U.S. DEPARTMENT OF ENERGY

Large Power Transformer Resilience

Report to Congress
July 2024

United States Department of Energy
Washington, DC 20585

Message from the Secretary

Large power transformers (LPTs) are essential components of the electric power transmission and distribution grid. The susceptibility of LPTs to emerging threats and hazards, combined with their extended replacement lead times, presents significant challenges to grid reliability and resilience. These challenges include not only localized outages due to physical attacks but also more severe incidents with the potential for widespread consequences. To address concerns about LPT vulnerabilities, both government and industry have emphasized the importance of maintaining a surplus or strategic reserve of transformers. Such a reserve would enhance the ability of individual utilities and industry collaborations to respond effectively to adverse situations, strengthening the resilience of the U.S. grid and enabling rapid recovery from extensive transformer failures.

Pursuant to statutory requirements, this report is being provided to the following Members of Congress:

- **The Honorable Cathy McMorris Rodgers**
  Chair, House Committee on Energy and Commerce

- **The Honorable Frank Pallone, Jr.**
  Ranking Member, House Committee on Energy and Commerce

- **The Honorable Tom Cole**
  Chairman, House Committee on Appropriations

- **The Honorable Rosa DeLauro**
  Ranking Member, House Committee on Appropriations

- **The Honorable Chuck Fleischmann**
  Chairman, Subcommittee on Energy and Water Development, and Related Agencies House Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Ranking Member, Subcommittee on Energy and Water Development, and Related Agencies House Committee on Appropriations

- **The Honorable Joe Manchin**
  Chairman, Senate Committee on Energy and Natural Resources

- **The Honorable John Barrasso**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Patty Murray**
  Chair, Senate Committee on Appropriations

- **The Honorable Susan Collins**
  Vice Chair, Senate Committee on Appropriations

- **The Honorable Patty Murray**
  Chair, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable John Kennedy**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

If you have any questions or need additional information, please contact me or Ms. Meg Roessing, Deputy Director for External Coordination, Office of Budget, Office of the Chief Financial Officer, at (202) 586-3128; Mr. Eric Delaney, Deputy Assistant Secretary for House Affairs, or Mr. Brian Eiler, Deputy Assistant Secretary for Senate Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Jennifer Granholm

Executive Summary

Large power transformers (LPTs) are essential components of the electric power transmission and distribution grid. The susceptibility of LPTs to emerging threats and hazards, combined with their extended replacement lead times, presents significant challenges to grid reliability and resilience. These challenges include not only localized outages due to physical attacks but also more severe incidents with the potential for widespread consequences. To address concerns about LPT vulnerabilities, both government and industry have emphasized the importance of maintaining a surplus or strategic reserve of transformers. Such a reserve would enhance the ability of individual utilities and industry collaborations to respond effectively to adverse situations, strengthening the resilience of the U.S. grid and enabling rapid recovery from extensive transformer failures.

This report provides an overview of the current landscape of LPT vulnerabilities, mitigation strategies, recent industry efforts aimed at addressing the issue of strategic LPT reserves, and the logistical aspects of operating such a reserve. A 2017 Department of Energy (DOE) Report to Congress [1] assessed options for a strategic transformer reserve and recommended a non-government solution driven by industry actions and compliance with North American Electric Reliability Corporation's Reliability Standard CIP-014-2 requirements. While this report does not advocate for a change in this recommendation, it does offer data indicating significant progress within the industry in addressing this issue.

The availability of spare LPTs and the concept of a strategic reserve remain complex and sensitive subjects. These were highlighted in the Infrastructure Investment and Jobs Act (Public Law 117–58), also known as the Bipartisan Infrastructure Law (BIL), section 40103(d), which called for assessments of efforts related to LPT sparing strategy and resilience. Various industry-driven initiatives aim to mitigate the risks and consequences of LPT failures. This report examines several of these efforts, including manufacturer and utility collaborations to enhance designs against threats, initiatives to address supply chain issues (including the transportation of replacement LPTs), standardization and improvement of LPT designs, and industry spare equipment sharing programs. Operational details of select LPT sharing programs, such as specifications, opportunities for flexible designs, spare LPT quantity requirements, storage and maintenance procedures, and security and transportation needs, are also included.

In summary, this report underscores the industry's commitment to managing the risks associated with potential LPT losses through a range of initiatives and strategies. To further address the complexity of the situation, it is crucial to engage in continued discussions with industry stakeholders. One possible approach is to convene the power community to explore options, utilizing existing forums or hosting workshops to generate new ideas, including potential cost-sharing arrangements with the Federal Government. Moreover, additional research and development efforts are needed to explore novel concepts, flexible systems (such as mobile transformers), and other assessment recommendations from the BIL list, such as focusing on the storage and security of recovery transformers and encouraging domestic manufacturing or expansion of existing transformer facilities. These discussions and actions will contribute to enhancing the resilience of the United States power grid and safeguarding its reliability in the face of evolving challenges.

LARGE POWER TRANSFORMER RESILIENCE

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I. Legislative Language

This report responds to the BIL section 40103(d), which called for assessments of efforts related to LPT sparing strategies and resilience. Various industry-driven initiatives aim to mitigate the risks and consequences of LPT failures. This report examines several of these efforts, including manufacturer and utility collaborations to enhance designs against threats, initiatives to address supply chain issues (including the transportation of replacement LPTs), standardization and improvement of LPT designs, and industry spare equipment sharing programs. Operational details of select LPT sharing programs, such as specifications, opportunities for flexible designs, spare LPT quantity requirements, storage and maintenance procedures, and security and transportation needs, are also included. Section 40103(d) states:

"(d) Energy infrastructure resilience framework

(1) In general

The Secretary, in collaboration with the Secretary of Homeland Security, the Federal Energy Regulatory Commission, the North American Electric Reliability Corporation, and interested energy infrastructure stakeholders, shall develop common analytical frameworks, tools, metrics, and data to assess the resilience, reliability, safety, and security of energy infrastructure in the United States, including by developing and storing an inventory of easily transported high-voltage recovery transformers and other required equipment.

(2) Assessment and report

(A) Assessment

The Secretary shall carry out an assessment of—

(i) with respect to the inventory of high-voltage recovery transformers, new transformers, and other equipment proposed to be developed and stored under paragraph (1)—

(I) the policies, technical specifications, and logistical and program structures necessary to mitigate the risks associated with the loss of high-voltage recovery transformers;

(II) the technical specifications for high-voltage recovery transformers;

(III) where inventory of high-voltage recovery transformers should be stored;

(IV) the quantity of high-voltage recovery transformers necessary for the inventory;

(V) how the stored inventory of high-voltage recovery transformers would be secured and maintained;

(VI) how the high-voltage recovery transformers may be transported;

(VII) opportunities for developing new flexible advanced transformer designs; and

(VIII) whether new Federal regulations or cost-sharing requirements are necessary to carry out the storage of high-voltage recovery transformers; and

(ii) any efforts carried out by industry as of the date of the assessment—

(I) to share transformers and equipment;

(II) to develop plans for next generation transformers; and

(III) to plan for surge and long-term manufacturing of, and long-term standardization of, transformer designs.

(B) Protection of information

Information that is provided to, generated by, or collected by the Secretary under subparagraph (A) shall be considered to be critical electric infrastructure information under section 824o–1 of title 16.

(C) Report

Not later than 180 days after November 15, 2021, the Secretary shall submit to Congress a report describing the results of the assessment carried out under subparagraph (A)."

II. Introduction

II.1 BIL REQUIREMENTS

For purposes of this report, a LPT is one that has a power rating of 100 MVA or greater [1]. The Department of Energy (DOE) estimates that 90 percent of all electricity consumed in the U.S. passes through a LPT at some point in its journey from generation to user [1].

LPTs sometimes need to be replaced, if for example, they are damaged by natural disasters or deliberate attacks or they simply reach their end of life (typically on the order of 40 years, although many LPTs have been in service for much longer). Replacement of an LPT is always challenging because LPTs typically weigh between 150 and 400 tons, leading to unique logistical challenges. In addition, another obstacle has recently emerged: lead times for acquisition of an LPT have become exceptionally long, with 36-month lead times being commonly quoted and maximum lead times reaching as much as 60 months [2, 3, 4]. Stakeholders have identified these long lead times and limited availability of spare LPTs as a potential concern for critical infrastructure resilience in the U.S. Both the public and private sectors are undertaking a variety of efforts to address this concern.

DOE has been tasked by Congress to develop, in coordination with public and private sector stakeholders, an Energy Infrastructure Resilience Framework as described in BIL section 40103(d). The legislation requires DOE to "develop common analytical frameworks, tools, metrics, and data to assess the resilience, reliability, safety, and security of energy infrastructure in the United States, including by developing and storing an inventory of easily transported high-voltage recovery transformers and other required equipment."

As a first step, Congress has asked DOE for a report to include:

(i) an assessment with respect to the inventory of high-voltage transformers, new transformers, and other equipment proposed to be developed and stored under BIL 40103(d), Paragraph 1, to include:

(I) the policies, technical specifications, and logistical and program structures necessary to mitigate the risks associated with the loss of high-voltage recovery transformers; (addressed in Chapters III & IV)

(II) the technical specifications for high-voltage recovery transformers; (addressed in Chapter IV)

(III) where inventory of high-voltage recovery transformers should be stored; (addressed in Chapters III)

(IV) the quantity of high-voltage recovery transformers necessary for the inventory; (addressed in Chapter III.4)

(V) how the stored inventory of high-voltage recovery transformers would be secured and maintained; (addressed in Chapters III)

(VI) how the high-voltage recovery transformers may be transported; (addressed in Chapter II)

(VII) opportunities for developing new flexible advanced transformer designs; (addressed in Chapters III & IV), and

(VIII) whether new Federal regulations or cost-sharing requirements are necessary to carry out the storage of high-voltage recovery transformers; (addressed in Chapters IV & V.5)

(ii) and to include any efforts carried out by industry as of the date of the assessment:

(I) to share transformers and equipment; (addressed in Chapters III)

(II) to develop plans for next generation transformers; (addressed in Chapters IV.2 & V.1), and

(III) to plan for surge and long-term manufacturing of, and long-term standardization of, transformer designs; (addressed in Chapters IV & V).

II.2 OBJECTIVES AND EXPECTATIONS

The primary objective of this report is to summarize the present and future industry needs with respect to mitigation of long LPT (not distribution transformers) acquisition lead times in the U.S. The specific requirements of the BIL outlined in 40103(d) are addressed herein. Although this report seeks to provide information responsive to the BIL requests, the authors also seek to provide a holistic view of industry efforts toward LPT resilience. There has been a robust industrial response to the problem of LPT availability, and the information collected in this effort is meant to inform decision makers, particularly with respect to industry status of programs, which may mitigate the need for a federally-owned or supported reserve.

This report addresses the objectives across three main chapters. Chapter IV summarizes the importance of LPTs, the highest impact threats that they face, and the challenges of LPT replacement. It is important to understand these aspects to appropriately evaluate the risks within the industry and the effectiveness of programs and efforts, which mitigate those risks. Chapter IV addresses the status of these industry efforts: sparing and sharing programs, next generation LPT designs, and efforts toward standardization of design and manufacturing. Finally, in Chapter V the future considerations for LPT resilience are discussed. This includes summaries of recommendations on LPT designs, resilience solutions, the need for national-level and local assessments, and the specific requirements of a federally-owned or supported LPT reserve.

III. LARGE POWER TRANSFORMERS

III.1 BACKGROUND

III.1.1 What are LPTs and why are they important?

In modern AC power systems, power is generated at relatively low voltage, transmitted from generators toward end users at very high voltage to minimize losses, and then provided to end users at low voltages to enhance safety. The devices that shift the electric power between these voltage levels are transformers.

Transformers are available in many different sizes and configurations for many different applications. In this report, the focus is on the largest transformers, referred to as "Large Power Transformers" (LPTs) which are defined here as transformers that are rated at 100 MVA or larger. These transformers are used to connect large generation stations to high-voltage transmission, and to shift voltage levels between different parts of the transmission system. Transformers perform several other functions as well. The U.S. Department of Commerce (DOC) estimated in 2019 that 137 LPTs (18 percent) were produced domestically for domestic use while 617 units (82 percent) were imported for domestic use, and only 4 units were exported. The agency estimated LPT capacity utilization of ~40 percent and a total maximum capacity of ~343 LPTs/year was derived for domestic manufacturers [5, p. 198]. In 2022, DOE estimated that there are between 4,900 to 6,799 LPTs currently in use in the U.S. [6, p. 13].

LPTs, along with the transmission lines that connect to them, are the backbone of the North American transmission system, linking power generators to electric loads. Approximately 90 percent of consumed electric energy in the U.S. flows through at least one LPT [7]. The transmission system in North America is largely networked, meaning that in most parts of the system there is more than one path through which power can flow from sources to consumers. Each path in the network typically contains LPTs. Thus, there is some redundancy in networked transmission, but still, it has been shown that attacks on a relatively small number of transformer substations, causing the loss of several LPTs simultaneously, could cause major grid disruptions or degraded reliability [8]. Also, the level of networking of the system typically becomes lower (fewer paths) as one gets closer to the consumer, and in some cases the transmission system becomes "radial", meaning there is only one path from the larger grid to a group of consumers. Loss of a single LPT in a radial system interrupts power service to customers served by that LPT, although these are typically smaller transformers than the LPTs addressed in this report. Given these scenarios, the ability to replace LPTs in a reasonable period of time is a key factor in power system reliability and resilience.

