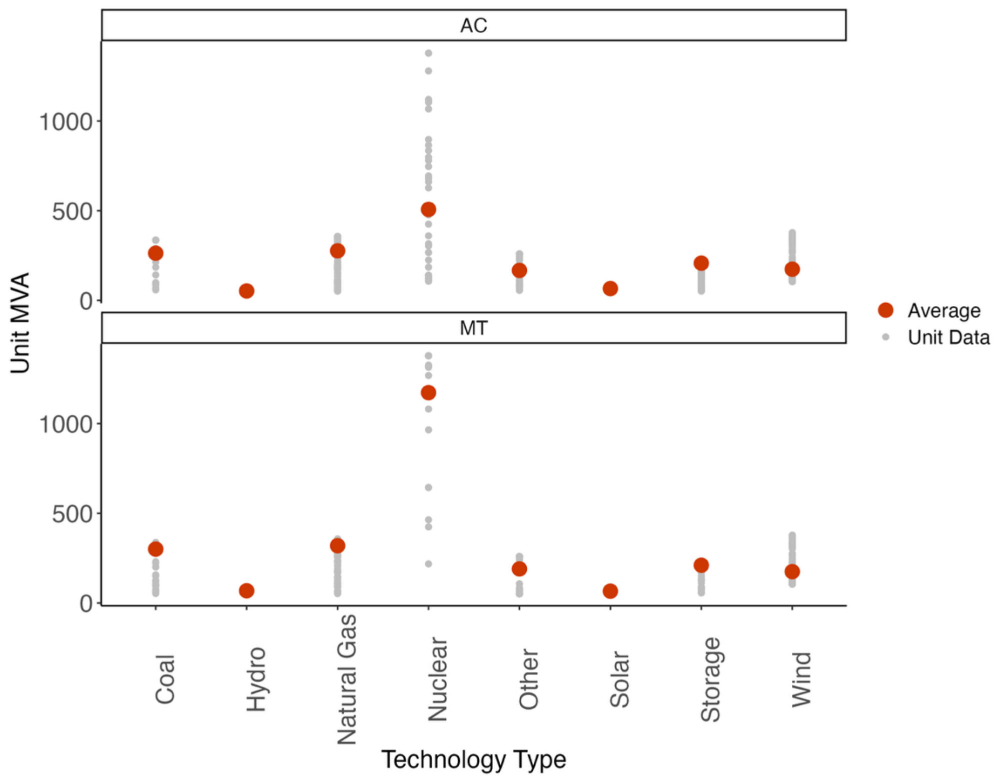

Figure 8. MVA rating for generating units by technology type and scenario

Across all transmission transformer categories, the AC scenario requires 15,094 new transformers or an average of 1,510 transformers per year. The MT scenario requires 13,713 transformers or 1,370 per year on average. GSUs account for more than 75% of new transformer requirements.

Table 7. Number of GSUs Required in Each Scenario by Unit Size 2025–2035

GSU Capacity (MVA)	AC	MT
100	7,054	5,922
200	2,939	3,147
400	1,467	1,483
600	3	2
800	7	2
1,000	3	1
1,500	7	22
Total	**11,480**	**10,579**

Using the MVA rating for each transformer and material concentrations from Table 3, we calculate the total material requirements for each scenario in Table 8.

Table 8. Material Requirements for New Transformers 2025–2035 (thousand tons)

Material	AC	MT
Steel (non-GOES)	285	235
GOES	1,140	940
Copper	710	590
Other[1]	240	200

[1]"Other" includes concrete, ferrite, transformer oil, plastic, and epoxy resin.

3.3 Circuit Breakers

The demand for new circuit breakers is derived from the number of new transmission lines, large power transformers, replacement transformers, and converter transformers. We exclude the circuit breakers for GSUs. For each component, we assume a breaker-and-a-half configuration or 1.5 circuit breakers on each end of a transmission line or transformer.

