U.S. DEPARTMENT OF ENERGY

Electric Grid Supply Chain Review:

Large Power Transformers and High Voltage Direct Current Systems

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, “America’s Supply Chains”

February 24, 2022

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About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- Carbon capture materials,
- Electric grid including transformers and high voltage direct current (HVDC),
- Energy storage,
- Fuel cells and electrolyzers,
- Hydropower including pumped storage hydropower (PSH),
- Neodymium magnets,
- Nuclear energy,
- Platinum group metals and other catalysts,
- Semiconductors,
- Solar photovoltaics (PV), and
- Wind.

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- Commercialization and competitiveness, and
- Cybersecurity and digital components.

More information can be found at https://www.energy.gov/policy/supplychains.

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Principal Authors
Nguyen, Ruby; Severson, Mike; Zhang, Bo; Vaagensmith, Bjorn; Rahman, Md Mamunur; Toba, Ange-Lionel; Price, Paige; Davis, Ryan; and Williams, Sophie, Idaho National Laboratory

Contributors

Calitz, David, Transformer Specialist Engineer, Siemens Energy

Edmonds, Travis, Head of Supply Chain Management, Transformers – North America, Hitachi Energy

Gaskey, Bart, Senior Vice President Marketing, Strategy & Business Development – North America, Hitachi Energy

Goodman, Andrew, Executive General Manager for Sales and Commercial Operations, GE Renewable Energy

Haysbert, John, Vice President Government, and Institutional Relations – U.S., Hitachi Energy

Kirby, Neil, Business Development Manager, HVDC & FACTS, GE Renewable Energy

Kunsman, Steven, Vice President and General Manager Substation Automation – North America, Hitachi Energy

Larsson, David, Vice President HVDC – North America, Hitachi Energy

Liu, Haitao, Head of Supply Chain Management, Grid Integration – North America, Hitachi Energy

Mann, Maggie, Group Manager Transportation Energy Storage and Infrastructure Analysis, National Renewable Energy Laboratory

Ndiaye, Ibrahima, Technology Manager, GE Research

Putsche, Vicky, National Renewable Energy Laboratory

Smith, Braeton, Principal Energy Economist, Argonne National Laboratory

Young, Jeff, Head of Legal, Grid Integration – Americas, Hitachi Energy

Reviewers

Donohoo-Vallett, Paul, Physical scientist, DOE Office of Policy

Henson, Jess, Office of International Trade and Investment Policy, U.S. Department of Treasury

Hsieh, Eric, Director of Grid Systems and Components, Office of Electricity

Igogo, Tsisilile, Lead Supply Chain Coordinator, DOE Office of Policy [Detailee]

Moyseowicz, Andrew, International Trade Specialist, U.S. Department of Commerce

Pereira, Andre, General Engineer, Office of Electricity

Twaite, Kari, Attorney Advisor, Office of Assistant General Counsel for Electricity, Fossil Energy and Carbon Management

Veeder, Christy, Senior Advisor, Office of Policy

Whiting, Amelia, Attorney Advisor, Office of the Assistant General Counsel for Legislation, Regulation & Energy Efficiency

Nomenclature or List of Acronyms

ABB	ASEA Brown Boveri
AC	alternating current
ACB	air circuit breaker
ANSI	American National Standards Institute
ARRTA	American Recovery and Reinvestment Act
ARPA-E	Advanced Research Project Agency - Energy
ATI	Allegheny Technologies Incorporated
BRS	Big River Steel
BTW	Baoding Tianwei Baobian Electric Co., Ltd.
CAGR	compounded annual growth rate
CHIPS	Creating Helpful Incentives to Produce Semiconductors
CGO	conventional oriented grade
CTC	continuously transposed conduction
COVID-19	coronavirus disease 2019
DC	direct current
DETC	de-energized tap changers
DOE	U. S. Department of Energy
EOL	end-of-life
EPO	European Patent Office
ESIG	Energy Systems Integration Group
ETP	electrolytic tough pitch
EU	European Union
EV	electric vehicle
FRP	fiber-reinforced polymer
GE	General Electric

GOES	grain-oriented electrical steel
GW	gigawatt
HICO	Hyosung Heavy Industries
HI-B	high-permeability grade
HS	Harmonized System
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated-gate bipolar transistor
JEDI	Jobs And Economic Development Impact Model
kV	kilovolt
kVA	kilovolt-ampere
LCC	line-commutated converter
LPT	large power transformer
LTC	on-load tap changer
MCT	modular controllable transformer
Mt	million metric tons
MMC	modular multilevel converter
MVA	mega-volt-ampere
MVDC	medium voltage direct current
MW	megawatt
NAICS	North American Industry Classification System
NDC	nationally determined contribution
NOES	non-oriented electrical steel
NREL	National Renewable Energy Laboratory
OFHC	oxygen free high conductivity
OIP	oil-impregnated paper

O-RAN	open radio access network
PCB	polychlorinated biphenyl
PCT	Patent Cooperation Treaty
POSCO	Pohang Iron and Steel Co., Ltd
R&D	research and development
RTO	Regional Transmission Organization
SBIR	Small Business Innovation Research
STTR	Small Business Technology Transfer
TAA	Trade Adjustment Assistance
U.K.	United Kingdom
U.S.	United States of America
VSC	voltage source converter
WTO	World Trade Organization

Executive Summary

The need to modernize and increase the capacity of the U.S. power grid is increasing due to growing population, aging infrastructure, grid resilience requirements, operational flexibility needs, and a growing portfolio of renewable energy. As part of the Paris Climate Agreement the United States has committed to reducing its net greenhouse gas emissions by 50 to 52 percent below 2005 levels in 2030 and has set a goal of 100 percent carbon pollution free electricity by 2035 (The United States of America Nationally Determined Contribution, 2021). Meeting these targets will require a significant expansion of the power system to integrate a large amount of new renewable resources (United States Department of State & United States Executive Office of the President, 2021). However, many critical components supporting the power grid have limited to no domestic manufacturing capacity and face complex challenges in supporting a rapid expansion of the grid to meet multiple objectives, including decarbonization goals.