III.2 THREATS TO LARGE POWER TRANSFORMERS

III.2.1 Aging Infrastructure

LPTs are typically considered to have a design lifetime on the order of 40 years. In 2014, a DOE report estimated that the average age of LPTs in the North American grid was 38–40 years [9], indicating that a substantial fraction of those LPTs are at or over that design lifetime. These LPTs will ultimately need to be replaced or refurbished.

Design and operational modifications can affect LPT lifespan. High core flux can cause over heating of the thin, insulated steel plates (laminations) that make up a transformer core. In a transformer fleet, degradation of the unit could occur when the insulation on these laminations is subjected to higher temperatures for a short duration. Overheating also causes the degradation of the transformer winding insulation and increases the potential of transformer failure. Moreover, higher temperatures also affect the life of insulation [3]. Furthermore, prolonged operation at high temperatures can cause fires if hot insulating oil escapes the tank [10].

Transformers naturally produce heat during operation and require varying levels of cooling capacity depending on both operating load and ambient temperature. At least one manufacturer, Hitachi Energy, designs larger units based on regional temperature data from customers. Hitachi Energy tests units based on expected operational conditions and adjusts designs as necessary to ensure safe operating temperatures. Cooling capacity can be added to an LPT design by increasing the size of the tank (allowing it to hold more oil) or adding radiators (to passively cool the oil) or fans (to actively cool). Additional capacity can be obtained by adding alternating fans for long-duration high-temperature events [3]. Replacing mineral oil cooled transformers with natural ester oil cooled units requires larger tanks to achieve the same cooling capacity, but because ester oil is much less flammable and more environmentally friendly, it reduces the fire risk of an overloaded transformer [10].

One approach to respond to individual transformer outages is to increase the power load of other transformers in the area to make up for the loss of capacity, allowing utilities to trade shortened equipment lifespans for minimally affected service. LPTs can be overloaded up to 10–20 percent above their rated power, but this accelerates insulation aging. Overloading is primarily an issue for windings and components which carry current, bushings and internal cables [3]. Different utilities have different requirements for both transformer design and permissible overloading, depending on factors including risk tolerance, outage tolerance, and regional wildfire risk [4].

III.2.2 Extreme Weather

Extreme weather events that impact the electric grid include hurricanes, tornadoes, snowstorms, geomagnetic disturbances (space weather), thunderstorms, extreme heat, and wildfires. Some of the most common natural events that impact LPT lifetime are discussed below.

Winter Weather

Winter weather includes a broad range of effects, such as snow accumulation, ice formation, and very low temperatures. Utilities include plans such as ice storm or wind preparedness into their operations.[1] While such weather events are known to affect the transmission grid, not all present danger to transformers. We briefly review the three major winter weather effects: snow accumulation, ice formation, and severe cold.

- Snow Accumulation. There is no evidence that snow accumulation has directly caused any high voltage transformer failures in the U.S. or elsewhere in the world. Reports from larger snow-related events such as the 2008 snowstorm in China[2] show that snow accumulation damaged transmission lines and substation equipment but not high voltage transformers.
- Ice Formation. Ice formation is not dangerous for the transformer coils but may create flashovers if ice accumulates on the bushings. According to different reports, bushing issues contribute to a significant portion of LPT forced outages **[11] [12]**. Despite the fact that ice storms are discussed as a serious threat to power systems, similar to snowstorms, they were not found to cause direct damage to transformers. There was no damage to transformers in the 1998 Quebec ice storm **[13, p. 68]**, 2006 Illinois ice storm,[3] 2008 New Hampshire ice storm **[14]**, 2013 Toronto ice storm **[15] [16]**, or 2023 Michigan ice storm **[17]**.
- Severe Cold. Winter weather can cause low temperatures, which affects oil inside the transformer. However, there is no documented evidence of the actual damage done to transformers by this phenomenon.

Thunderstorms

Between 1991 and 2010, lightning was attributed as the cause of roughly 13 percent of power transformer failures (according to one US manufacturer) [18]. It is a well-researched cause of transformer failure, with multiple studies investigating the processes related to transients and exploring how to prevent or reduce the resulting damage [19] [20] [21] [22]. Lightning affects transformers through two principal ways: line surge and direct strike [23]. The latter is known to happen often in sub-transmission and distribution grids [24] but there is no evidence of transmission level transformers being damaged by direct strike. Line surge does not involve direct strike. The lightning can strike nearby causing electric fields, which create a voltage and current surge in the transmission lines that are connected to transformers.

Wildfires

Wildfires are a common cause of transformer damage, with many studies available on the subject [25]. Utilities typically have prevention and response plans. Some examples can be found from California and Oregon [26] [27]. The relationship between wildfires and transmission grid damage is known to be bidirectional. Utilities in some areas engage in preventive deenergizing of the transmission grid to avoid potential wildfires [28] [29].

[1] Quarterly Report Verification/Monitoring Investigation of Wind and Ice Storm Preparedness and Restoration of the Ameren Illinois Companies. The Liberty Consulting Group, 2009.
[2] Zhou B. et al., "The great 2008 Chinese ice storm. Its socioeconomic-ecological impact and sustainability lessons learned," DOI:10.1175/2010BAMS2857.1.
[3] Investigation of Wind and Ice Storm Preparedness and Restoration of the Ameren Illinois Companies. The Liberty Consulting Group, 2008.

Heat

According to a study from the European Union (EU), about 2 percent of all large transformer failures are due to overheating [30]. Overheating can directly lead to failures, and it can also indirectly lead to premature failure via reduced life of internal components. Therefore, it may be difficult to clearly decide which effect is observed in the transformer. The effect of heat on large transformers has been recognized in the industry [31] [32] [33] and is subject to ongoing theoretical studies [34]. The threat of overheating may increase if more heat waves are observed in areas with previously moderate climate [35]. Modern transformer monitoring techniques are capable of detecting overheating issues.

Earthquakes

Earthquakes are a well-researched and well-documented type of impact on high voltage transformers [36] [37]. The Institute of Electrical and Electronics Engineers (IEEE) 693 standard provides recommendations for substation design in seismic zones, including qualifications for tanks, bushings, surge arresters, and transformer components [38].

Hurricanes and Tornadoes

Direct transformer damage from wind is not a common occurrence, although there is evidence from Canada [39] and Cyprus [40] showing that a strong storm could cause wind damage to a high voltage grid. However, most utilities in hurricane prone areas have invested substantially in grid hardening measures, flood mitigation, and operational practices to reduce the threat of LPT damage or failure resulting from a hurricane.

Flooding

Flooding can have a significant impact on transformers. Key impacts of flooding on transformers include:

- Insulation Damage: Transformers have insulation materials that help isolate different voltage levels and protect the windings. Flooding can lead to the saturation of insulation materials, compromising their effectiveness. Water can degrade the dielectric properties of the insulation, causing electrical breakdowns, short circuits, and potential damage to the transformer windings.
- Loss of Cooling: Transformers require effective cooling mechanisms to dissipate heat generated during operation. Flooding can disrupt the cooling systems, such as oil pumps, cooling fan motors and controls, or radiators, by submerging them in water. Inadequate cooling can result in the overheating of the transformer, leading to insulation deterioration, reduced lifespan, and potential failure.
- Oil Contamination: Transformers are filled with insulating oil that provides cooling and insulation properties. Flooding can cause water to mix with the transformer oil, leading to oil contamination. Water-contaminated oil loses its dielectric strength and can cause arcing, short circuits, and damage to the transformer components.

- Mechanical Stress: Flooding can subject transformers to significant mechanical stress. The buoyancy of water can cause transformers to shift or move from their original positions, leading to mechanical damage. Additionally, debris carried by floodwaters, such as branches, can impact the transformer, causing physical harm and compromising its structural integrity.
- Corrosion and Oxidation: Exposure to floodwater can accelerate the corrosion and oxidation processes in transformer components. The presence of moisture can cause metal components, such as windings, terminals, and core laminations, to corrode and/or oxidize. Corrosion and oxidation can increase resistance, introduce electrical faults, and reduce the overall efficiency of the transformer.
- Electrical Grounding Issues: Floodwaters can compromise the electrical grounding system of transformers. Submergence of grounding electrodes or connections in water can increase resistance, hinder proper grounding, and affect the safe operation of the transformer.

The severity of the impact of flooding on transformers depends on factors such as the depth and duration of the flood, the quality of the transformer's construction, and the mitigation measures in place. Quick action to de-energize and isolate flooded transformers, followed by proper inspection, cleaning, drying, and, if necessary, repair or replacement, is essential to mitigate damage and restore the transformer's functionality.

III.2.3 Coronal Mass Ejection & Geomagnetic Disturbances

Geomagnetic disturbances (GMDs) are a naturally occurring phenomenon initiated by solar activity. They occur when a coronal mass ejection (CME), a significant discharge of magnetic field/plasma from the Sun, collides with Earth's magnetosphere and results in the formation of electrojets in the ionosphere. The electrojets cause electric fields which couple to terrestrial power transmission lines, in turn driving the flow of very low-frequency geomagnetically induced currents (GICs). Ultimately, these GICs flowing through many types of LPTs is the cause of nearly all GMD-related issues. GICs can cause half-cycle saturation in LPTs by introducing a magnetic flux offset in the transformer core, which can result in increased harmonic generation, transformer heating, and system instability. An illustration of half-cycle saturation is shown in Figure 1.

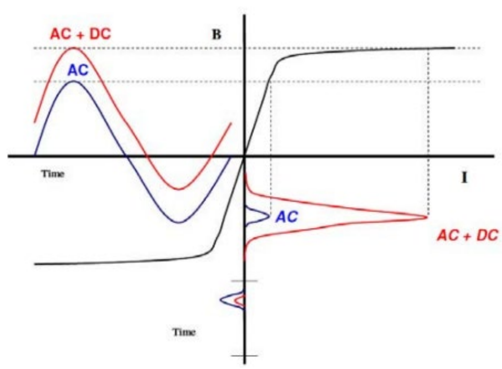

Figure 1 – Half-cycle saturation in a transformer [41].

GMDs have damaged transformers in the past. The most famous event occurred on the Hydro-Québec grid on March 13, 1989 [42] [43]. There is also evidence that GMDs caused transformer coil destruction in the U.S. [44].

Transmission operators are required to take steps to mitigate the potential impacts of GICs [45]. The hardening of the power system against GMDs can be divided into two broad categories: (1) protecting LPTs directly from GICs and their impacts, (2) operating the power system in way to minimize the risk (e.g., increasing system operating margins, preparing in advance for special GMD-related contingencies, etc.). The most direct and commonly applied approach to protect LPTs from GICs is with a passive blocking or mitigation device that prevents core saturation [46].

The North American Electric Reliability Corporation (NERC) standard TPL-007 requires North American transmission operators to conduct studies of expected GMD impacts on their systems and take certain mitigation measures [47].

III.2.4 Intentional Attack

Significant investment has been made in applying physical security protections at stations and substations containing LPTs as the electric grid continues to be the target of both physical and cyber-attacks that have disrupted high voltage (HV) and extra-high voltage (EHV) transformers. In Figure 2, data collected from Form OE-417 shows trends in electric grid attacks from 2018 to 2022 [48].