To determine the type of circuit breaker required, we conducted geospatial analysis of the nodal dataset to identify nodes that meet the criteria for gas-insulated circuit breakers (Marine Cadastre, 2024; U.S. Census Bureau, 2020).[7] The criteria include nodes with voltages of 500 kV and above or nodes in coastal or urban areas. In total, 91% of nodes meet one of these criteria for gas-insulated circuit breakers. All others are assumed to have air-insulated circuit breakers.

Table 9 summarizes the requirements for gas- and air-insulated circuit breaker units for each scenario, and Table 10 summarizes the total material requirements.

[7] The NTP (U.S. Department of Energy, Grid Deployment Office, 2024) solutions contained more than 120,000 nodes across the contiguous United States.

Table 9. Requirements for Circuit Breakers by Breaker Type and Scenario 2025–2035

Number of Circuit Breakers	AC	MT	
		AC	DC
Gas-Insulated	12,710	8,440	3,000
Air-Insulated	1,190	830	-
Total	**13,900**	**9,270**	**3,000**

Table 10. Material Requirements for New Circuit Breakers 2025–2035 (thousand tons)

Material	AC	MT
Aluminum	118	107
Steel	50	45
Copper	26	23
Porcelain	1	1
Other[1]	2	2

[1]"Other" includes foundations and steel work for busbar support, gantries, and connectors.

3.4 Transmission Towers

The number and type of towers are estimated based on the number, voltage, and estimated length of new transmission lines (Section 2.4). The AC and MT scenarios require approximately 250,000 and 350,000 transmission towers, respectively, with tangent towers accounting for the largest share (Table 11). The additional transmission towers in the MT scenarios equates to an additional 1 million U.S. tons of steel required.

Table 11. Estimated Number of Transmission Towers Required

Scenario	Tower Type				Total Number of Towers	Total Steel (thousand tons)
	Tangent	Running Angle	Non-Angled Deadend	Angled Deadend		
AC	175,070	49,100	12,380	12,380	248,940	5,300
MT	270,650	58,160	16,970	16,970	362,740	6,300

3.5 Annual Demand for Transmission Components and Materials

The demand estimates for transmission components and materials presented in the previous sections can be combined to characterize annual demand over the 2025–2035 planning period. Figure 9 shows the annual demand for transmission components for transmission lines, transformers, circuit breakers, and towers broken down by component type, and Figure 10 shows the total material requirements across all component categories.