This report focuses on two key grid components: large power transformers (LPTs) and high-voltage direct current (HVDC) transmission.

Large Power Transformers

These transformers are used to step up voltage to decreases the power losses from electricity transmission, and to step down voltage for distribution at lower, more usable voltage levels. It is estimated that over 90 percent of the nation's consumed power passes through an LPT (Office of Electricity, 2021). The average age of installed LPTs in the Unites States is ~40 years (U.S. Department of Energy, 2014), which is the end of their expected life time. Aging LPTs cause higher failure risk. This fact combined with challenges in the LPT supply chain and potential bottlenecks to rapid grid expansion raised concern about the vulnerability of the domestic electric grid.

Within the LPT supply chain, raw material suppliers for grain-oriented electrical steel (GOES), continuously transposed conduction (CTC) copper wire, and insulating materials have a significant influence on final LPT availability and price. The two weakest segments are GOES and LPT manufacturing. There is only one GOES manufacturer in the United States and this company is unable to meet domestic demand with highest quality and comparable prices with imported GOES. Additionally, component suppliers for bushings and tap changers to the transformer manufacturers can cause supply chain bottlenecks through long lead times which are exacerbated by the COVID-19 pandemic. The LPT manufacturing capacity also has a bottleneck regarding shared test space for multiple transformer types. It was estimated that in 2019, utilized domestic capacity was about 40%, and 82% of LPTs consumed in the United States were imported (U.S. Department of Commerce, 2020). Adding more complexity is the emerging electric vehicle (EV) application that consumes non-oriented electrical steel (NOES) which reduces GOES supply because both materials come from the same manufacturing facilities. The trend to invest in NOES for EV is growing. Pohang Iron and Steel Co., Ltd. (POSCO), a major global steel maker based in Korea, doubled its annual production capacity from 80,000 tons to 160,000 tons in 2017 (H.-s. Lee, 2017) and planned to build a new factory with 300,000-ton NOES production capacity in 2021 (Hwang, 2021). In parallel, POSCO also planned to cut GOES production to improve its profitability (H.-s. Lee, 2017).

The short-term opportunity to reduce LPT supply chain vulnerability is to improve domestic GOES production capability. Big River Steel acquired by U.S. steel has NOES production capability which can be upgraded to produce GOES. Domestic LPT producers can help establish base demand for GOES thanks to their diverse sourcing strategy. The medium-term opportunity is to focus on reducing LPT import reliance. Because LPT manufacturers produce both LPTs and non-LPTs using the same facility, increased test space could solve their manufacturing bottlenecks. Another medium-term focus is on workforce training which would require a change in both training curricula at various levels and offering of apprenticeships and internships in collaboration with industry. Long-term efforts require more research and development to improve efficiency, reduce material content, and cut costs.

High-Voltage Direct Current (HVDC) Transmission

This technology provides an alternative electrical transmission system to conventional alternating current (AC) which increases the power grid's capacity to receive, transmit, and deliver a large amount of energy. HVDC technology is more cost-effective compared to HVAC for longer transmission distances. In addition, this technology improves grid resilience and security, operation flexibility and accommodates the integration of renewable energy transmission into the existing grid to reach the nation's goal of carbon neutrality. Many large-scale renewable resources are in remote or offshore areas, which are typically far away from load centers, and require efficient delivery of the energy over long distances.

The HVDC transmission systems supply chain considered in this report consists of four main components including converters, DC switchgears (breakers), DC filters, and AC switchyards. These four components require sub-components such as insulated-gate bipolar transistors (IGBTs), capacitors, inductors, arrestors, AC switches, resistors, and distribution transformers. The major bottleneck of this supply chain is a lack of domestic HVDC transmission system manufacturing due to low demand. There are two main reasons for not having high HVDC demand in the United States. First, large transmission projects require collaboration from multiple Regional Transmission Organizations (RTOs) which proves to be difficult. Second, cost recovery aspect of an HVDC project needs a new customer base -similar to a tollway project business model- that is hard to forecast due to competition with existing, lower cost transmission systems. The short-term opportunity to increase HVDC domestic manufacturing is through enhancing collaborations among RTOs and developing government policies to stimulate demand. The medium-term opportunities are to increase research activities and train the workforce in this field. Stable demand and skilled workforce provide security for manufacturers to locate facilities in the United States to reduce costs in the long-term.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

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1 Introduction

The need to modernize and increase the capacity of the U.S. power grid is increasing due to growing population, aging infrastructure, grid resilience requirements, operational flexibility needs, and a growing portfolio of renewable energy. As part of the Paris Agreement goal to hold the increase of the global average temperature to well below 2° C (preferably 1.5° C) above pre-industrial levels, the United States has declared a Nationally Determined Contribution (NDC) of reducing its net greenhouse gas emissions by 50 to 52 percent below 2005 levels in 2030 and reach 100 percent carbon pollution free electricity by 2035 (The United States of America Nationally Determined Contribution, 2021). To help accomplish the NDC goals, the U.S. Department of Energy has begun the Energy Earthshots Initiative to transform key technologies that will enable more abundant, affordable, and reliable clean energy solutions within the decade. The first three Earthshots goals are (1) to reduce the cost of clean hydrogen by 80% (U. S. Department of Energy, 2022b), (2) to reduce the cost of grid-scale energy storage by 90% for systems delivering 10+ hours of duration within this decade (U. S. Department of Energy, 2022c), and (3) to innovate in methods to capture CO_2 and store at scale for less than $100/net metric ton of CO_2-equivalent (U. S. Department of Energy, 2022a). If the hydrogen goals are realized, hydrogen could account for 14% of total energy demand in the United States in 2050 (U.S. Department of Energy, 2020). In addition, the Wind Vision outlined a scenario where 30 GW and 86 GW of offshore wind will be added in 2030 and 2050, respectively (Department of Energy, 2021; U.S. Department of Energy, 2020; Wind Energy Technologies Office, 2017). SunShot 2030 goals for solar energy also projected 20% solar penetration in 2030 and 30% penetration in 2050 (Solar Energy Technologies Office, 2016). All these goals will require a rapid transformation of the power grid to accommodate a large amount of renewable energy. Deployment of HVDC transmission can support integration of large amounts of renewables while increasing the flexibility, reliability, security, and resilience of the grid (Figure 1).