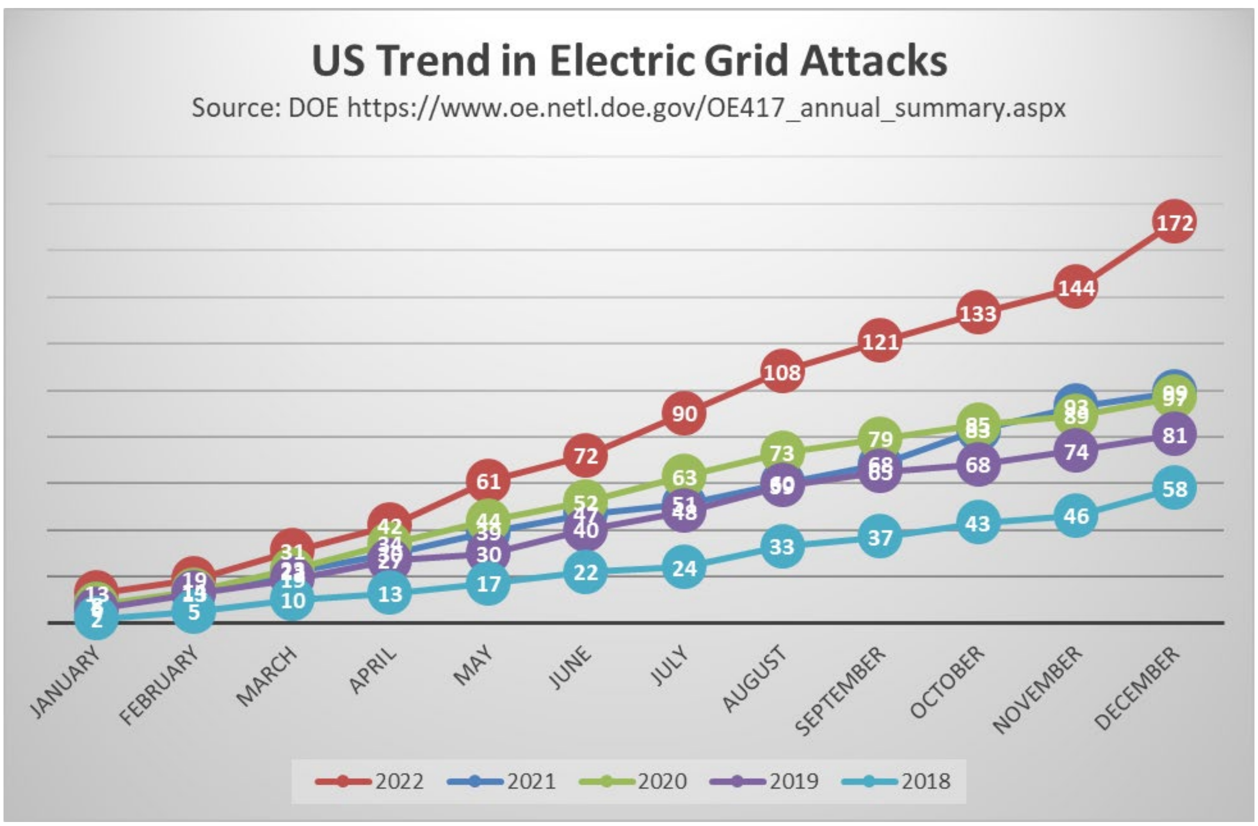

Figure 2 U.S. Trend in Electric Grid Attacks (Shows cumulative number of attacks) [48].

Utilities have been actively looking at ways to decrease physical vulnerabilities. Fences around substations to disrupt remote line of sight to equipment, although less effective than reinforced shielding, are also less expensive. While it is expensive to use thicker steel on the transformers' shell, utilities have been monitoring oil temperatures remotely and acoustically monitoring substations in order to detect rifle shots and cut power to damaged transformers before they are irreparable.

III.2.5 High Altitude Electromagnetic Pulse (HEMP)

A HEMP (high altitude electromagnetic pulse) is an electromagnetic pulse that is created by a nuclear weapon explosion high in the atmosphere, nominally between 75 km and 300 km above ground. Each HEMP has three potential parts of its waveform that may affect an LPT. E1 HEMP is a 2.5 ns rise time electric field with peak of approximately 50 kV/m. The E1 is finished at about 1 microsecond. The E1 pulse can induce voltage and current spikes on wires and cables, impacting the equipment they are connected to—such as exposed transformer cables, which monitor and control temperatures, fans, and pumps. These auxiliary equipment devices have not been tested in a laboratory setting to determine their resilience to an E1 HEMP but are currently being assessed for placement in the testing queue by the DOE and the National Laboratories. The potential susceptibility of these systems was discussed in person with an LPT manufacturer[4]. Although such a response is not known, a failure of these LPT auxiliary devices would generally result in a required reduction of power to accommodate a loss of cooling system component controls. Without the cooling components operational, the LPT rating would overheat and potentially fail. The LPT winding insulation systems have been tested for E1 HEMP at Sandia National Laboratories and were found to be robust to a E1 HEMP.

E2 HEMP has a frequency content and magnitude similar to a nearby lightning strike. Since transformers are already designed to withstand surges due to nearby lightning strikes by their design of Basic Impulse Level and the use of lightning surge arrestors, E2 HEMP is typically ignored and not considered a threat.[5] E3 HEMP is the third part of a HEMP of concern for LPTs. This 'late-time' component of a HEMP occurs from 1 second to about 300 seconds after the weapon's detonation. The electric field created by E3 is very low in frequency, appearing very similar to the electric field caused by a GMD. However, the E3 HEMP can result in larger electric fields (hence larger GICs), which can have a greater effect on the saturation of LPTs and severely suppressing system voltage, or collapsing it, with potential to cause a partial or multi-state system blackout [49]. The short duration of these GICs; however, will not cause LPT overheating or damage [50]. Appropriate mitigations for E3 would include neutral blocking devices on susceptible transformers. However, unlike a GMD, incrementally larger transformer cores may not provide benefit, and improved insulation systems would not be necessary as there would not be sufficient heating to cause damage.

[4] Guttromson, Ross, et al, "Electromagnetic Pulse – Resilient Electric Grid for National Security: Research Program Executive Summary". United States: N. p., 2020. Web. doi:10.2172/1879618.
[5] Sandia National Laboratories is conducting a detailed three-year study (2023-2026) on the potential impacts to power systems and component failures from E2 EMP. The analysis will attempt to validate or refute the claims regarding the ability of E2 to cause dielectric failures, as well as its potential for causing wide-spread relay trips.

III.2.6 Cyber-attack

Transformers are at risk of both physical and cyber-attacks. Depending on the nature and severity of the cyber-attack, a transformer might need to be replaced. Due to the sensitivity of cybersecurity risks and mitigations; this information was not included in this report.

III.2.7 Harmonic and Saturation Impacts

Harmonic Effects

LPTs may experience the presence of higher-order harmonics because of the presence of transmission-connected inverter-based resources. These resources produce harmonics on their own, and they can also excite existing resonances in the system, making the harmonics larger. When harmonics are present in the electrical system, they can cause additional heating and stress on a transformer's windings, insulation, and core, shortening its lifetime. To mitigate the impact of harmonics on LPTs, utilities and grid operators can take several measures, including ensuring that inverter-based resources conform to grid codes such as IEEE Std 2800-2022, installing harmonic filters, and using transformers designed to handle harmonics. Transformer manufacturers can also design and test transformers to withstand higher levels of harmonics, and regulators can establish standards and guidelines for transformer resilience to harmonics.

Saturation Effects

Saturation can have a significant impact on LPT performance. Saturation occurs when the magnetic flux density in the transformer's core reaches its maximum capacity and its affinity to contain magnetic flux (its permeability) drastically decreases. Then any increase in magneto motive force (MMF) results in a limited increase in the magnetic flux density, and flux 'leaks' out of the core. This leakage is generally harmful because the magnetic flux will cause currents to flow in structural parts of the transformer that were not designed to carry current, which can cause problematic heating.

When a transformer's core is saturated, the transformer's performance can be affected in several ways. Saturation can cause increased core losses and generate additional heat, which can cause insulation breakdown and reduce the transformer's lifespan. In addition, saturation can cause a decreased reactance, resulting in suppressed terminal voltage and leading to reduced efficiency and voltage regulation. Saturation can also cause harmonic distortion, which can cause additional stress on the transformer's windings and insulation, which can ultimately result in transformer failure.

To mitigate the impact of saturation on transformers, utilities and grid operators can take several measures. These include designing transformers with an oversized core and selecting core lamination materials with a high magnetic permeability. Additionally, regulators can establish standards and guidelines for transformer resilience. Regular maintenance and monitoring of transformers can also help detect and prevent saturation-related issues before they cause significant damage.

III.3 LARGE POWER TRANSFORMER REPLACEMENT CHALLENGES

III.3.1 Supply Chain Issues

The LPT supply chain is complex. LPTs are expensive, difficult to transport, and highly customized devices with long lead times for manufacture, testing, delivery, and installation of new units. The procurement and manufacturing of LPTs typically includes prequalification of manufacturers, a competitive bidding process, device design, manufacture, testing, and the arrangement of special modes of transportation for device delivery. Transportation from the manufacturer to grid installation is also a significant element of the LPT total cost. Due to the size and weight of the devices, as well as the often-remote installation locations, the last 5 to 10 miles of transport are particularly expensive and challenging.

LPTs are usually custom-built to fit the specifications of their use case. In addition to voltage rating, technical characteristics such as impedance and required safety equipment vary by jurisdiction. Required voltages are specific to the installed location. Each jurisdiction and locality have different requirements, and different design tradeoffs are reflected in each jurisdiction's design choices [4].

As a result of these factors, LPT manufacturing lead times can become very long, particularly if the device is sourced internationally. Prior to the Coronavirus Disease of 2019 (COVID-19) pandemic, it was possible to place an order for a large transformer with a lead time of less than a year, and recent conversations with domestic producers have indicated that much longer lead times, up to and exceeding 36 months, are occurring today [3] [4]. Delays may also occur if the ordering queue is backed up, or if the manufacturer has difficulty obtaining key inputs, such as specialty steel laminations, specialty copper wire and other materials, or appropriately skilled labor [51, p. 13]. These challenges within the LPT supply chain represent potential bottlenecks to rapid grid expansion, raising concerns about the vulnerability of this key segment of the U.S. domestic energy infrastructure [6, p. 21]. Figure 3 outlines the required inputs for LPT production [6]. Within the LPT supply chain, raw materials such as grain-oriented electrical steel (GOES), continuously transposed conduction (CTC) copper wire, and insulating materials have a significant impact on final LPT availability and price [6, p. 9]. According to a 2020 U.S. Department of Commerce industry survey, GOES and CTC each account for roughly 25 percent of final LPT production costs [5, pp. 9, 221]. In addition, the majority of GOES used for U.S. LPT manufacture is not produced domestically.

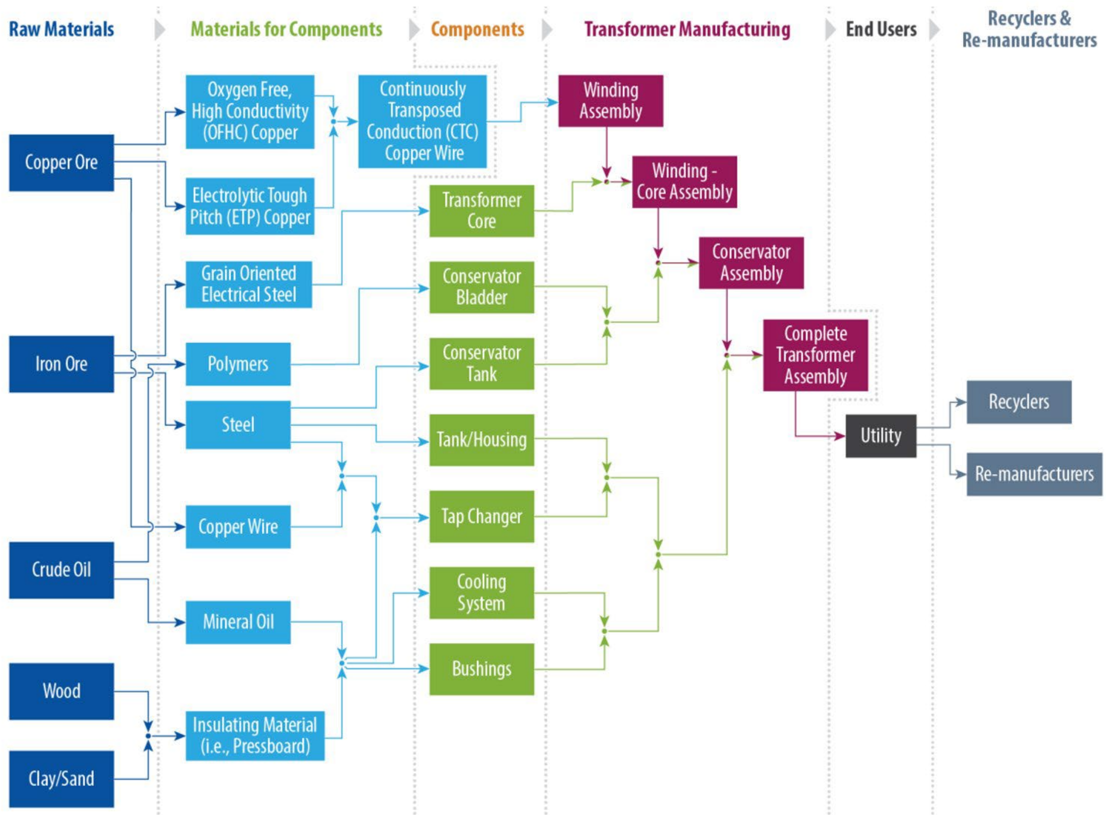

Figure 3: LPT Supply Chain Inputs [6]

III.3.2 Supply and Demand

In 2020, the Asia-Pacific region had the largest global LPT market share in sales with 39 percent, followed by Europe with 24 percent, and the Middle East & Africa with 17 percent market share. North America had 15 percent while South America had the lowest market share at about 4 percent [6, p. 3].

In 2019, U.S. demand for new transformers (> 60MVA) was ~750 units. Over 80 percent of these new units were imported due in part to long domestic transformer lead-times and lower manufacturing costs of imported devices. A recent DOE report suggested that U.S. domestic demand is expected to increase to ~900 units annually by 2027 [6, p. 2], but in interviews conducted for this report, U.S. transformer manufacturers reported experiencing much larger jumps in demand, as much as 70 percent year-over-year, in the last 1–2 years [3] [4].