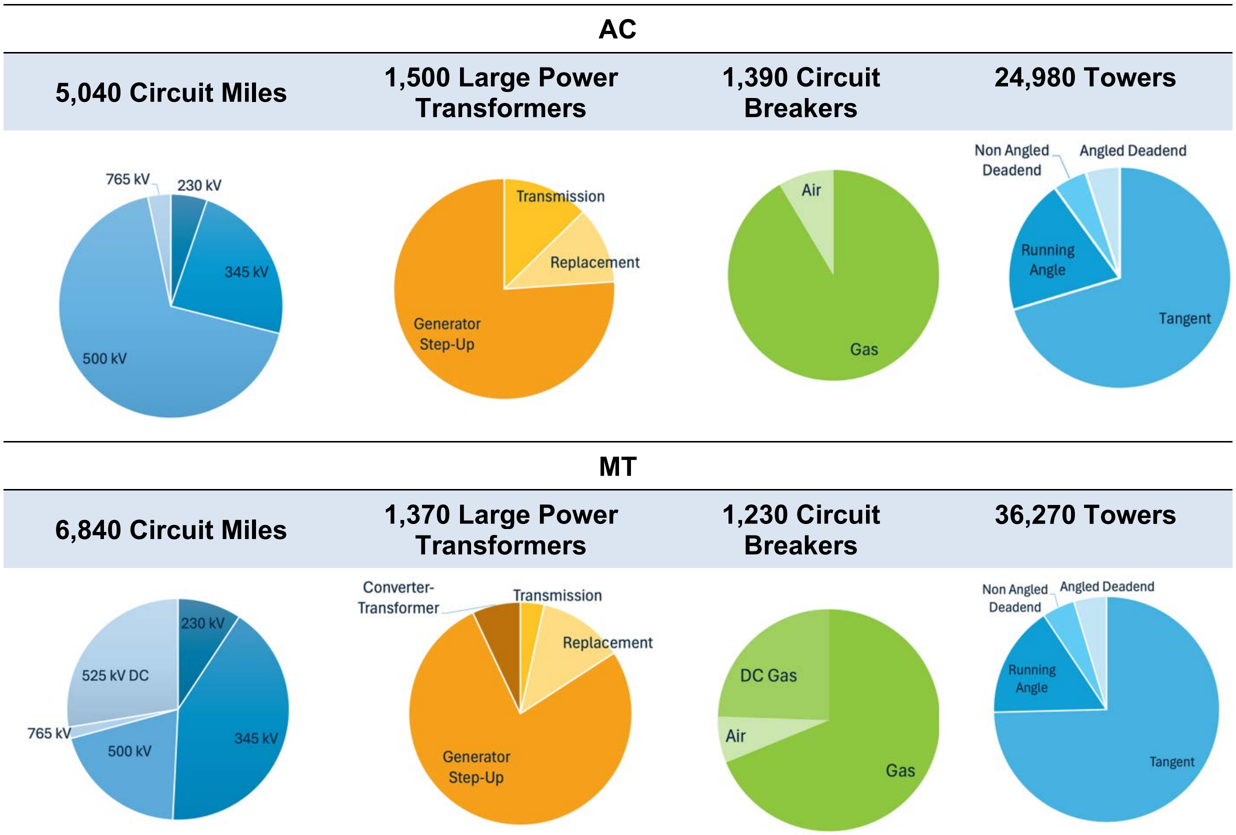

Figure 9. Summary of annual transmission component requirements by scenario

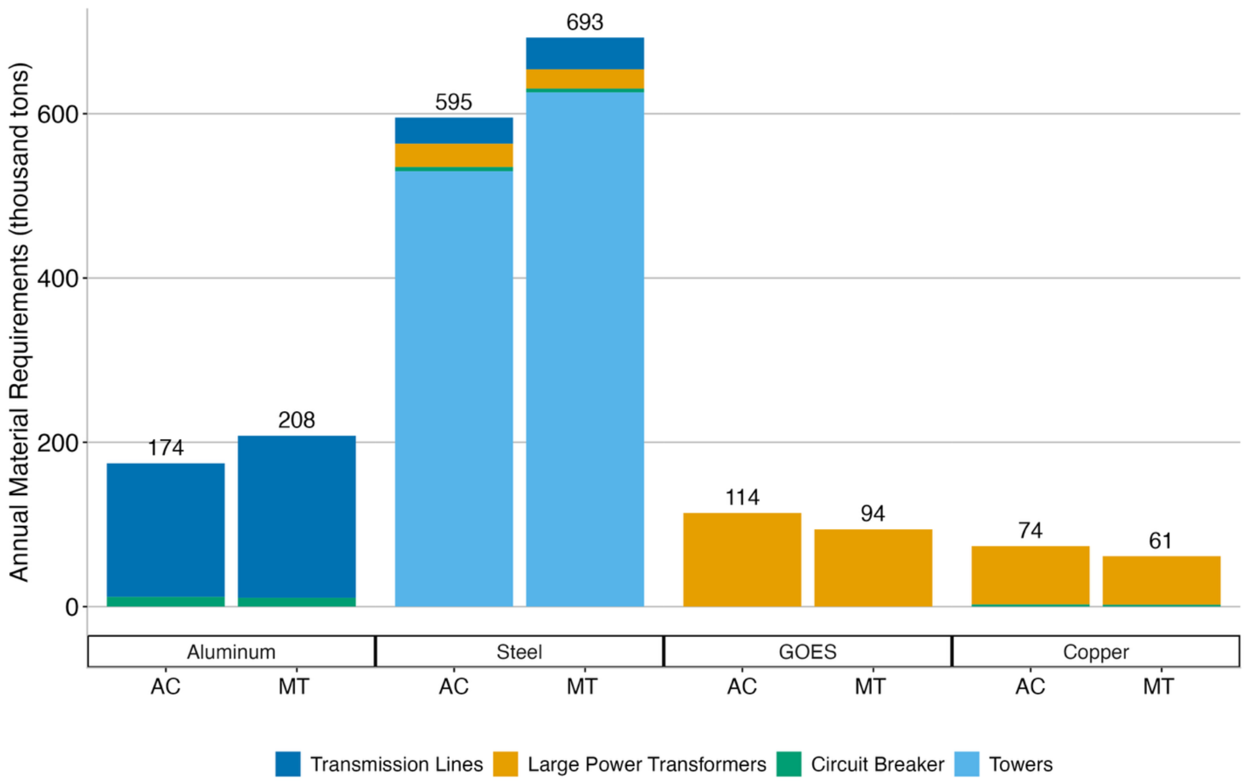

Figure 10. Annual material requirements by scenario across all component categories

Transmission expansion under either future scenario would require an average annual supply of 174–208 thousand tons of aluminum, 595–693 thousand tons of steel, 94–114 thousand tons of GOES, and 61–74 thousand tons of copper. This represents less than 4% of the average annual apparent consumption for aluminum, steel, and copper in the United States over the 2019–2023 period (USGS, 2024). For GOES, this level of annual demand is equivalent to more than 45% average annual apparent consumption over the same period (U.S. International Trade Commission, n.d.). Transmission towers have the largest input material requirement followed by transformers and transmission lines. The MT scenario requires more aluminum and steel as a result of longer transmission lines and greater demand for transmission towers. The AC scenario requires more GOES and copper to meet increased demand for transformers.

4 Estimating Component Demand From Capacity Expansion Models

CEMs are used to plan future energy systems by determining the optimal mix of generation and infrastructure investments, typically over a time horizon spanning decades. Although CEMs can explore a broad suite of power system investment pathways, they often assume transmission equipment is readily available for deployment. Estimating transmission component demand from CEM scenarios can provide an early assessment of the feasibility of the planned system and highlight potential areas of risk to long-term resource adequacy, given the existing and anticipated capability of component supply chains to meet this demand.