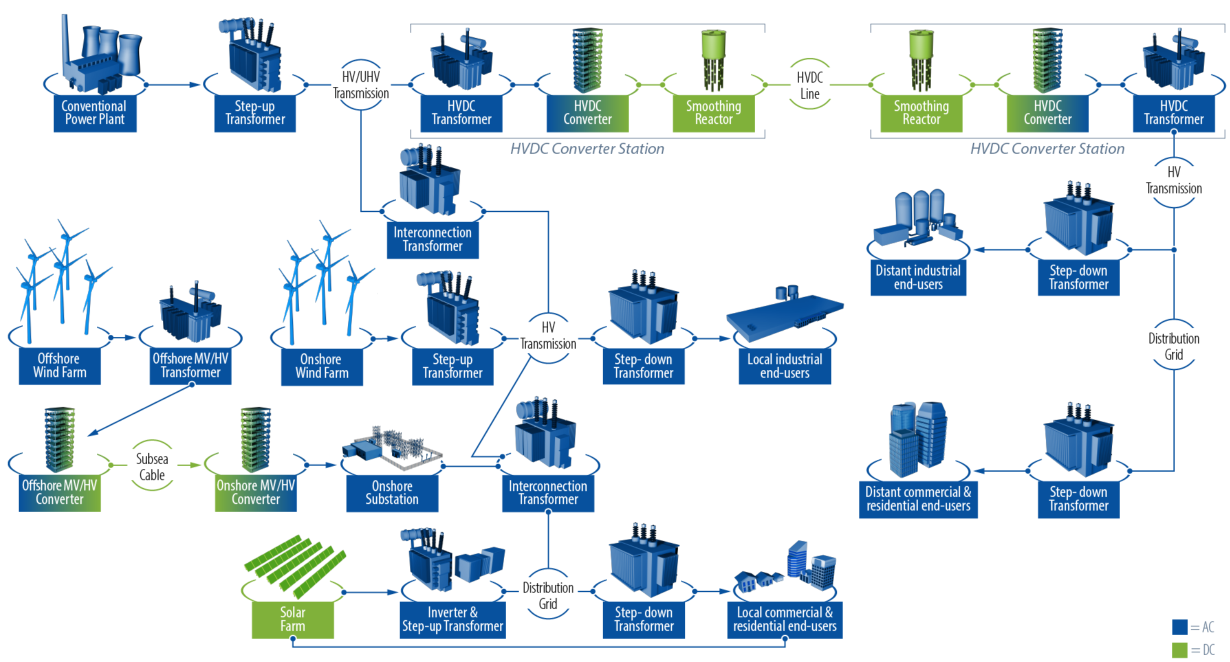

Figure 1. Types of transformers and HVDC transmission in energy sector industrial base.

The Net Zero America study by Princeton University shows that an investment of $320 billion in transmission expansions and end-of-life (EOL) line replacements is needed to support efforts to incorporate wind and solar energy generation by 2030 (Pascale, Jenkins, & Leslie, 2021). Early investment in transmission projects is vital to successfully integrating clean energy into the electrical grid since transmission projects can take 3-10 years while generation projects, such as solar, take about a year to complete (D. Lee & Marshall, 2021). LPTs and HVDC systems are two examples of grid infrastructure that will face a growing demand to meet this transformation. Both face complex challenges with a strained or virtually non-existent domestic manufacturing capability.

1.1 Large Power Transformers

1.1.1 Role of Large Power Transformers in the Electric Grid

Transformers play an important role in several different capacities within the U.S. electric grid. For the purposes of this report, the focus is on large power transformers (LPTs), which have been defined as a transformer with a capacity rating of 100 MVA or higher. Some market reports use 60 MVA as a threshold for classification of LPTs. However, it should be noted that there is not an industry standard that defines the power output of a "large" transformer (U.S. Department of Energy, 2014). These LPTs function to step up or step down voltage through the principle of electromagnetic induction (U.S. Department of Energy, 2014). This is accomplished through sets of coil windings wound around a core allowing voltage changes between each set of windings depending on the number of turns (U.S. Department of Energy, 2014; U.S. Department of the Interior Bureau of Reclamation, 2005). The step-up of voltage decreases the power losses from electricity transmission, while the step-down of voltage converts high-voltage energy for distribution at lower, more usable voltage levels. It is estimated that over 90 percent of the nation's consumed power passes through an LPT (Office of Electricity, 2021). The average age of installed LPTs in the Unites States is ~40 years (U.S. Department of Energy, 2014). More than 70% of U.S. LPTs are aged more than 25 years (Hoffman & Bryan, 2014). Some units in the grid are even more than 70 years old and still operating (Hoffman & Bryan, 2014). Aging LPTs cause higher failure risk. This fact combined with challenges in the LPT supply chain and potential bottlenecks to rapid grid expansion raised concern about the vulnerability of the domestic electric infrastructure. LPTs are expensive, difficult to transport, and highly custom devices that often have long lead times (Office of Electricity, 2021). For this reason, this report seeks to identify challenges and bottlenecks that exist within the LPT supply chain.