The primary LPT demand drivers include replacement of aging units currently in use, the addition of new LPTs to the electricity grid to accommodate transmission expansion supporting economic growth, and the growth in deployment of renewable energy-based generation plants and energy storage facilities on the transmission system.

The demand for lower-voltage, lower-power transformers is also increasing. Because transformers used at other voltage levels use many of the same raw materials as LPTs, demand for those transformers impacts material availability for LPT construction and LPT cost.

The intended use-life of an LPT is typically about 40 years and the average age of currently installed devices in the U.S. is about 40 years, with some units still in operation after more than 70 years of service. According to a 2014 estimate, more than 70 percent of U.S. LPTs were aged more than 25 years [6, p. 13]. Aging LPTs increase failure risk, putting increased pressure on domestic demand [9].

III.3.3 Grain-Oriented Electrical Steel

Within the LPT supply chain, raw materials such as GOES, CTC copper wire, and insulating materials have a significant impact on final LPT availability and price. GOES is manufactured in several grades, including conventional oriented grade (CGO), high-permeability grade (HI-B), Permanent Domain-Refined GOES (PDR), and intermediate-grade (MOH). HI-B domain-refined grade is highly demanded by LPT manufacturers because of its low core loss to reduce LPT weight. According to a 2020 U.S. Department of Commerce industry survey, GOES and CTC each account for roughly 25 percent of final LPT production costs.

Furthermore, high and increasing domestic demand for transformers competes for the limited supply of domestically produced and imported high-quality GOES and other essential inputs. In addition, the steady increase in domestic electric vehicle (EV) demand puts pressure on this LPT supply chain segment: domestic EV production consumes non-oriented electrical steel (NOES), which competes for steel production capacity with domestic GOES. As a result, domestic NOES demand crowds out the less profitable domestic production of GOES. DOE concluded in 2022 that domestic GOES production "is a major weak link in the LPT supply chain with an insignificant domestic market, an insignificant global market demand, the inability to compete with the global market, the lack of technology or material substitutions, and shrinking supply due to other competing applications" [7, p. 52].

III.3.4 Manufacturing Capacity

DOE identifies limited cost-effective domestic LPT manufacturing capacity as a second significant weak link in the domestic LPT supply chain, and the best medium-term opportunity to reduce LPT import reliance. The total production capacity of U.S. LPT manufacturers is difficult to estimate because LPT manufacturing facilities typically use their capacity to produce multiple products at the same time. The U.S. Department of Commerce estimated that in 2019, 137 LPTs (18 percent) were produced domestically for domestic use while 617 units (82 percent) were imported, and only four units were exported. The agency estimated LPT capacity utilization of ~40 percent, and a total maximum capacity of ~343 LPTs/year was derived for domestic manufacturers [5, p. 198].

Manufacturing facilities have a certain number of build slots: each slot can be used for an LPT, a smaller transformer, or a refurbishment of a transformer core, but capacity cannot easily be expanded except by building a new facility. New factory construction takes 1–3 years; aside from the logistical and financial challenges common to large construction projects, the most significant constraint faced by transformer factories is sourcing equipment. Specialty equipment such as winding machines or core tables can take 1–2 years to obtain from suppliers [4] [3]. Minor equipment purchases such as cranes, air pallets, or interior space reallocations can only expand capacity marginally, but at lower cost and quicker timeframe than facility expansions [4].

III.3.5 Dependence on Foreign Equipment and Materials

The LPT supply chain is complex and highly globalized, depending on materials and components sourced from around the world [3]. Higher grades enable more efficient transformers. The highest grade GOES PDR is only available from a single manufacturer, Nippon Steel in Japan, and is not manufactured in the U.S. An intermediate grade GOES, MOH, is widely available from Japan and South Korea. U.S. producer AK Steel makes an equivalent to MOH GOES; however, the U.S. option is more expensive with no efficiency benefit and is therefore not commonly used by U.S. LPT manufacturers [5, p. 108].

Approximately 80 percent of GOES was imported in 2019 [5, pp. 13, 47]. Specific numbers depend on whether the GOES is imported in uncut rolls (20 percent), pre-cut lamination sheets (88 percent), pre-assembled stacked cores (80 percent), wound cores (100 percent, requires PDR GOES), or completed transformers (35 percent of all transformers, 82 percent of LPTs) [5, p. 132]. Furthermore, high and increasing domestic demand for smaller and more numerous substation and distribution transformers competes for the limited supply of domestically produced and imported high-quality GOES and other essential inputs [6, p. 18].

According to a 2022 DOE LPT supply chain assessment, the most effective near-term opportunity to reduce LPT supply chain vulnerability is to improve domestic GOES production capability. There is only one GOES manufacturer in the U.S. and this company has been unable to meet domestic demand at quality and prices comparable to imports [6, p. 15].

On average, imported GOES hovers around 20 percent market penetration. Previously-reported information has put the percentage of imported GOES as low as 12 percent, or as high as 37 percent between 2015–2019, with specific quantities varying depending on the year and the specific suppliers that were subject to a 2017 25 percent tariff on imported GOES [5, p. 98]. However, a DOC manufacturer survey showed unclear boundaries between GOES rolls, laminations, and cores. Many manufacturers purchase GOES as pre-cut laminations, either from a value-adding steel manufacturer or an intermediary supplier that buys GOES rolls and cuts them into laminations and/or stacks laminations into cores. These value-added steps do not have a separate category in trade data, and manufacturers categorize their GOES purchases inconsistently. For instance, 60 percent of GOES trade volume is accounted for in manufacturer-reported lamination volume. Cleveland-Cliffs (through its 2020 acquisition of AK Steel) is the sole active domestic GOES supplier. The company is able to meet between 12–20 percent of domestic GOES demand, but is not currently profitable [6, pp. 20, 47] [5, p. 9] [9].

ATI (previously Allegheny Technologies Incorporated) formerly produced GOES but shut down GOES production in 2016 due to unprofitability. Trade data showed a 155 percent increase in GOES imports the following year as a result of this shutdown. U.S. Steel has the capability to produce GOES through its 2022 acquisition of Big River Steel; however, it is producing NOES (non-oriented electrical steel) instead [5, p. 12]. NOES uses the same production equipment as GOES but is not cold-rolled; NOES is primarily used for electric motors and generators, and demand for NOES has grown rapidly to supply EV motors.

U.S. LPT manufacturers primarily import GOES from Japan and South Korea, which produce the highest quality GOES [5, p. 68]. Trade data and manufacturer surveys suggest that when an American LPT manufacturer wants to purchase uncut low-grade GOES rolls, they may purchase from AK Steel, and that much of AK Steel's GOES is intended for export. However, when LPT manufacturers purchase laminations or cores, they primarily import from foreign suppliers. Foreign suppliers can provide higher quality for lower costs, both because of reduced manufacturing costs and because GOES is subject to a 25 percent tariff when imported from major exporter countries, while laminations and cores are not.

III.3.6 Amorphous Steel

Amorphous steel is an emerging alternative to GOES. While GOES is cold-rolled to orient electrical steel's magnetic fields in one direction, amorphous steel is rapidly cooled in thin sheets to create electrical steel with randomly oriented magnetic fields. Amorphous steel cores have lower losses than GOES cores and thus transformers made with amorphous steel cores can have higher efficiency. However, amorphous steel is brittle, which leads to decreased yields and increased shipping costs and labor costs both in production and core stacking. Amorphous steel transformers were first used in the U.S. in 1982, but due to higher associated labor costs, these have been more popular in China (1.1 million transformers installed) and India (1.3 million) than in the U.S. (600 thousand) [5, pp. 136-138]. Metglas is currently the only U.S. producer of amorphous steel, although amorphous steel is not generally used in domestic LPTs.

III.3.7 Spare LPT Long-Term Storage

Spare LPTs have many of the maintenance requirements of in-service transformers. Many utilities thus find it beneficial to store spare LPT's onsite or at a central substation. This enables routine maintenance to be performed as an extension to the regular activities of the other equipment at that substation. Incremental labor is negligible, and the expected lifespan of the spare LPT is equal to or greater than that of the in-service transformers it would replace. However, the on-site spare LPT is subject to any physical threats or risks that the in-service LPTs might face.

Off-site storage is a more costly option but helps to mitigate risks associated with co-locating spares with in-service transformers. Although a more expensive option, storage depots can provide safe storage and can be strategically located to serve a high number of substation locations.

III.3.8 Workforce

Labor expenses vary widely between manufacturers, ranging from 1 percent–87 percent, but on average labor accounts for 36 percent of manufacturing cost [5, p. 221]. A 2020 U.S. Department of Commerce survey of 87 domestic LPT component manufacturers found that "eighty-nine percent of survey respondents reported having had difficulties in finding qualified or experienced workers, including 66 percent that identified the problem as an ongoing issue" [5, p. 221]. These respondents identified a need for increased training in areas such as welding, coil winding, and transformer testing [5, p. 221]. The issue is exacerbated by low foreign labor rates, significant foreign government subsidies, and foreign manufacturer dumping at artificially low prices [6, p. 53]. Delta Star stated that labor costs are its biggest hurdle in competing with international manufacturers. The larger a transformer, the more labor it requires to wind and assemble, increasing the cost differential between domestic manufacturers and foreign manufacturers in countries with lower labor costs such as Mexico and South Korea [4].

Because LPT manufacturers typically produce both LPTs and smaller, more numerous substation and distribution transformers using the same facilities, increased test space could also help to ease manufacturing bottlenecks [6, pp. viii-ix]. An additional potentially effective medium-term focus is to increase LPT workforce training, which could require “a change in both training curricula at various levels and increased apprenticeship and internship opportunities in collaboration with industry” [6, p. ix]. Long-term efforts could include increased research and development to improve production efficiency, reduce material content, and cut LPT production costs [6, p. ix].

There can also be constraints in the number of skilled workers to install and maintain LPTs. While utilities have contracts and crew sharing agreements with each other to provide additional workforce to restore/repair transformers and other infrastructure after a severe event, multiple utilities contract with the same companies. Therefore, if there is a regional event affecting multiple utilities, fewer auxiliary crews may be available than the emergency plans predicted. There is a need for better standardization procedures and designs in the power industry, to facilitate cross-training of work crews to dispatch across multiple utilities.

III.3.9 Transportation Logistics

Transportation time during LPT replacement is highly dependent on the size of the transformer, the travel distance, and the proximity to roads or railroads at both ends of the route. In addition, there is high variability in the available route choices, which is driven by several factors:

- LPTs can be two to three times the weight of the heaviest “normal” loads for a railroad, so they require specialized staffing and data resources at the rail companies as well as at the governmental agencies responsible for approving the transportation route and issuing the relevant permits.
- LPTs are susceptible to serious damage from excessive vibration or impact, so they require special handling during rail operations.
- Heavy hauler contractors, heavy crane contractors, and riggers must be scheduled. They are often independent contracting companies, and not under the control of utility companies.
- Schnabel cars, other specialized railroad cars, and highway heavy hauler vehicles needed for carrying LPTs must be scheduled. These specialized vehicles are few in number and often not owned or controlled by the utilities. When needed, these cars may be far away or otherwise not readily available.
- Roadway and railroad path clearances must be checked as part of transport route assessment. Bridges need to be analyzed and may need inspection. These functions are

usually performed by state government employees, who are not under the direct control of the utilities.

- Road closures must be planned, including traffic detours and temporary power line relocations. These tasks involve local government staff, who are not under the direct control of the utilities.
- Moving LPTs, especially across state boundaries, requires various transportation permits and sometimes environmental permits. The requirements for obtaining permits from numerous agencies may further constrain what routes can be used.

Figure 4 depicts the time required to replace a damaged LPT with an existing spare LPT via various locations of the existing spares. Actual delivery times would be specific to each utility, transformer, and location. The intent is to demonstrate the impact of LPT replacement source on the length of time required for restoration.

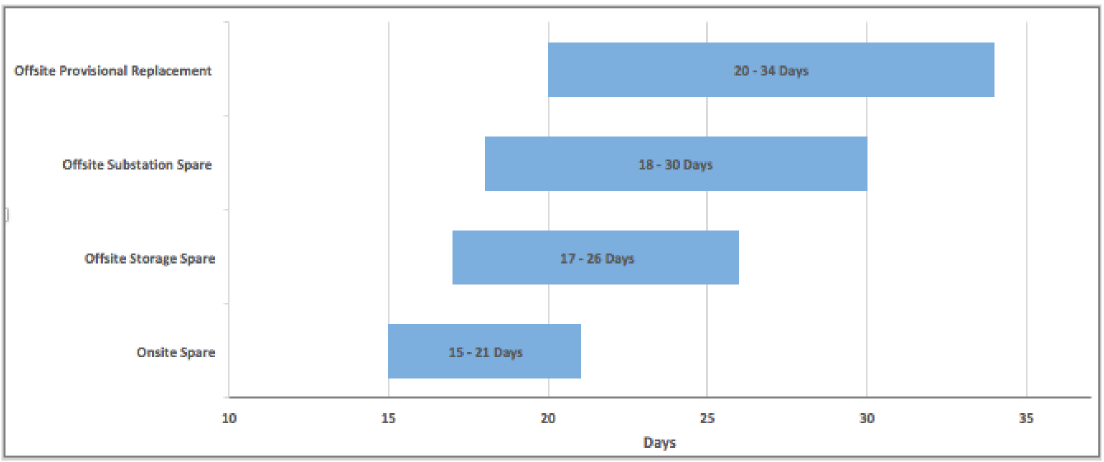

Figure 4: Nominal time required to replace an LPT on an expedited, emergency basis. [Provisional replacement is replacement by an in-service asset].