Because of computational constraints, CEMs often simplify the representation of the transmission grid with less technical and spatial resolution than a detailed nodal production cost model. Common simplifications include representing the grid as large zones or regions with assumed internal transmission networks that does not constrain the internal operation, characterizing transmission capacity and expansion through transmission corridors rather than individual lines, and capturing power flow direction and magnitude without accounting for reactive power requirements and detailed network topology. Similarly, the outputs from CEMs include less system detail than from a nodal production cost model. Transmission investment outputs may be limited to increases in transfer capacity between zones in terms of megawatts or megawatt-miles. Generation investment outputs may include total capacity added by technology type in each zone with no plant or unit level information.

This section explores potential heuristics to derive estimates for transmission component or material demand from CEMs. To develop these heuristics, we calibrate the component demand calculated from the NTP AC and MT scenarios using the nodal production cost model results to zonal CEM outputs developed using the Regional Energy Deployment System (ReEDS™) model for the same scenarios (Chapter 2, U.S. Department of Energy, Grid Deployment Office, 2024). The AC scenario does not allow economic investments in the new DC capacity but does include planned DC connections expected to come online during the planning horizon or expansion of existing DC corridors. It should be noted that some of these metrics could have dependencies on the heuristics that were used to translate zonal CEM results to the nodal PCM results.

4.1 ReEDS Outputs

The ReEDS CEM outputs transmission investments in terms of additional transfer capacity (MW) between zones and total gigawatt-mile (GW-mile) of transmission investments for each modeled year. These data are separated for AC and DC investments. Generation investments include total capacity (MW) added in each location and modeled year, separated by generator type. Table 12 shows the relevant ReEDS outputs for the AC and MT scenarios.

These outputs will form the basis for our heuristics to estimate demand for transmission components given only investments in transmission capacity and generation capacity.