1.1.2 Transformer Global and Domestic Market Assessment

Globally, the demand for power transformers in 2020 was reported as approximately 12,500 units, in which 4,600 units were reported for 61 MVA and higher ratings (Global Market Insights, 2021). Forecast for 2027 is expected to reach 23,400 units, of which 7,700 units have ratings of 61 MVA and higher. North America's approximated demand for power transformers in 2020 was 1,300 units and the projection for 2027 will be 2,800 units (Global Market Insights, 2021). In 2019, U.S. apparent consumption of LPTs was 750 units (U.S. Department of Commerce, 2020). Apparent consumption is defined as domestic production plus import subtracted by export. The U.S. demand for ratings of 61 MVA and higher has been consistent since 2016 (Global Market Insights, 2021). Forecast for U.S. demand for LPT based on this power rating will reach ~900 units in 2027 (Global Market Insights, 2021). The global and U.S. market value for LPTs in 2020 was ~$15 billion and ~$2.6 billion (Market Research Future, 2021), respectively. The projected compounded annual growth rate (CAGR) for the United States until 2027 is ~ 6 – 7% while the global CAGR is estimated at 6 – 7% as well (Global Market Insights, 2021; Market Research Future, 2021). With this growth rate, the estimated U.S. market value for LPTs in 2027 is $4 billion while the global market value is ~$24 billion. Overall, the United States represents 9 – 17% of the total global LPT market. Major drivers for the transformer market growth include: (1) upgrading aging infrastructure, (2) increased demand in energy consumption over time and (3) increased penetration of renewable energy. On the other hand, high capital investment costs and reluctance to replace aging infrastructure are the two dominant restraints to growth (Market Research Future, 2021).

Geographically, in 2020, the Asia-Pacific region had the largest global LPT market share in sales (39%), followed by Europe with 24%, then Middle East & Africa with 17% market share (Global Market Insights, 2021). North America had 15% while South America had the lowest market share of 4% (Global Market Insights, 2021). Major global players for all transformer markets include Hitachi Energy (formerly ABB), Siemens Energy, Schneider Electric, Mitsubishi, and Eaton. Their respective market shares in 2019 were 12.0%, 10.7%, 6.4%, 6.1% and 6.0% (Market Research Future, 2021). The major transformer manufacturers with production capabilities in the United States include Delta Star, Hitachi Energy, Hyosung Heavy Industries (HICO), Hyundai Power Transformers USA, Niagara Power Transformer, Pennsylvania Transformer Technology, SPX Transformers (acquired by General Electric) and Virginia Transformers (formerly EFACEC) (U.S. Department of Commerce, 2020; U.S. Department of Energy, 2014). In addition to these domestic production facilities, many of the companies possess production facilities in foreign countries.

1.2 High-Voltage Direct Current Systems

1.2.1 Benefits of HVDC Technology in the Electric Grid

HVDC technology provides highly efficient ways to receive, transmit, and deliver a large amount of renewable energy over long distances. Compared to typical high-voltage AC power system networks, HVDC transmission has the following advantages:

- HVDC technology is more economical for long-distance and high-power electricity transmission. It does not require reactive power compensation to boost the power factor compared to AC transmission as the distance increases. Typically, HVDC networks become more cost-effective for longer distances compared to AC systems. However, there is not a universal rule of thumb on what the minimum distance should be. While one source indicated 400 miles (GE, 2016), another source mentioned 124 miles (U.S. Energy Information Administration, 2018) for onshore projects. The minimal distance for undersea projects is 37 miles (U.S. Energy Information Administration, 2018). Table 1 lists some examples of HVDC transmission projects with different transmission distances (Guidehouse Insights, 2018; Larson, 2021; Tabrizi, Obessis, & MacLeod, 2020; TenneT, 2022b). Descriptions of line-commutated converter (LCC) or modular multilevel converter (MMC) systems can be found in Section 2.2.2 regarding converter types. Figure 2 shows the cost breakdown of an HVDC system at different voltages versus an HVAC system and the component level costs for a 1,242 mile, 6 GW transmission system (Alassi, Bañales, Ellabban, Adam, & MacIver, 2019). This figure also points out that using the same HVDC technology, the higher the voltage gets, the less costly the system is.
- HVDC technology creates a decoupling and controllable connection terminal with AC/DC converter stations. As a result, the power grid's resilience and security increase compared to the pure AC power grid when having a wide-region AC grid outage or failure (U.S. Energy Information Administration, 2018; B. Zhang & Nademi, 2020).
- HVDC technology has better voltage stability compared to the AC grid for long-distance transmission. AC transmission voltage is affected by parasitic capacitance/inductance along the transmission line, but DC transmission does not have this shortcoming (U.S. Energy Information Administration, 2018; B. Zhang & Nademi, 2020).

Table 1. Examples of onshore and offshore HVDC projects with different transmission distances.

HVDC Project	Country	Voltage	Distance	Type
Changji-Guquan	China	±1100 kV	2,040 miles	Onshore, LCC (Modern Power Systems, 2016)
New England Coast	United States	±320/525 kV	195 miles (170 nautical miles)	Offshore, MMC (Equinor, 2021)
North Sea Link	Norway-UK	±515 kV	450 miles	Offshore, MMC (NorthSeaLink, 2021)
SOO Green	United States	±525 kV	350 miles	Onshore, underground, under development (SOOgreen, 2021)