III.3.10 Rail Transport

LPTs are typically transported via road, rail, and water. Current road, rail and port conditions are becoming increasingly time consuming and expensive for LPT transport [52]. Clearing a rail route for LPT transport can take over nine months. LPTs are larger and heavier than normal rail cars, and each GA inventory type has known dimensions and required axles to account for the weight. Wide load transport by road is an alternative, but it is much slower than rail transport; water transport by barge is the easiest method to move LPTs, but available destinations are severely limited [2]. Additionally, LPTs cannot be transported by normal rail cars because this risks damage to both the LPT and the rail car. Most railcars have a loading capacity of about 100 tons. Typical LPTs can weigh 2-3 times this limit, so customized freight cars are required for these atypically heavy loads [52]. One such car is the Schnabel rail car, which is designed to support a load from connection points on each end. This makes the load a structural part of the railcar [53]. An example schematic of a Schnabel rail car is shown in Figure 5.

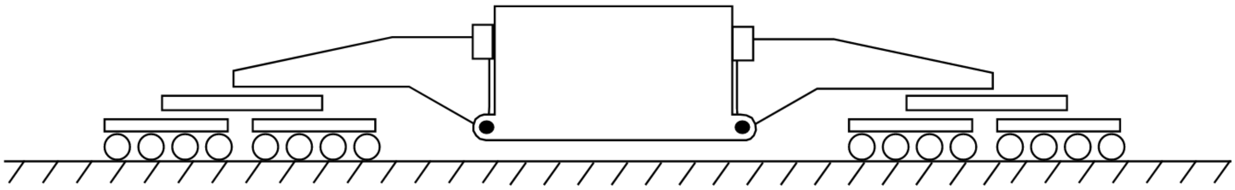

Figure 5. Example of a Schnabel rail car [53].

A version of this car in operation on January 27, 2013, passing through Theodore, AL can be seen in Figure 6. The cars have 12-20 axles to better distribute the weight across the rail section. LPTs typically require 18- and 20-axle Schnabel cars, while medium and small power transformers can be carried on 12- and 8-axle cars [2]. Additionally, the car is designed to accommodate the height of the transformer so that railway height clearances are not violated. A rail line needs to run a simulation of the load on a requested route to ensure it can fit past, under, and across obstacles and bridges. 20-axle rail cars with a shiftable bed can be maneuvered around a corner or obstacle, bridge crossings can be reinforced, overhangs can be lifted, and obstacles can be circumvented with a different route, but all of these steps add time and cost to the transport process. In total, the clearance process can take nine months to complete. Only about three of these specialized transport cars are available in North America. Some manufacturers rent out Schnabel cars, which can cost up to $2500/day plus other fees (as of 2014). Additionally, access to railroads can sometimes be limited due to closures, damage, or removal of rail lines [52].

Figure 6. Schnabel car in operation in Theodore, AL on Jan 27, 2013 [54].

III.3.11 Road Transport

Transport via public roads requires special permits and routes from each state through which the LPT will travel. DOT permits require inspection for all infrastructure over which the LPT will be transported (e.g., bridges), which can add to the overall transport time. Logistics and transportation make up 3–20 percent of the total cost of an LPT [52].

Additionally, specialized vehicles are required when transporting vehicles across roadways. These vehicles must have additional axles and wheels to better distribute the weight of the LPT over the length of the transport trailer. One such trailer is the Goldhoffer trailer [55]. This trailer is suited for super-heavy hauls in excess of 100 tons. An example of the Goldhoffer trailer moving a 500,000 lb. LPT is shown in Figure 7.

Figure 7. Goldhoffer Trailer Moving 500,000 lb LPT [56].

III.3.12 Logistics of LPT Replacement

The inventory numbers, locations, and transport routes for LPTs are all kept private as a national security measure, so a detailed discussion of LPT replacement logistics is not possible. Logistics support is an area for potential government assistance for industry sharing programs to help with transportation and permitting. Therefore, this section presents a general discussion on methods for handling logistics for both assembling and transporting LPTs.

III.3.13 Supply Chain Management: Allocation of LPT Components for Assembly

Customers' needs are diverse due to the highly customized nature of LPTs. Logistics can be used at the component level to accelerate the time required to acquire parts of sufficient quality. Manufacturers often use subjective judgements to select component suppliers [57]. However, there are more systematic methods, which can be used to make such decisions. Some methods for optimally choosing suppliers for the manufactured LPTs are detailed in Chien et al. [57].

III.3.14 Installation Logistics

In addition to the transportation and delivery of replacement transformers, logistics also include installation, construction and assembly, oil filling and settling, as well as commissioning and testing activities. These steps must be scheduled and coordinated not only for individual transformer replacements, but also for multiple simultaneous projects, multiple replacements within a substation (which may have space or transportation access constraints), and continuous sequential replacements. Some of the resources that will impact a utility's ability to perform LPT replacements include:

- Number of crews available to support projects.
- Availability of construction resources such as cranes or heavy haulers.
- Available transformer installation resources such as oil processing rigs, oil storage containers, and vacuum carts.
- Commissioning resources such as transformer tester crews and test equipment.
- Available space within a substation, especially when multiple crews must install and energize an EHV LPT that consists of three single-phase transformers.

Figure 8 depicts the steps required to replace an LPT. In an actual restoration, there would also be activities related to removing the failed unit, cleaning up any oil spills, etc. Whether these tasks could be deferred until after the replacement transformer is in service is dependent upon the nature of any environmental hazards and whether the failed asset must be removed before the new one can be installed.

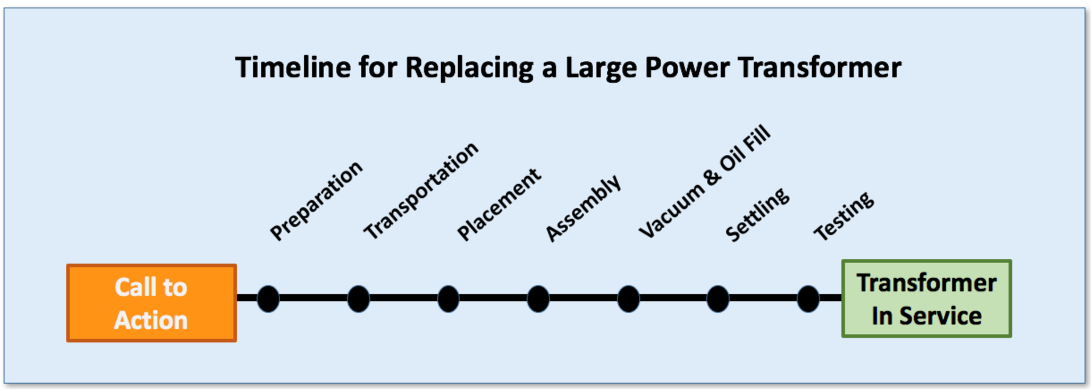

Figure 8: General steps to replace a Large Power Transformer.

Table 1 summarizes the logistics for LPT replacement, giving minimum elapsed times to accomplish each step in an expedited manner.

Table 1: Steps and nominal times to transport and energize a conventional replacement LPT.

Major activity	Step	Approx. time	Comment
1. Prepare the site	a. Remove damaged LPT	N/A	Assume this is completed concurrently with steps 2 and 3.
	b. Repair substation infrastructure, pour and cure new pad if necessary	N/A	
2. Prepare replacement LPT	a. Empty oil from replacement LPT	1 day	Not needed if LPT will be transported with oil.

	b. Teardown/disassembly	3 days	Concurrent with step 2a.
3. Transport replacement LPT	a. Heavy hauler to rail line or roadway	3–10 days (avg. 7)	This depends on the type and length of the route and the proximity to rail sidings.
	b. Rail or roadway transport		
	c. Heavy hauler to substation		
4. Assemble and energize	a. Place on pad in substation; assemble LPT and auxiliary equipment	3 days	
	b. Wiring testing	3 days	
	c. Apply vacuum	3 days	
	d. Fill with oil	1 day	
	e. Oil sit time (settling)	5 days	
	f. Testing/commissioning	1 day	
	Total	**3–4 weeks**	

IV. INDUSTRY STATUS OF LARGE POWER TRANSFORMER SPARES AND REPLACEMENTS

IV.1 EXISTING SPARING AND SHARING PROGRAMS

The issue of long LPT lead times may be mitigated through the creation of an inventory of LPTs ahead of time, keeping them in reserve until needed. There are several ways in which this can be achieved. The first is for each utility to maintain its own stockpile. Most transmission operators already do this, to varying degrees. However, self-supply of spare LPTs is relatively expensive as these spare LPTs are costly, infrequently utilized, and must be maintained and protected while producing no revenue. Many of these "self-supplied" spare LPTs are stored under less-than-ideal conditions, including storing them in the same substations as the in-service LPTs, making the spare LPTs vulnerable to the same events that affect the in-service LPTs [58].

Another option is an industry spare LPT sharing program in which transmission operators agree to pool and share spare LPTs during major events. Existing LPT sharing programs are described in the following sections of this document. A third option would be an entity that independently purchases, maintains, and provides an inventory of spare LPTs and related equipment. One such entity presently exists, a private entity called Grid Assurance (GA). All three of these options are presently being used in industry, as described further in the following sections.

IV.1.1 Spare Transformer Equipment Program (STEP)

The Spare Transformer Equipment Program (STEP) was initiated by the Edison Electric Institute (EEI) in 2006 [7]. STEP is a collective agreement among investor-owned utilities (IOU) to share spare transformers in case of emergency [59]. This program was started to strengthen the energy sector's ability to restore energy transmission capabilities as quickly as possible in the event of a terrorist attack. Under this program, each participant is required to maintain and, if necessary, acquire a specific number of transformers up to 500 kV [7, 59]. Each utility participating in STEP is required to sell its spare transformers to any other participating utility in the case of a triggering event.

More than 50 energy companies that are geographically dispersed across the country and engaged in bulk power transmission services are members of STEP. The enrollment fee for this program is $10,000 and the annual fee is $7,500 [59].

For sharing to be triggered under STEP, there must be either a presidentially-declared terrorist attack, or a presidentially-declared state of emergency [7, 59, 60]. Due to the stringent requirements placed on triggering events, to date STEP has never been utilized [60]. Also, STEP does not provide new or incremental capacity to the utility industry; it only allows sharing of existing assets [60]. STEP is further described in [61], and the reader is referred there for further information.

IV.1.2 SpareConnect

SpareConnect is a less formal voluntary mutual assistance initiative. This initiative was spearheaded by the EEI, supported by the American Public Power Association, the Canadian Electricity Association, the Electric Power Supply Association, the Large Public Power Council, and the National Rural Electric Cooperative Association [61]. SpareConnect is similar to STEP, except in SpareConnect transmission operators self-network using exiting communication channels to allow participants to meet equipment needs during an emergency not connected to terrorism [59]. When an event occurs, an affected utility can post a need to SpareConnect, and if another participant has the equipment, they can connect to the affected utility via SpareConnect. However, availability of equipment is not guaranteed and SpareConnect does not provide additional capacity to the utility industry. Rather, SpareConnect only enables the sharing of existing assets [60]. SpareConnect is further described in [61], and the reader is referred there for further information.

IV.1.3 Regional Equipment Sharing for Transmission Outage Restoration

The North American Transmission Forum (NATF) Regional Equipment Sharing for Transmission Outage Restoration (RESTORE) program is designed to enhance the resiliency and reliability of the energy grid by identifying sources and facilitating replacement of equipment following a disastrous event [62]. The RESTORE Program establishes a voluntary, but formal, agreement among transmission owners to commit to own, maintain, and sell to one another available spare equipment following an event that results in major damage to the transmission grid. This program provides supplemental support and is not intended to be a replacement for any current industry programs.

The RESTORE program identifies an inventory of designated spare equipment to be utilized only after a particular type of “triggering event” has occurred. Under the RESTORE program, a triggering event is defined as an event that is “catastrophic in nature, creating an urgent grid need in which, for an extended period, the affected utility loses its ability to serve significant load or is at risk of losing that ability, or otherwise cannot maintain grid stability” [63]. When a triggering event occurs, each participant may be required to sell the specified equipment within the applicable class to affected utilities as needed to recover from the event. However, participants can use designated spare equipment for internal needs before making designated equipment available for acquisition by another affected utility.

Each utility that participates in RESTORE is responsible for managing (i.e., acquiring, storing, and maintaining) any equipment that it commits to the program and hosting the designated equipment at its own facilities. To ensure designated equipment is available from the reserve when needed, the equipment must be maintained in accordance with best practices and replaced within 18 months if it fails or is damaged, or is used, sold, or retired by the utility. If a utility complies with this "best practices" requirement to meet its designated equipment commitment, it may continue participation in RESTORE while awaiting any equipment replacement.