Table 12. ReEDS Transmission and Generation Additions for the Interzonal AC and MT Scenarios

Technology		AC	MT
Transmission (GW-mile)	AC	82,770	70,920
	DC	2,940[1]	98,040
	Total	**85,710**	**168,960**
Generation (GW)	Coal	56	55
	Geothermal	3	3
	Hydropower	27	34
	Natural Gas	104	106
	Nuclear	30	30
	Solar	668	567
	Storage	129	55
	Wind	647	728
	Waste	4	4
	Other[2]	48	49
	Total	**1,716**	**1,631**

[1]The AC scenario does not allow economic investments in new DC capacity but does include planned DC connections expected to come online during the planning horizon or expansion of existing DC corridors.

[2]"Other" includes pumped storage hydropower, oil-gas-steam turbines, and hydrogen combustion turbines.

4.2 Heuristics for Estimating Component Demand From CEM Results

We use the capacity demand requirements calculated from the nodal expansion model in Section 3 to develop simple metrics for component and/or material requirements from ReEDS CEM results. These metrics, based on two CEM scenarios, can be interpreted as a starting point for calibrating supply chain needs from CEM results. This initial assessment can be strengthened through additional scenarios and capacity expansion modeling to characterize the range of component and/or material needs and uncertainties associated with each.

4.2.1 Transmission Lines

For transmission lines, we estimate the total material required for aluminum and steel per gigawatt-mile of transmission added (Table 13). We focus on material requirements rather than the number of lines because line lengths may vary significantly across scenarios, which makes the number of transmission lines difficult to estimate. For example, the MT scenario adds 6% fewer transmission lines but 97% more transmission capacity in gigawatt-mile terms than the AC scenario.

Table 13. Aluminum and Steel Requirements for Transmission Lines per Gigawatt-Mile of Transmission

		ReEDS Output	Nodal Expansion Analysis		Calculated Heuristic	
Scenario	Line Type	Transmission Investment (GW-mile)	Material Requirements (thousand tons)		Ton per GW-mile	
			Aluminum	Steel	Aluminum	Steel
AC	AC[1]	82,770	1,626	318	19.6	3.8
MT	AC[1]	70,920	1452	285	20.5	4.0
	DC[2]	98,040	521	101	5.3	1.0

[1]AC includes "AC," "Reinforcements," "Spur"; [2]DC includes Back-to-Back ("B2B"), "DC, LCC," and "DC, VSC."

AC lines require around 20 tons of aluminum and 4 of tons steel per gigawatt-mile, while DC lines require around 5 tons of aluminum and 1 ton of steel per gigawatt-mile (Table 13).

4.2.2 Transformers

Requirements for new large power transformers are driven by both transmission and generation investments. We use transmission investments to estimate requirements for large power transformers and converter transformers and generation investments to estimate requirements for GSUs. Table 14 shows the calibration of large power transformers to transmission investments.

Table 14. Large Power Transformer and Converter Transformer Requirements per Gigawatt-Mile of Transmission

		ReEDS Output	Nodal Expansion Analysis	Calculated Heuristic
Scenario	Line Type	Transmission Investment (GW-mile)	Transformer Units[3]	Transformers per GW-mile
AC	AC[1]	82,770	3,614	0.044
MT	AC[1]	70,920	2,714	0.038
	DC[2]	98,040	960	0.0098

[1]AC includes "AC," "Reinforcements," "Spur"; [2]DC includes "B2B," "DC, LCC," "DC, VSC"; [3]AC transformer units include 170 replacement transformers per year.

From the nodal analysis, the average size for large power transformers was 667 or 700 MVA for AC transformers and 400–600 MVA for converter transformers. **AC transmission lines require around 0.05 large power transformer per gigawatt-mile sized 667–700 MVA, while DC transmission lines require around 0.01 converter transformer per gigawatt-mile sized 400–600 MVA.**

Generation technologies can vary widely in terms of plant and unit size. Therefore, we derive technology-specific assumptions for the size and number of GSUs. Figure 11 shows the trends in MVA rating by technology and scenario.