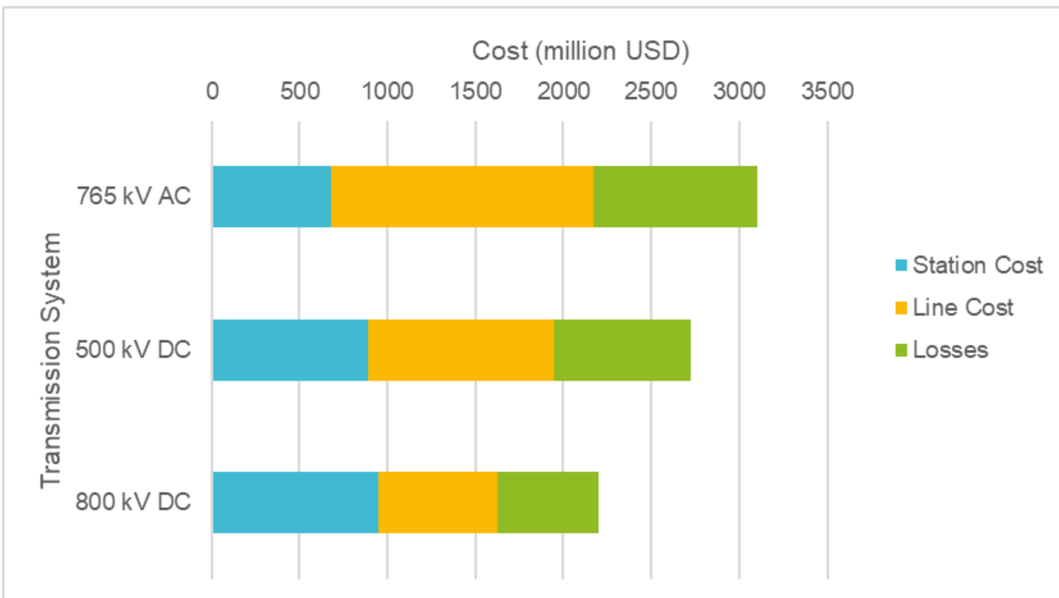

Figure 2. Cost estimation of 6 GW HVDC transmission over 1,242 miles (Alassi et al., 2019).

The United States has a goal to deploy 30 GW of offshore wind by 2030 and 86 GW by 2050 (Department of Energy, 2021; Wind Energy Technologies Office, 2017). Given that HVDC is a major transmission technology for integrating offshore wind farms to an onshore grid, at least ten offshore HVDC transmission systems and associated converter stations with 3 GW each or equivalent could be needed by 2030 (Acevedo et al., 2021; Azar et al., 2021; Brown & Botterud, 2021). In areas along the Eastern U.S. continental shore, large-scale HVDC technology would be advantageous to transport and integrate offshore wind to the mainland electricity system (Azar et al., 2021). At a nation-wide scale, given the demand for long-distance and high-power electricity transmission to ensure decarbonization, multiple interconnections of HVDC transmission hubs are preferred. The Energy Systems Integration Group (ESIG) study (Azar et al., 2021) indicated that tens of GWs of HVDC, considering the geography aspects, can be utilized for onshore national AC/DC macro grid connection. The economic feasibility of HVDC projects is also favorable, as the nation-wide macro grid reduced overall system costs by 46 percent compared to the state-by-state approach to reaching a zero-carbon electricity system (Brown & Botterud, 2021).

1.2.2 Global HVDC Market

The global HVDC market was approximated at $8.2 billion in 2018 with projections to reach 12.3 billion by the year 2024 (Markets and Markets, 2019). Reports also indicate that HVDC interconnector revenue exceeded an average of $7 billion per year (2013-2020) with a CAGR of 5.5% (Alassi et al., 2019). The market also expects to see HVDC transmission capacity of more than 400 GW by the year 2022 with 52% of the capacity originating from Asia (Alassi et al., 2019). Conversely, North America has represented a much smaller capacity in past years (2010-2017) with only 3.6% of the global HVDC power transmission capacity (Alassi et al., 2019). Globally, General Electric (GE), Hitachi Energy, and Siemens Energy are the three leading HVDC manufacturers.

1.2.2.1 Current Domestic HVDC Projects

The United States is behind on the number of projects and installed HVDC capacity compared to countries like China and Europe. The U.S. market for HVDC systems is influenced by ongoing projects, including offshore wind and interstate transmission projects.

HVDC project connecting offshore wind hub and onshore grid

The "Beacon Wind" project, a 170-nautical-mile HVDC project off the coast of New England started in early 2019, is a typical example of delivering offshore wind power to New York City. In this case, over 1.2 GW of power will be delivered (Equinor, 2021; Larson, 2021). Another offshore wind power project named "Empire Wind 2" with 1.26 GW is also planned 20 miles south of Long Island in New York (Renewable Energy Magazine, 2022).

HVDC systems for national macro-AC/DC grid network

The 2.1 GW "SOO Green" HVDC Link project (Larson, 2021) will connect an HVDC converter station in northern Iowa to a converter station in Illinois just west of Chicago, roughly 350 miles away, as shown in Figure 3. It uses paired 525-kV cross-linked polyethylene-class cables installed underground primarily along existing railroad right-of-way to make the connection (Larson, 2021).

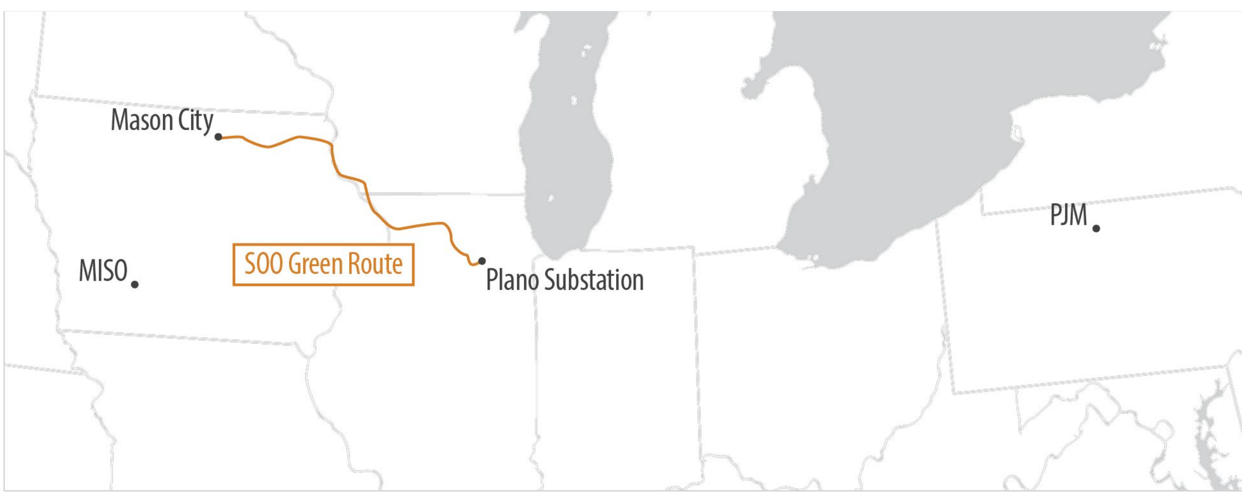

Figure 3. The SOO Green HVDC Link between MISO terminal at Iowa and PJM terminal at Illinois.