The goal of the RESTORE program is to make the contributing party "whole" for any equipment provided to another participant. Under the RESTORE Sharing Agreement, the affected participants (buyers) are required to pay replacement costs for equipment obtained from another participant. The agreement provides a framework for arranging the purchase and transfer of equipment between the buyer and seller. Additionally, the agreement serves as a firm commitment and as a reliable resource for utility operators responding to critical events.

IV.1.4 Grid Assurance

GA is a company founded by American Electric Power (AEP), FirstEnergy, and Berkshire Hathaway. GA maintains an inventory of critical equipment, including LPTs and related equipment; provides secure storage for this critical equipment; and provides logistical support for moving the equipment from storage to where it is needed [58].

GA is an industry response to the issue of long lead times for replacement LPTs. GA's primary mission is the mitigation of new-LPT lead times through the creation of an LPT inventory. GA uses a subscriber model, and today there are 31 utility companies who are subscribers to GA, with service territories covering portions of 23 states. AEP is the largest owner, followed by First Energy and Berkshire Hathaway. All utility power system operators, including IOUs, municipal utilities, and public power, are eligible to subscribe to GA.

GA's "trigger event" definition is very broad and includes man-made (physical attack, cyber-attack, EMP), weather (hurricanes, tornadoes, derecho, ice), earth (forest fires, earthquakes), and solar (GMD) incidents. GA's priority is crisis response. It provides spare assets dedicated to emergency needs that add incremental supply to the industry. GA prioritizes spare transformers as they have the longest lead times of any grid equipment. As of this writing, GA has not yet actually provided a replacement LPT.

GA and LPT Inventory

GA's strategic inventory includes LPTs and associated circuit breakers and bushings. GA's LPTs cover five transformer classes and support seven sets of ratings, some of which can be adjusted to different voltage settings. Transformer classes are determined by voltage and ratings are the amount of power that can be transferred. GA does not publicly disclose how many units of each class and rating are in its inventory, but it does offer its risk-assessment tools to its subscribers to assess their own situation. Specific voltage, impedance, and other technical specifications by model are determined by collecting data from multiple customers.

Utility companies routinely analyze their systems to determine the locations of their most critical contingencies. GA works with its subscribers to determine risk levels based on the system information they provide. To ensure that GA can meet the expected level of need for LPTs during a major event, GA hired ICF International, which specializes in probability analysis. As part of its work for GA, ICF built a tool that analyzes diversity of risk, geography, and other factors, to determine how many LPTs must be held to meet a given need. The ICF's structured model incorporates event parameters and event diversity in a Monte Carlo simulation for over 10,000 events, including events that simultaneously impact multiple LPTs. GA maintains an inventory such that ICF's probability analysis indicates a 98 percent likelihood of being able to meet the anticipated needs arising from these events.

GA attempts to standardize asset specifications to maximize the ability to share equipment among member utilities. Many parameters, such as voltages and mega volt-ampere (MVA) ratings, have been at least somewhat standardized, but others, especially the transformer impedance, are more difficult to standardize because of their impacts on the rest of the system (e.g., downstream system protection). Other standardized parameters include tertiary winding ratings, load tap changer configurations, basic impulse levels, losses and efficiency, and cooling design, as well as transportability considerations such as dimensional and weight constraints for road and rail clearance and rail car designs. Because LPTs are so costly to install and transport, GA units are designed to be permanent replacements, as opposed to temporary spares.

Maintaining Spare LPTs

GA has staff on site at its warehouses that maintain its inventory of LPTs in "like-new" condition. Due to this maintenance regimen, GA can hold an LPT in its inventory for up to 25 years, retaining the original 12-month OEM standard warranty to be assignable to the utility purchaser. GA units are minimally vulnerable to cyber threats while in storage, since their relays and controls are powered off and not connected to outside data networks.

GA's assets are stored in two warehouses that each serve GA's subscribers in a specific geographic region. Both are close to transportation channels including water, rail, and major highways. These warehouses have strong security—physical perimeter, armed guards, and electronic surveillance monitored by AEP's security organization. All LPTs are stored indoors. Each warehouse subcontracts key tasks, including asset experience and knowledge, monitoring and maintaining, heavy and wide transportation expertise, and assembly and processing [58].

Transporting LPTs

GA has a transportation logistics department that works with shipping, rail, trucking, jacking and lifting, and oil-filling companies to plan all portions of an LPT's route to its in-field destination. Each GA inventory type has known dimensions and includes the required axle number and specialized rail car design to account for its weight.

The GA logistics department investigates and updates its rail routes yearly, so that any changes in the ability of a rail line to handle an LPT are known in advance. GA allows each customer to specify five drop-off points within their territory. Customers are responsible for “last-mile” transportation, since they are most familiar with their local installations: once the LPT is delivered to the customer’s chosen drop-off point, the customer works with trucking firms to move it to the final site [58]. It should be noted that GA does not own its own fleet of Schnabel rail cars, because these are very expensive to obtain and maintain. The availability of suitable rail cars is a subject that should be discussed further.

Financial barriers to joining GA

For utilities that cannot earn on payments they invest into mitigation, there is an economic challenge to subscribing to an organization like GA. Utilities are heavily regulated to ensure low costs to customers, but when regulations allow them to raise rates to recover from disasters but not to prevent them, utilities are disincentivized from investing in prevention efforts such as transformer stockpiles. Rate recovery would help utilities increase resiliency by allowing them to raise rates to account for long-term investments, such as GA membership. Federal assistance could also encourage states to fund resiliency-enhancement measures [2].

IV.1.5 WattStock [64]

WattStock is a company based in Texas that developed a concept program to deal with lead time issues for LPTs via a temporary modular solution. WattStock’s concept centers around a single-phase transformer called the FLEX transformer, which can be used as part of a modular design to realize larger three-phase LPTs. Each single-phase FLEX transformer unit is designed to avoid many of the transportation logistics issues that make moving three-phase LPTs so difficult. This concept was demonstrated by manufacturing a set of these single-phase temporary LPTs in St. Louis, Missouri, transporting them to Houston, Texas, and replacing a three-phase 400 MVA LPT in a period of about seven days.

The WattStock FLEX solution was designed to be a temporary solution that can be deployed quickly and that will serve until a permanent replacement LPT can be acquired. Because it is a temporary solution, FLEX transformers can often be run outside of their normal specified operating ranges, providing additional flexibility. WattStock envisioned warehousing these single-phase LPTs in regional distribution centers across the country, to facilitate rapid deployment.

WattStock worked with an analytics company that developed a tool to allow WattStock to do an analysis of a utility’s transformers and inform that utility of which LPTs WattStock’s solution could replace. Using this analysis tool, WattStock developed designs for two LPT replacement systems and nine GSU replacement systems. WattStock’s analytics suggested that these two LPT-replacement FLEX transformer designs could be used to provide temporary replacements for as much as 60 percent of the substation LPTs in North America, and the nine GSU designs could replace up to 80 percent of the GSUs. A small number of single-phase units were built, but WattStock’s program was postponed for lack of funding, so at the present time WattStock has no inventory.

IV.2 EFFORTS TOWARD NEXT GENERATION TRANSFORMERS

IV.2.1 DHS/EPRI Recovery Transformer: RecX

A team led by Electric Power Research Institute (EPRI) developed a Recovery Transformer (RecX) that is designed to be a rapidly deployable, temporary replacement for a failed LPT [7]. RecX is a 345 kV unit comprised of three separate single-phase modules to help simplify transportation logistics. A pilot deployment was demonstrated in 2012. The result is that the RecX was successfully installed and energized in less than six days [7].

According to EPRI [65], this program resulted in successful design, manufacture, installation, energization, and field testing of a temporary replacement LPT design. However, as of 2014, the DHS/EPRI RecX has only been implemented at a single utility, CenterPoint Energy. Because of the logistical difficulty of moving and installing LPTs, the enthusiasm for a temporary solution has been somewhat muted; system operators are more interested in permanent solutions that can be quickly deployed [2].

IV.2.2 ABB Modular Transformer

In 2018, ABB reported on the development of a transformer design constructed from multiple single-phase modular units [66]. This design achieves voltage, power, and impedance flexibility using series-parallel arrays of small modules that are designed for ease of transport and installation. The design underwent simulation tests, yielding promising results. However, Reference [66] acknowledges that this is a relatively high-cost approach. As of this writing, there do not appear to be reported results from any hardware demonstrations or field tests of this concept.

IV.2.3 GE/Prolec variable-impedance LPT

In October 2021, GE demonstrated that it is possible to create a variable-impedance transformer by placing coils on the core that create negative flux in the core to modulate the leakage inductance [67]. An autotransformer utilizing this design which also included taps to enable it to operate at any of several common voltages was built and recently underwent a six-month field trial in the U.S. [68]. A final report on these field trials is pending publication, but a draft provided by the manufacturer [69] indicates that this transformer met or exceeded its design expectations. The transportation logistics for this LPT are similar to those of other LPT designs, although this variable-impedance design was reported to have a shipping weight about 12 percent heavier than that of a conventional-design LPT of similar power rating. The initial capital cost of the flexible LPT is also somewhat higher than that of a conventional design due to the additional active parts it contains.

IV.3 EFFORTS TOWARD STANDARDIZATION OF DESIGN AND MANUFACTURING

IV.3.1 Transformer Parameter Standardization Efforts

Several efforts have been undertaken to move LPT users toward more standardized, and thus more sharable, designs. In conversations with industry participants conducted as part of preparing this report, many interviewees from different parts of the industry mentioned that LPT impedance is a particularly difficult parameter to standardize. Transformer impedance requirements depend on many factors that are largely determined by the power system environment in which the unit will be deployed, such as the specifications of any parallel transformers and the protection philosophies used in downstream portions of the system. In addition, the transformer impedance values that lead to the greatest manufacturing efficiencies do not typically align well with the values required by utilities [2]. However, as described above, it appears possible to create variable-impedance LPTs that may help to address this [69].

Part of the reason for this standardization difficulty lies in the fact that many of today's investor-owned utilities consist of combinations of pre-existing power systems. Each of those pre-existing companies has its own historical design philosophy, and these can be difficult and expensive to change or harmonize.

Interestingly, the longevity of transformers is one key obstacle to their standardization. There are examples of design standards from the 1950s that are still in use because that equipment is still in service.

IV.4 CURRENT INVENTORY LEVELS (EEI/APPA/NRECA)

LPTs, just like any other type of equipment, may fail, and will need to be replaced. Because of the long lead time to manufacture LPTs, grid security requires that there be an adequate number of spare LPTs available to replace ones that fail. How many spare LPTs are sufficient? Where should they be located? These are not questions that can be answered precisely. Considerations include:

- LPTs are very site-specific in their designs, so transformers with the same high- and low-side voltages but different impedances may not be interchangeable.
- The number of replacements needed is dependent upon the number of LPTs expected to fail at one time (e.g., caused by a single event).
- Power systems are planned to survive any foreseen contingency, such as the failure of one (or 2, or N) assets or pieces of equipment. Therefore, the number of replacement LPTs is also dependent upon how many (and which) operational LPTs will be out of service before the power system's performance is unacceptable.
- LPTs are difficult and slow to transport. A spare LPT, to be a viable replacement, must be close enough to the failed LPT and its transportation path must be feasible physically to transport it. Spare LPTs located in substations don't require transport, but their physical proximity means they may have been exposed to the same hazard that caused the original LPT to fail.

Utilities undertake many planning exercises and studies to evaluate the numbers and locations of spare LPTs needed. Measures to harden substations and protect transformers can reduce the anticipated number of LPT failures. Inter-utility equipment sharing and assistance agreements (see section III.1) and measures to enhance the viability of possible transportation routes can make it more feasible to rely on spares that are more remote from a damaged substation, thus reducing the number of spare LPTs required.

While not a deterministic metric, a study contributing to the 2017 Report to Congress [51] approached this issue by comparing the number of spare LPTs (whether located in substations or in centralized equipment repositories) with the number of substation LPTs whose loss would have the largest effects on grid performance.

IV.4.1 Estimating the number of most crucial LPTs

The study contributing to the 2017 Report to Congress identified the most crucial high-voltage substations based on a ranking system. The analysis was based on a series of PSS/E power flow simulations of the Eastern, Western and Texas Interconnections. Each power flow simulation consisted of the summer peak model of the interconnection with a single high voltage (345 kV substations for Texas Interconnection, 500 kV substations for Western Interconnection, 500 kV and 765 kV substations for Eastern Interconnection) substation's LPTs removed, and the rest of the substation modeled as operational.

The substations were then ranked based on how much the substation's removal resulted in a decrease in the interconnection's incremental load capability (i.e., thermal) and how much it resulted in a decrease in the interconnection's reactive power headroom (i.e., voltage). Incremental load calculation is a metric of the amount of load-serving capability margin in the system. In the case of incremental load capability, substations are ranked based on the reduction in incremental load-serving capability—lower (or more negative) incremental load-serving capabilities represent more crucial rankings. Reactive power generation headroom is a measure of the ability of the system to support voltage, which can be obtained by measuring the reactive power generation headroom across the system for each simulation run. In the case of reactive power headroom, lower values represent more crucial rankings.