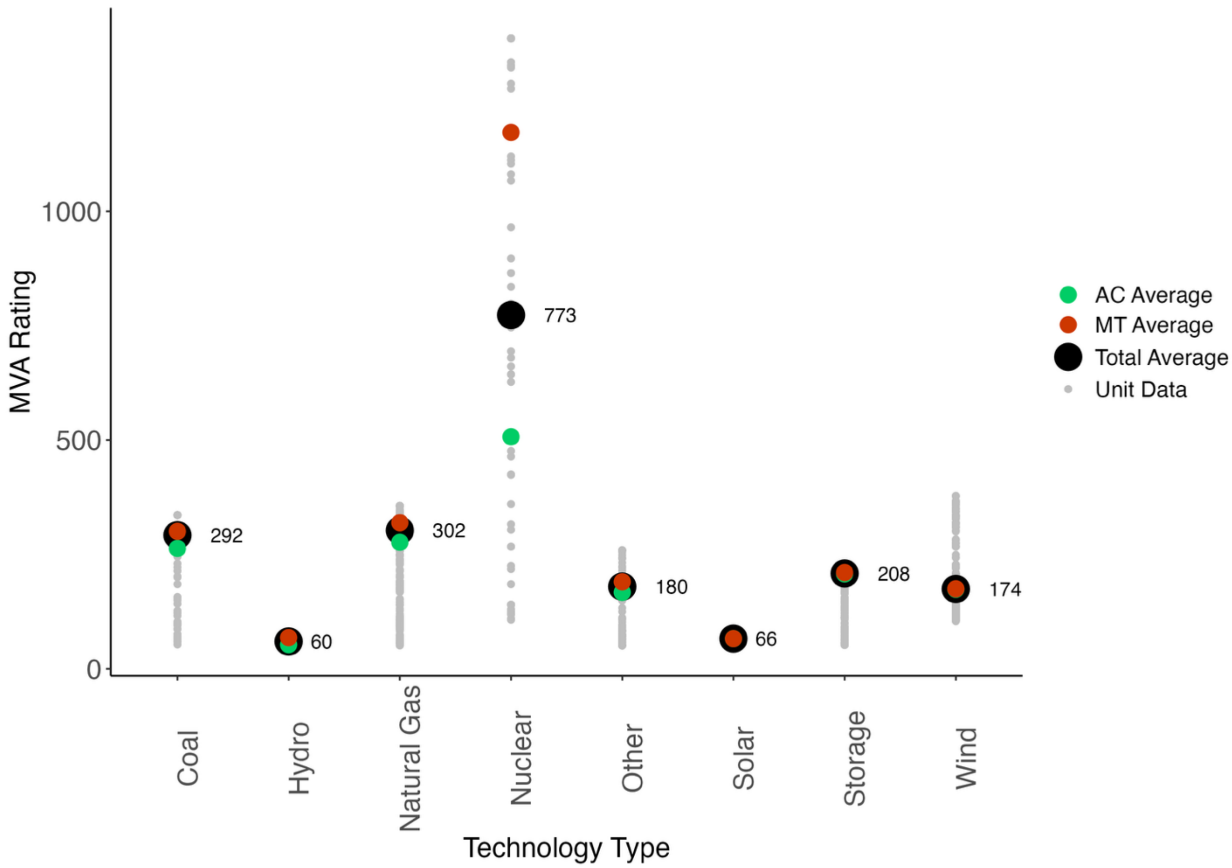

Figure 11. MVA rating by technology and scenario.

Excludes units with MVA < 50. The green and red circles indicate the average MVA by technology for AC scenario and MT scenarios, respectively. The black circle is the average MVA by technology across both scenarios. "Other" includes pumped hydro, oil-gas-steam turbines, and hydrogen combustion turbines.

With the exception of nuclear technologies, average GSU sizing is consistent across scenarios (Figure 11). GSUs for geothermal, municipal waste, and wood waste plants were below 50 MVA for all units and are not included in these estimates.

We calculated a heuristic GSUs per GW using the new capacity built from the ReEDS model and the number of GSUs estimated in the nodal expansion analysis (Table 15).