Table 2 lists several HVDC transmission lines in the United States that offer promising routes and technologies (Azar et al., 2021). In some cases, land acquisition and permitting processes have started. These lines are advantageous because they unite high load zones with exceptional renewable energy zones.

Table 2. U.S. onshore planned/operating HVDC systems over 1 GW (excluding joint link with Canada).

Project name	Capacity	Point of Injection	Point of Receipt	Status
Intermountain Power	2.4 GW	Utah	California	Commissioned in 1986, LCC-HVDC type (Wu, Shockley, & Engstrom, 1988)
Pacific Direct Current Intertie	3.1 GW	Oregon	California	Commissioned in 1970, upgraded in 2017, LCC-HVDC type (Barnes, Hertem, Teeuwsen, & Callavik, 2017; Sundaresh, Yuan, Sun, Pan, & Liu, 2020)
Plains & Eastern	4 GW	Oklahoma	Tennessee	NextEra Energy Resources acquired it in 2018, still at planning stage (Azar et al., 2021; Office of Electricity, 2018)
SOO Green	2.1 GW	Iowa	Illinois	Expect to commence in 2023 (Azar et al., 2021; SOOgreen, 2021)
Southern Cross	2 GW	Texas	Alabama	Expect construction to commence in 2022 (Azar et al., 2021; SouthernCross:, 2021)
Sunzia	4.5 GW	New Mexico	Arizona	Expect construction to commence in 2023 (Azar et al., 2021; Sunzia, 2021)
Transwest Express	3 GW	Wyoming	Nevada	Plan announced in 2021 (Azar et al., 2021; Transwest Express LLC, 2021)

1.2.2.2 *Global HVDC Example Projects*

In Europe, the North Sea Wind Power Hub (North Sea Wind Power Hub Programme, 2021) is a major offshore wind energy source for several countries within the European Union operated by TenneT, a Germany/Netherland Transmission System Operator. Because the North Sea wind farm is far away from the onshore grid, HVDC transmission is the best option to provide the long-distance transmission to the load demand centers in Germany, Netherland, U.K., Norway, Denmark, Belgium, France, and other countries. In the summer of 2020, the German government decided to expand the capacity from 15 GW to 20 GW to achieve the climate and energy objectives of the Paris Climate Agreement efficiently and cost-effectively. With this plan, Germany and the Netherlands will achieve 20 and 11.6 GW of production capacity in 2030, respectively, using offshore HVDC platforms and 525 kV undersea transmission cable systems (Tennet, 2022a). With the large potential for offshore wind power offered by the North Sea, it is planned to generate 180 GW by 2045. In addition, part of the generated electricity is converted to hydrogen and transported to shore using pipelines, the remainder of wind energy is transported to shore using electrical connections (North Sea Wind Power Hub Programme, 2021). More than 40 GW of electrolyzers is planned by 2030 (Parnell, 2020). Other HVDC projects can also be found in Table 3.

In China, the northwest region has a lot of wind resources, and the western region has multiple hydropower plants. However, those sources are far away from the end-users in the southeast regions. To achieve long-distance and high-power transmission, tens of ±1,100 kV, ±800 kV, and ±500 kV HVDC systems are operated across the nation to deliver over 1000 GW of electricity from the rural northwest areas to economic centers in southeast regions (Xu, 2016).

Table 3. Parts of > 800 MW HVDC systems currently operating in Europe.

Project Name	Capacity	Point of Injection	Point of Receipt	Type	Status
ALEGrO	1 GW	Belgium	Germany	VSC/MMC-HVDC	Commissioned in 2020 (Amprion GmbH, 2021)
BorWin2	0.8 GW	North Sea	Germany	VSC/MMC-HVDC	Commissioned in 2015 (TenneT, 2022b)
BorWin3	0.9 GW	North Sea	Germany	VSC/MMC-HVDC	Commissioned in 2019 (TenneT, 2022c)
BritNed	1 GW	UK	Netherlands	LCC-HVDC	Commissioned in 2011 (Tennet, 2022d)
Caithness - Moray	1.2 GW	UK-Caithness	UK- Moray	VSC/MMC-HVDC	Commissioned in 2019 (Scottish & Southern Electricity Networks 2021)
DolWin1	0.8 GW	North Sea	Germany	VSC/MMC-HVDC	Commissioned in 2015 (TenneT, 2022e)
DolWin2	0.9 GW	North Sea	Germany	VSC/MMC-HVDC	Commissioned in 2016 (TenneT, 2022f)
DolWin3	0.9 GW	North Sea	Germany	VSC/MMC-HVDC	Commissioned in 2017(TenneT, 2022g)
Fenno–Skan2	0.8 GW	Finland	Sweden	LCC-HVDC	Commissioned in 2011 (ABB, 2021)
HVDC Cross-Channel	2 GW	France	UK	LCC-HVDC	Commissioned in 1986 (DBpedia, 2021)
IFA-2	1 GW	France	UK	VSC/MMC-HVDC	Commissioned in 2021 (National Grid, 2021)
INELFE	2 GW	France	Spain	VSC/MMC-HVDC	Commissioned in 2015 (Coronado, 2020)
Nemo Link	1 GW	Belgium	UK	VSC/MMC-HVDC	Commissioned in 2019 (NemoLink, 2021)
NordLink	1.4 GW	Norway	Germany	VSC/MMC-HVDC	Commissioned in 2021 (TenneT, 2022h)
North Sea Link	1.4 GW	Norway	UK	VSC/MMC-HVDC	Commissioned in 2021 (NorthSeaLink, 2021)
SAPEI	1 GW	Italy-Latina	Italy-Fiume Santo	LCC-HVDC	Commissioned in 2011 (Hitachi Energy, 2021a)
SylWin1	0.864 GW	North Sea	Germany	VSC/MMC-HVDC	Commissioned in 2015 (TenneT, 2022i)