Figure 9 illustrates this procedure for "removing" a substation's LPTs and using the power flow simulation to determine the effects on the bulk power system.

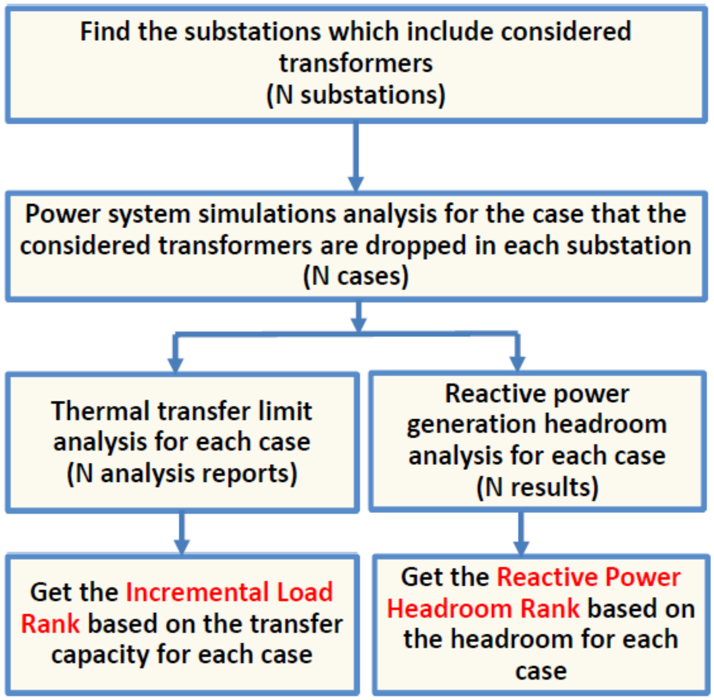

Figure 9: Procedure to identify crucial substations.

For the substations examined in all three interconnections, a consistent pattern was observed in both the thermal (incremental load capability) and voltage (reactive power margin) metrics. For each metric in each interconnection, the loss of LPTs at a relatively small number of stations (10–20 percent) was seen to cause significant reductions in the load-serving capability and/or reactive margin, indicating a significant impact on system reliability. Removal of the LPTs in most of the remaining stations showed virtually no change in the metrics, indicating that other constraints are more limiting to the ability to serve load than the particular LPTs at that station (Figure 10 and Figure 11).

The points of large slope changes in the plots of the cruciality metrics (thermal incremental load capability and reactive power margin) were identified. These points were used to establish the boundaries between crucial and non-crucial stations; values of the thermal or voltage metric that fell below this boundary were considered crucial. For each interconnection, this boundary was determined for both the thermal and voltage metrics. A station was classified overall as "crucial" if either metric indicated that classification.

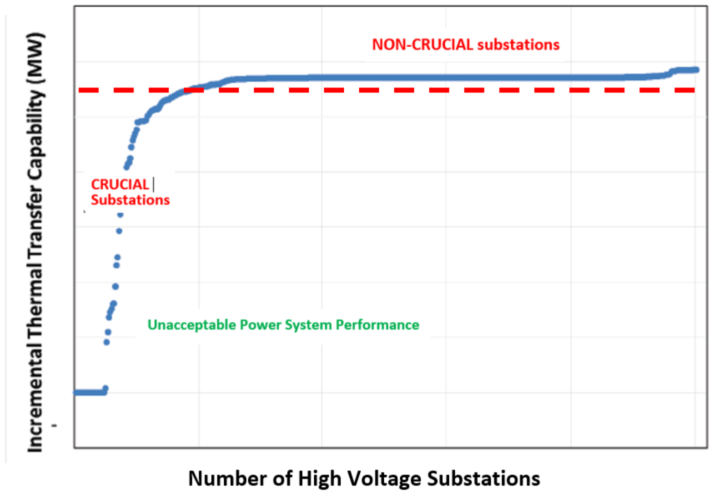

Figure 10: Thermal-based substation cruciality ranking.

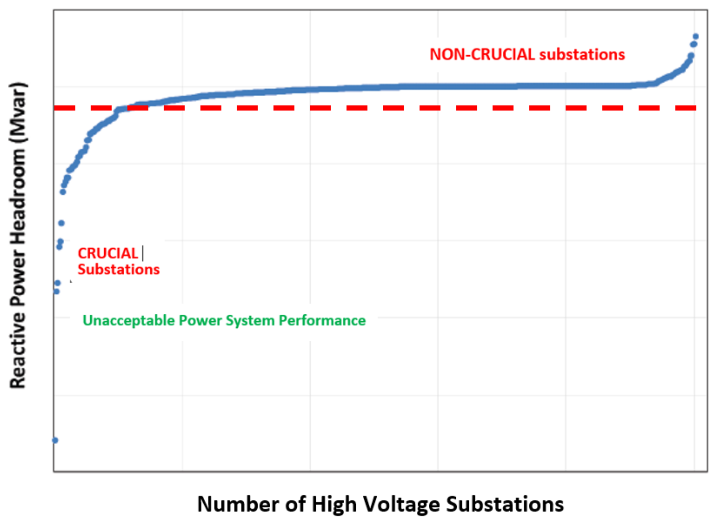

Figure 11: Voltage-based substation cruciality ranking.

IV.4.2 Number of crucial substations and LPTs in 2016

This analysis was performed for 345 kV substations in the Texas Interconnection, 500 kV substations in the Western Interconnection, and 500 kV & 765 kV substations in the Eastern Interconnection. Overall, across the three interconnections at the above voltages, about 17 percent of the substations were “crucial” for at least one of the performance metrics. Of the top tier voltage LPTs in each interconnection, about 28 percent were located in crucial substations[6].

[6] Note for this analysis LPTs were represented as 3-phase transformer equivalents. E.g., three 1-ϕ transformers were counted as one 3-Φ equivalent transformer even through physically they were 3 separate pieces of equipment.

IV.4.3 Industry-reported availability of spare LPTs in 2016

With assistance from EEI, utilities across the U.S. were asked to report how many spare LPTs they owned. Spare LPT inventory numbers were obtained from almost all members of EEI, APPA and National Rural Electric Cooperative Association (NRECA), plus some Federal Power Marketing Administrations. The reported numbers of spares covered:

- 765 kV high side with 500, 345, 230 & 138 kV low side
- 500 kV high side with 500, 345, 287, 230, 161, 138, 115, & ≤ 100 kV low side
- 345 kV high side, 138 kV low side

Across the U.S., the number of high voltage spare LPTs the utilities reported was 116 percent of the number of high-voltage LPTs located in substations the Oak Ridge National Laboratory (ORNL) analysis designated as "most crucial" to the acceptable operation of the bulk power system.

IV.4.4 Industry-reported availability of spare LPTs in 2023

The 2016 analysis to estimate the number of high voltage LPTs located in the most crucial substations was not updated for this report. However, it may be relevant that the Energy Information Administration data show that annual sales of electricity in the U.S. increased by 0.75 percent from 2016 to 2021, and the utility total nameplate generating capacity increased by 0.56 percent. DOE has not updated the 2016 analysis of how many high voltage substations (and transformers) are most crucial, but these EIA numbers on the growth of U.S. electric sales and increase in U.S. generating capacity suggest that the percentage of LPTs whose loss would have the greatest impact on the grid's power transfer and delivery capability has not materially changed.

With the assistance of EEI, utilities across the U.S. were asked to update their reported inventories of spare high voltage LPTs (345 kV and above). As of August 2023, the reported utility inventories of high voltage LPTs increased by over 10 percent compared to the comparable numbers reported in 2016. Utility mutual assistance programs described in Section III.1 have continued to increase member utilities' access to spare LPTs during an emergency. These programs do not increase the number of LPT spares, but they do improve the ability to deploy spare LPTs when needed.

Additionally, since 2016, a new organization (GA) was established (see Section III.1.4) and has purchased an inventory of spare LPTs and auxiliary equipment and also worked to improve the logistics, equipment and personnel necessary to transport LPTs rapidly after a destructive incident or event, thus improving the efficacy of the fleet of spare LPTs across the Nation. GA does not disclose the number of spare LPTs in its inventory. While it is difficult to assess how many spare LPTs are needed, the 2023 inventories reported by U.S. utilities plus the GA efforts suggest that the industry's efforts to provide an accessible inventory of spare LPTs have exceeded the rate of growth of the bulk power system's capacity and electricity sales. In 2017, the DOE Report to Congress [1] concluded that the number of spare LPTs available was appropriate for prudent power system reliability planning. Since then, threats from deliberate attacks and extreme weather events from climate-change have increased. However, the utility industry has responded by significantly augmenting their inventories of spare LPTs.

V. FUTURE CONSIDERATIONS ON LPT RESILIENCE PRACTICES

V.1 OPPORTUNITIES FOR NEW FLEXIBLE ADVANCED TRANSFORMER DESIGNS

V.1.1 LPT Hardening via Hybrid Designs

Hybrid transformer designs involve combining traditional electromagnetic transformers with power electronic converters. The power electronic converters allow active mitigation of the stressors to which an LPT is subjected. It is envisioned that these active mitigation approaches can overcome the limitations of conventional approaches in at least three ways: 1) controllable behavior that can tune response to each type of insult (e.g., based on intensity of the solar storm [G-scale], or respond to similar insults such as from a high-altitude electromagnetic pulse [EMP/E3]) [70]. 2) Active mitigation schemes can have controllable behavior that can consider system-wide dynamics for optimal response to insult. In contrast, conventional approaches focus on limiting GICs at one individual transformer but may cause increased GICs at neighboring transformers. 3) Novel mitigation topologies. Conventional mitigation solutions have focused on blocking GIC flows in the transformer neutral path, but with the ability of power electronics to quickly and accurately control voltage/current/power, alternative approaches are possible (e.g., mitigate GICs with flexible ac transmission systems [FACTS] equipment [71], mitigate impact of GICs by compensating for magnetic flux offset [72], and others). Further research on all these topics is likely to lead to improved ways to harden LPTs against the effects of GMDs.

V.1.2 Solid State Transformers

Solid state transformers (SSTs) are power electronic devices that use power converters to shift voltage levels. A block diagram of a common SST implementation is shown in Figure 12. AC systems 1 and 2 on the left and right of Figure 12 operate at different voltages, and potentially at different frequencies. At the center of the SST is a DC (direct current) link that operates at DC voltage and contains an energy storage element, which is shown here as a large capacitor. The AC/DC block connected to AC system 1 at the left converts between the AC of AC system 1 and the DC of the DC link. Similarly, the DC/AC converter on the other end converts between the DC link and the AC of AC system 2. SSTs can also include an energy storage element such as a battery, which would be connected to the DC link via a DC/DC converter as shown in dashed lines in Figure 12. SSTs can provide several performance advantages over conventional electromagnetic LPTs. These include:

- Modularity. The power converters in SSTs are commonly built from several smaller modules, which improves reliability through redundancy and potentially improves repairability. Modularity could also enhance flexibility since the voltages at which SSTs operate are obtained by stacking modules in series. Thus, SSTs of any desired voltage could be constructed from suitable arrangements of appropriate modules.
- Software-defined functionality. The power converters in SSTs can be controlled via software to vary voltages continuously (as opposed to stepwise changes obtained from tap changers in conventional LPTs) over any range that is in the device’s capability. Software

can also be used to effectively control the impedance of the SST, although the ability of this impedance flexibility to address the inability to standardize LPT impedances is limited because of the overcurrent limitations of SSTs.

- Isolation. The SST isolates AC system 1 from AC system 2 in several important ways. For example, if there is a frequency transient on AC system 1, that transient can be blocked from propagating into AC system 2 by the SST, because of the intervening DC link. This could have important ramifications for mitigation of cascading failures, among other things.

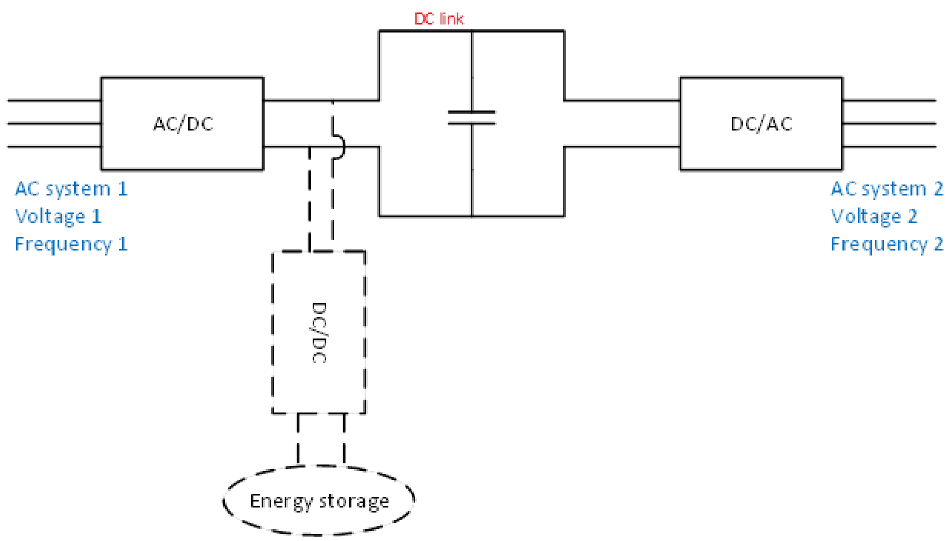

Figure 12. Block diagram of a basic Solid-State Transformer.