Table 15. GSU Requirements per GW Installed Generation Capacity by Technology Type

	ReEDS Output		Nodal Expansion Analysis		Calculated Heuristic		
Technology Type	New Capacity (GW)		Number GSUs		GSUs per GW		
	AC	MT	AC	MT	AC	MT	Average
Coal	56	55	42	145	0.8	2.6	**1.7**
Hydro	27	34	334	275	12.4	8.1	**10.2**
Natural Gas	104	106	222	339	2.1	3.2	**2.7**
Nuclear	30	30	42	28	1.4	0.9	**1.2**
Solar	668	567	6,569	5,561	9.8	9.8	**9.8**
Storage	129	55	587	211	4.6	3.8	**4.2**
Wind	647	728	3,517	3,864	5.4	5.3	**5.4**
Other[1]	48	49	167	156	3.5	3.2	**3.3**

[1]"Other" includes pumped hydro, oil-gas-steam turbines, and hydrogen combustion turbines.

We can further simplify our calculated heuristic (Table 15) into assumptions of GSU number and sizing requirements per generation technology (Table 16).

Table 16. Generation Technologies Have Technology-Specific GSU Number and Sizing Requirements

Technology	GSU Size (MVA)	GSUs per GW
Coal	300	2
Hydro	100	10
Natural Gas	300	3
Nuclear	800	1
Solar	100	10
Storage	200	4
Wind	200	5
Other	200	3

The material requirements for transformers can be calculated using the assumptions developed in Section 2.2.4 for the average transformer weight per MVA and share of transformer weight by material. Alternatively, a separate calibration can be used to approximate the material requirements for transformers per gigawatt-mile of new transmission presented in Table 17.

Table 17. Large Power Transformer and Converter Transformer Requirements per Gigawatt-Mile of Transmission

		ReEDS Output	Nodal Expansion Analysis			Calculated Heuristic		
Scenario	**Line Type**	**Transmission Investment (GW-mile)**	**Material Requirements (thousand tons)**			**Ton per GW-mile**		
			Steel	**GOES**	**Copper**	**Steel**	**GOES**	**Copper**
AC	AC[1]	82,770	285	1140	713	3.4	13.8	8.6
MT	AC[1]	70,920	204	818	511	2.9	11.5	7.2
	DC[2]	98,040	30	122	76	0.3	1.2	0.8

[1]AC includes "AC," "Reinforcements," "Spur"; [2]DC includes "B2B," "DC, LCC," "DC, VSC"; [3]AC transformer units include 170 replacement transformers per year.

In summary, transformer material requirements can be derived using bottom-up transformer size per MVA and material concentrations. Or, material requirements can be based on average material requirements per gigawatt-mile of new transmission.

AC transformers require around 3.2 tons of steel, 12.7 tons of GOES, and 7.9 tons of copper per gigawatt-mile, while DC transformers require around 0.3 tons of steel, 1.2 tons of GOES, and 0.8 ton of copper per gigawatt-mile.

4.2.3 Circuit Breakers

Estimates for circuit breaker requirements can be derived from the measurement in gigawatt-miles of added transmission (Table 18). The share of gas-insulated and air-insulated circuit breakers can be based on the geospatial nodal analysis presented in Section 2.3, whereby 91% of nodes have gas-insulated circuit breakers and 9% are air-insulated. Once the number of circuit breakers is estimated, the material requirements can be calculated based on the material concentrations in Table 4.

Table 18. Circuit Breaker Requirements per Gigawatt-Mile of Transmission

		ReEDS Output	Nodal Expansion Analysis	**Calculated Heuristic**
Scenario	**Line Type**	**Transmission Investment (GW-mile)**	**Number of Circuit Breakers**	**Circuit Breakers per GW-mile**
AC	AC[1]	82,770	13,900	0.17
MT	AC[1]	70,920	9,270	0.13
	DC[2]	98,040	3,000	0.03

[1]AC includes "AC," "Reinforcements," "Spur"; [2]DC includes "B2B," "DC, LCC," "DC, VSC."