Project Name	Capacity	Point of Injection	Point of Receipt	Type	Status
Western HVDC Link	2.2 GW	UK- Western Scotland	UK- North Wales	LCC-HVDC	Commissioned in 2019 (Macchione, 2018)

2 Supply Chain Mapping

2.1 Large Power Transformers

2.1.1 Supply Chain Segments

The transformer industry structure, shown in Figure 4, includes raw material suppliers, component suppliers, transformer manufacturers, end-users, and recyclers/re-manufacturers. Data for this section were obtained through literature and stakeholder engagement (details are provided in Section 3.1.1). When these data are used, stakeholder engagement is mentioned but no citation is provided to protect the anonymity of the respondents. Raw material suppliers have the most influence on component and transformer prices due to material availability, including metals, insulating materials, oil, and sealing materials. The material suppliers for components such as GOES, CTC copper wire, insulating materials, and polymers also have a significant influence on the final products. The component suppliers provide bushings, insulators, tap changers, switches, valves, and other mechanical components to the transformer manufacturers.

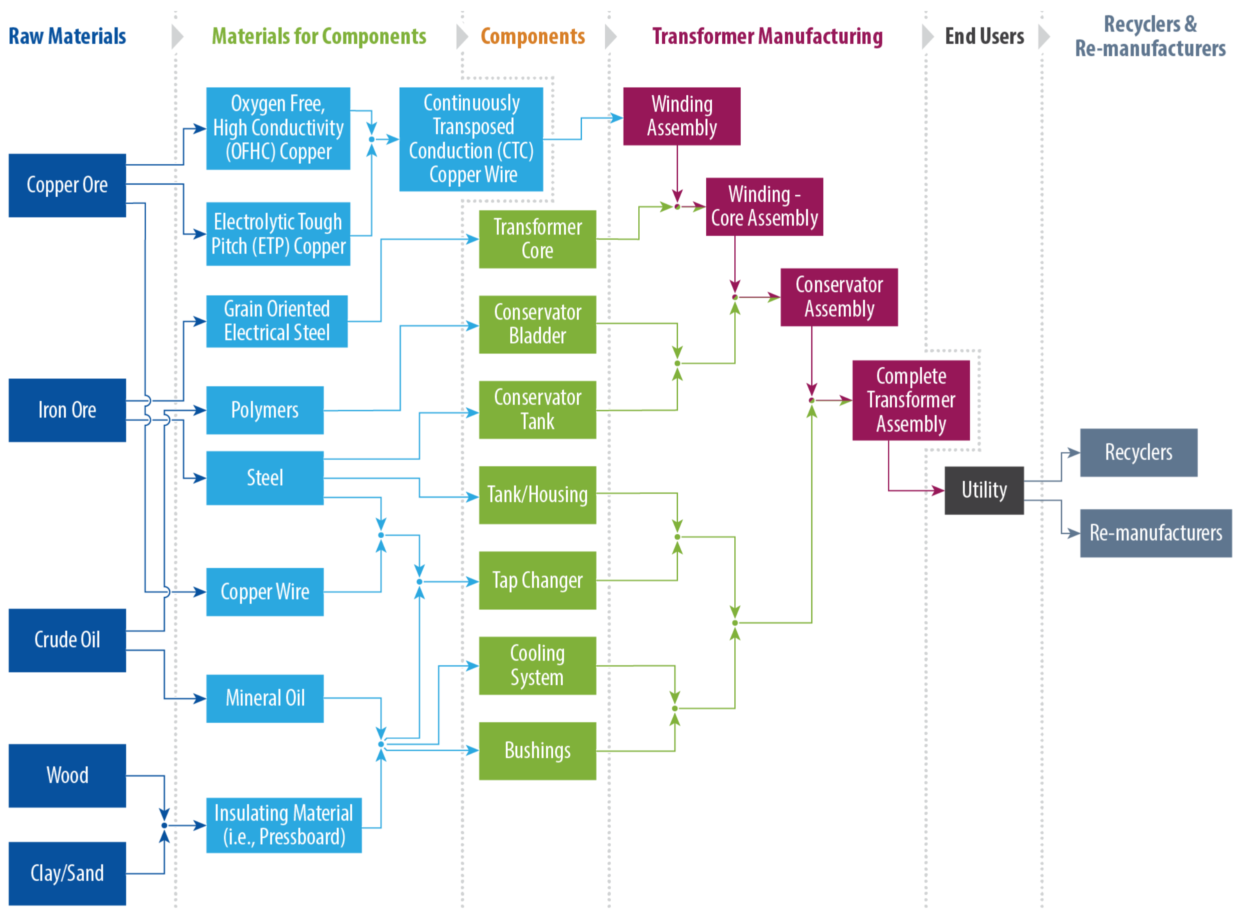

Figure 4. Industry structure of the critical segments and sub-segments for large power transformers.

Leading manufacturers such as Hitachi Energy, Siemens Energy and GE have integrated component supply into their network to maintain consistent lead time and quality (Global Market Insights, 2021). In some cases, the cores, windings, conservators, and housing are manufactured at the LPT facility (U.S. Department of Commerce, 2020). Leading companies also have forward integration to distribute, install, and provide after-sales service, maintenance, and system replacement. When LPTs reach their EOL, some parts and components can be recycled or remanufactured into new transformers with lower power or voltage ratings, depending on the condition of the LPT.