For the time being, SSTs that could fully replace LPTs remain in the research domain. Several challenges must be overcome, including:

- Cost. Today's SSTs are significantly more expensive than their electromagnetic transformer counterparts.
- Reliability. SSTs are far more complex than electromagnetic transformers and contain large numbers of semiconductor devices that are vulnerable to transient overvoltages and overcurrents. LPTs, in contrast, are simple devices with proven field lifetimes of more than 40 years. It is a major research challenge to drive the reliability of SSTs up to the point at which they can compete with LPTs in this regard.
- High-voltage, high-power operation. To achieve the high voltages at which SSTs operate, SSTs use large arrays of series/parallel devices. Properly coordinating and controlling all these devices while ensuring device protection is a significant challenge that is the subject of active research.

- System protection. Like all power electronic converters, SSTs have an upper overcurrent limit that they will not exceed because doing so could damage the SST. If, for example, the SST in Figure 12 is sending power from AC system 1 to AC system 2 and there is a fault on AC system 2, the SST can send only a limited amount of fault current into AC system 2. This impacts the design of the protection system for AC system 2.

V.2 STANDARDIZED AND FLEXIBLE LPT DESIGNS

V.2.1 Novel Transformer Designs

Although LPTs have been around for a long time and their designs are highly mature, technical innovation to solve some of the challenges associated with them is still ongoing. As previously discussed, there are several efforts to develop LPT designs that provide flexibility in transportation logistics, operating ranges, and critical parameters. At least one of these efforts resulted in a working prototype that was field-tested and found to work well [68].

V.3 ADVANCED MATERIALS FOR HARDENED TRANSFORMERS

Many new materials exist today that were not available when LPT designs were standardized. New magnetic core materials, many of them composites, have been designed, fabricated, and tested. These materials can now be found in commercially available inductors but have not been implemented in LPT designs [73] [74]. In addition to commercially available soft magnetic composites (SMCs), researchers are pushing the limits of SMC designs through the incorporation of different magnetic alloys, magnetic nanoparticles, new matrix chemistries, and design approaches [75]. Through the incorporation of high magnetization alloys, some of these SMCs have a saturation magnetic polarization (Js) that can exceed that of silicon (Si) steel [76]. These SMCs offer a cost competitive material that can be incorporated into LPT core designs and enhance their resiliency to GMD and EMP events. A representative image of one SMC is displayed in Figure 13.

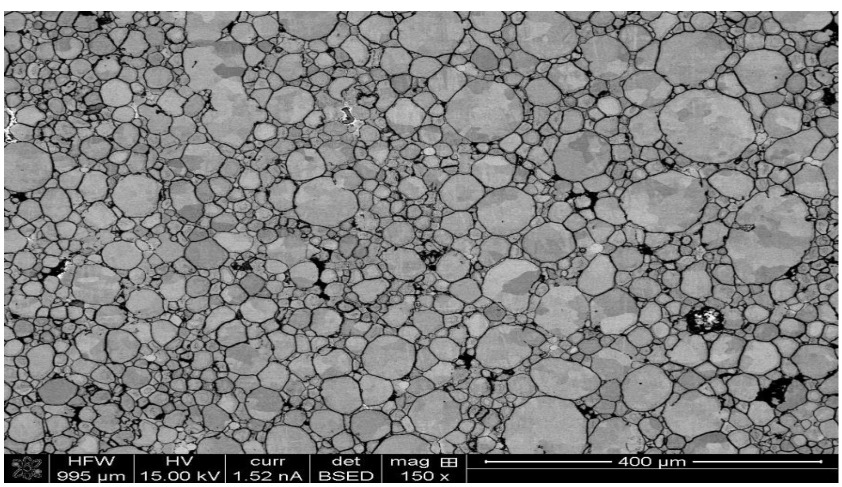

Figure 13: Cross sectional transmission electron microscope image of a $CoFe/Al_2O_3$ soft magnetic composite [76].

It is also possible to fabricate LPT cores using multiple materials. LPT cores with multiple materials that have a range of values of key magnetic parameters such as relative permeability (µr) and saturation magnetic polarization can make the core more resilient to GMD and EMP events, allowing it to continue to absorb and route magnetic flux even when the silicon steel magnetically saturates. Researchers have demonstrated multi-material designs for inductors [77]; however, little effort has been made to apply this concept to LPTs. Design and optimization of multi-material LPT magnetic cores with enhanced resiliency will be made easier using multi-objective optimization codes [78]. For several magnetic core materials, in particular 3 percent and 6.5 percent Si steel, advanced manufacturing techniques have the potential to speed up core manufacturing, decrease overall core cost, and enable innovative core designs/shapes [79] [80].

In addition to advanced magnetic core materials, many new options now exist for core and winding insulation. However, many of these insulation materials and additives are still under development. One class of advanced materials are additives to enhance the breakdown strength and lifetime of kraft paper [81]. Another class of new materials, in which there is quite a bit of work in comparison to kraft paper, are additives to improve the insulation properties and lifetime of transformer oil [82] [83] [84]. Improving the overall robustness and lifetime of LPTs through advanced (yet still cost effective) insulation materials could have great benefit.

V.4 MICROGRIDS FOR ENHANCED RESILIENCE DURING LPT OUTAGES

A microgrid is a section of the power system that can operate in parallel with the grid, and to separate and serve its own loads from its own sources [85]. Microgrids can be important tools for increasing the reliability and resilience of the electric power system because their local sources give them a certain level of immunity to disruptions in large central generators and the transmission system, including the loss of LPTs [86].

The key parameter that will determine how effectively a microgrid buffers against electric service disruptions caused by the loss of LPTs is the length of time that it can operate off-grid, often referred to as the microgrid's Days of Autonomy (DOA). A common recommendation for DOA that is used by the US Department of Defense is 14 days [87], but only a few civilian microgrids approach this level of stand-alone capability; in fact, the National Renewable Energy Laboratory (NREL) defines a "long-duration" microgrid as one with more than 1 DOA [88]. The DOA of a resilience microgrid should be chosen in coordination with the risk studies made by the transmission operator that serves the microgrid site, including the anticipated outage period induced by expected worst-case LPT outage events. However, the reality is the DOA of a microgrid is typically determined or constrained by the available budget, especially if the microgrid relies on batteries for energy storage. Low-cost, long-lived, high-capacity energy storage would be highly beneficial for high-DOA microgrids. Ideally, microgrids would be designed with the capability to connect temporary generation supplied by the system operator in the event of an extended outage. Note that the worst-case interruption time and the LPT lead time discussed extensively above are typically not the same. The worst-case interruption time will generally be much shorter because of the availability of spares and replacements, the ability of the system operator to reroute power over networked transmission, and the ability of system operators to deploy and operate temporary generation.

V.5 ADDRESSING REQUIREMENTS OF A STRATEGIC INVENTORY OF RECOVERY TRANSFORMERS

In its 2017 Report to Congress [51], the DOE noted that a federally-owned LPT reserve program would require five or more geographically diverse sites nation-wide, and well over 100 transformers. The financial, engineering, and logistical specifics of such a reserve were not addressed in that report. Further assessment was requested through the BIL section 40103(d), to investigate:

- the policies, technical specifications, and logistical and program structures necessary to mitigate the risks associated with the loss of high-voltage recovery transformers
- the technical specifications for high-voltage recovery transformers;
- where inventory of high-voltage recovery transformers should be stored;
- the quantity of high-voltage recovery transformers necessary for the inventory;
- how the stored inventory of high-voltage recovery transformers would be secured and maintained;
- how the high-voltage recovery transformers may be transported; and
- whether new Federal regulations or cost-sharing requirements are necessary to carry out the storage of high-voltage recovery transformers.

This report highlights the industry’s ongoing efforts to address various critical aspects of LPT reserve program. These efforts encompass the need for robust risk mitigation strategies, which include countering operational threats such as physical and cyber risks and tackling logistical challenges like replacement and procurement lead times. The industry has been proactive in implementing a range of methods, including internal LPT sparing, spare-sharing programs, subscription-based sparing, physical transformer protection, and asset management strategies, all aimed at mitigating these risks.

The report also delves into the technical specifications of LPTs, emphasizing their unique design to suit specific installations. It examines the challenges associated with these specifications and provides insights into the industry’s ongoing efforts to address them. Furthermore, the document discusses the complexities surrounding the storage, quantity, security, and maintenance of replacement LPTs, shedding light on existing industry solutions. The transportation of replacement LPTs, from storage depots to designated locations, is explored in detail, with a focus on streamlining these processes. The report suggests that Federal assistance, particularly in the areas of rail and highway logistics and permitting approvals for spare LPT movement, could be beneficial. Lastly, the report underscores the importance of regulations and cost-sharing in LPT resilience enhancement. While current regulations have already prompted industry progress in ensuring an adequate supply of LPT assets for future risks, the potential for further regulations to introduce financial and technical challenges is acknowledged. A comprehensive analysis is deemed necessary to strike a balance between national risk tolerance and the costs associated with enhancing the power system's reliability and resilience.

VI. CONCLUSION

DOE's assessment of the situation reveals a concerted effort within the industry to address the vulnerabilities associated with LPTs. As highlighted in the Executive Summary, industry initiatives have been making advancements to mitigate the threats posed to LPTs. This progress is indicative of the commitment to bolstering the reliability and resilience of the U.S. electric grid.

It is challenging to determine the exact number of spare LPTs needed. However, based on the 2023 inventories reported by U.S. utilities and the actions taken by industry, it appears that there is now an accessible inventory of spare LPTs has grown at a rate exceeding the expansion of the bulk power system's capacity and electric sales. The 2017 DOE Report to Congress [1] concluded that the number of spare LPTs available was appropriate for prudent power system reliability planning. Since then, the landscape has evolved with increased threats from deliberate attacks and climate-change-induced extreme events. Nevertheless, the utility industry has responded by significantly augmenting their inventories of spare LPTs.

To further address the complexities of the situation and ensure the continued improvement of LPT resilience, several actions can be considered:

Engage in Ongoing Industry Collaboration: It is crucial to emphasize the importance of continued discussions with industry stakeholders. One approach is to convene the power community, utilizing existing forums or hosting workshops to identify new ideas and concepts. Recommendations, such as exploring cost-sharing arrangements with the Federal Government, could emerge from these discussions. DOE could play a pivotal role in hosting and facilitating such workshops.

Invest in Research and Development: The pursuit of novel concepts and flexible systems, such as mobile transformers, is essential to enhance LPT resilience. Further investment in research and development efforts will drive innovation in this critical area.

Prioritize Storage and Domestic Manufacturing: As the long lead times for LPT continue, efforts should focus on the storage and security of recovery transformers, encouraging domestic manufacturing of transformers, or expanding existing facilities. These actions could be outcomes of discussions with industry to address the challenges of the business model, where LPTs are low volume products but have high impact and consequences when it comes to resilience.

In conclusion, this report has provided a comprehensive overview of the challenges and solutions related to LPT resilience. It has considered the requirements outlined in the BIL, contextualized the issues surrounding LPT acquisition lead times, and summarized the importance of LPTs to the nation's electricity grid. Additionally, it has highlighted industry efforts and future considerations for LPT resilience. As the industry and government continue to work together, implementing the recommendations and strategies outlined in this report will contribute to a more robust and resilient U.S. electric grid, better equipped to withstand emerging threats and challenges.

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ACRONYMS

AEP	American Electric Power
ATI	Allegheny Technologies Incorporated
BIL	Bipartisan Infrastructure Law
CGO	Conventional oriented grade electrical steel
CIP	Critical Infrastructure Protection
CME	Coronal Mass Ejection
CTC	Continuously transposed conduction
DC	Direct Current
DOA	Days of Autonomy
DOC	Department of Commerce
DOE	Department of Energy
DOT	Department of Transportation
EEI	Edison Electric Institute
EHV	Extra-high voltage
EMP	Electromagnetic pulse
EPRI	Electric Power Research Institute
EU	European Union
EV	Electric vehicle
FACTS	Flexible AC Transmission Systems
GA	Grid Assurance
GIC	Geomagnetically induced currents
GMD	Geomagnetic disturbances
GOES	Grain oriented electrical steel
HEMP	High altitude electromagnetic pulse
HI-B	High permeability grade
HV	High voltage
IEEE	Institute of Electrical and Electronics Engineers
IOU	Investor-Owned Utilities
LPT	Large Power Transformer
MMF	Magneto Motive Force
MVA	Mega volt-ampere
NATF	North American Transmission Forum
NERC	North American Electric Reliability Corporation
NOES	Non-oriented electrical steel
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PCB	Polychlorinated bipheny
PDR	Permanent domain refined GOES
RecX	Recovery Transformer
RESTORE	Regional Equipment Sharing for Transmission Outage Restoration
SMC	Soft magnetic composite
SST	Solid State Transformers
STEP	Spare Transformer Equipment Program