AC lines require around 0.15 circuit breaker per gigawatt-mile (91% gas-insulated), while DC lines require around 0.03 circuit breaker per gigawatt-mile (all gas-insulated).

4.2.4 Transmission Towers

Requirements for transmission towers are estimated based on the total material required for steel per gigawatt-mi of added transmission (Table 19). We focus on material requirements rather than the number of towers because supply chain concerns cited in literature have focused on steel prices and availability rather than tower manufacturing and assembly.

Table 19. Steel Requirements for Transmission Towers per Gigawatt-Mile of Transmission

Scenario	Line Type	ReEDS Output Transmission Investment (GW-mile)	Nodal Expansion Analysis Material Requirements (thousand tons) Steel	Calculated Heuristic (ton per GW-mile) Steel
AC	AC[1]	82,770	5,296	64
MT	AC[1]	70,920	5,427	77
	DC[2]	98,040	831	8.5

[1]AC includes "AC," "Reinforcements," "Spur," [2]DC includes "B2B," "DC, LCC," "DC, VSC."

AC lines require around 70 tons of steel per gigawatt-mile for transmission towers, while DC lines require around 8.5 tons of steel per gigawatt-mile for transmission towers.

5 Conclusions

Constraints in transmission supply chains could limit the pace of transmission expansion to reliably meet growing demand at lowest cost. The constraints in supply chains exist amongst a range of other financial, regulatory, and policy constraints. The analytical approach outlined in this report can allow system planners to identify and evaluate potential supply chain constraints for critical components or input materials early in the planning process.

Using two transmission expansion scenarios from the NTP study as case studies, we demonstrate an approach to translate nodal transmission expansion scenarios to demand estimates for transmission grid components and material requirements. Transmission expansion based on AC-only technology requires average annual additions of more than 5,000 circuit miles of new transmission lines, 1,500 new power transformers, 1,390 circuit breakers, and almost 25,000 transmission towers. Transmission expansion that also allows multi-terminal HVDC technology results in less new generation capacity and more long-distance transmission lines. As a result, the MT scenario requires 35% more circuit miles of new transmission and 45% more transmission towers compared to the AC scenario but 9% fewer large power transformers and 11% fewer circuit breakers. Across the two scenarios, demand for steel exceeds 575,000 tons per year driven largely by requirements for new transmission towers. More than 65,000 tons of aluminum is estimated to be needed each year, primarily due to aluminum needed for new transmission lines and, to a lesser extent, for circuit breakers. Large power transformers account for more than 94,000 tons of GOES and most of the more than 61,000 tons of copper required each year. This is less than 4% of the annual consumption for aluminum, steel, and copper over the 2019-2023 period and more than 45% of the annual consumption for GOES (U.S. International Trade Commission, n.d.; USGS, 2024). These findings demonstrate how the analytical approach can be used to quantify supply chain needs based on national-scale studies. As the generation resource mix and anticipated demand growth continue to evolve, the results can be updated to reflect changing system conditions. Finally, this report explored heuristics to translate results from CEMs to demand for transmission components and materials. The metrics developed can be used as a starting point for calibrating supply chain needs from CEM results.

The approach presented in this report includes several key assumptions and potential areas for improvement. First, we centered our analysis around two nodal expansion and CEM scenarios taken from the same study. As such, they use similar assumptions regarding load growth, technology sizing and configuration. Testing the methods against nodal expansion and CEM outputs from an expanded range of scenarios and models could help identify areas for further refinement. Second, the assumptions for component size and material intensities were drawn from a small number of industry datasheets. Increased input from industry to improve these assumptions and provide insight as to how these technologies and material intensities may change over time could improve the accuracy and credibility of the demand estimates. This information could also be used to incorporate supply chain constraints into CEMs to identify how these constraints may impact that planned system. Finally, further work to link this analysis with other known supply chain constraints outside the scope of this work, such as labor shortages, could provide a more robust understanding of potential supply chain challenges for the transmission grid. A subsequent report will expand this analysis to evaluate the ability of U.S. supply chains to meet anticipated demand for transmission components and input materials.

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