2.1.2 Manufacturing Process

2.1.2.1 Large Power Transformers

There are four main steps in manufacturing LPTs: (1) coil winding, (2) core assembly, (3) core-coil assembly, and (4) final assembly and testing, as shown in Figure 5.

The CTC is a specialized copper wire used for transformer coil winding to minimize losses and hot-spot temperatures. CTC enables compact winding with improved short-circuit performance (Waukesha Transformers, 2022). Cylindrical winds, using a continuous-disc or helical winding design, are made manually in a temperature controlled and clean room environment. Radial spacers made of high-density pressboard are placed between the windings to provide cooling. After winding, the coils are pressed, clamped, and dried in an oven to increase short-circuit withstand ability.

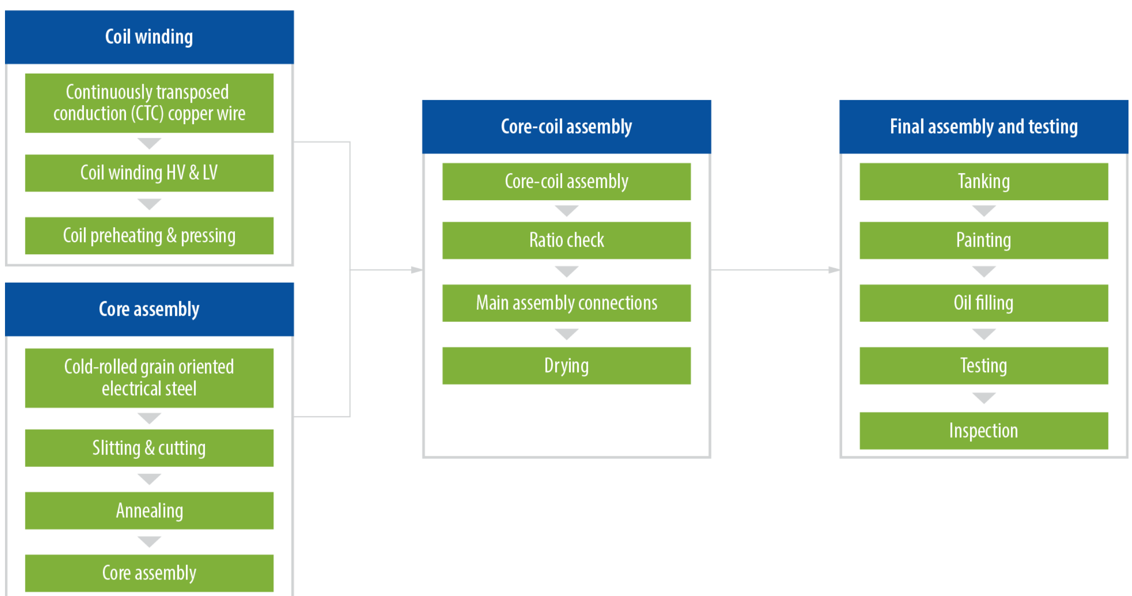

Figure 5. LPT manufacturing process, adapted from (Waukesha Transformers, 2022) and (Kumar, 2016).

Cores, also known as laminations, are made from high-permeability and domain-refined GOES (Waukesha Transformers, 2022). GOES is cut to a geometrical shape using computer-controlled equipment to ensure optimum flow of magnetic flux and minimum air gap between the joint of two consecutive sheets. The cut GOES is then annealed to ensure optimal loss performance. Multiple sheets are stacked to meet the design requirements. These are known as stacked cores which are different from wound cores commonly found in smaller power transformer units. Insulating paper is inserted between some laminations to reduce eddy currents and minimize magnetic short-circuit. Then the core is grounded to prevent static charge accumulation. After stacking, epoxy is applied to bind the core legs. Steel end frames are used to provide mechanical strength for the core during transportation and short-circuit conditions (Waukesha Transformers, 2022).

The core is stood upright to be assembled with the coil. Each core leg will have two to five windings on it (Waukesha Transformers, 2022). The core-coil assembly goes through a thorough cleaning process before pressing. It is then put under pressure to be cleaned and inspected. Top yoke steel is assembled to the legs to ensure no core loss on the test floor. Pre-compressed pressboard and kraft paper are used for insulating and compressed wood is used to improve mechanical strength. A de-energized tap changer is assembled to the wood frames. The ends and tapping leads of windings are connected using extra flexible insulated copper cables. A ratio check is done to ensure ratio accuracy of a transformer of both primary and secondary turns as well as proper functioning of tap changers (E2B Calibration, 2018). Then, the whole assembly is dried in an oven and a Megger test is conducted to verify insulation before the transformer is tanked up (Kumar, 2016).

Tanks are made from low carbon mild steel sheets (0.05-0.25% C) (Steel Warehouse, 2021). The tanks are painted and fitted with drain valves, bushings, conservators, oil indicators, and explosion vents. The core-coil assembly is placed in the tank with proper locking. Oil is added to the tank and terminal connections to the bushings are made. Tanks are tested for leakage under pressure for several hours.

2.1.2.2 Grain-Oriented Electrical Steel

The production process for GOES in Figure 6 is similar to that of carbon steel but requires a higher level of process control at each stage. GOES is also called lamination in some cases. First, steel scrap and pure alloys of silicon (Si) and other metals are melted to make cast slabs. Next, the slabs are reheated to finely dissolve inhibitor materials within the alloy (You & Park, 2018). This step is skipped if thin strip casting technology is used because the thin steel strip of 2-3 mm can precipitate inhibitors by rapid cooling. Then, the slabs are rolled at high temperatures into heavy gauge coils using a hot strip mill. This step helps precipitate inhibitor materials finely in the GOES structure, which is crucial for secondary recrystallization step (You & Park, 2018). Yield loss of this step is 3.5 wt% (Lewis, 2012). Because GOES contains a high Si content of more than 3% to improve core loss in LPTs, it is prone to cracking and oxidization. After the hot rolling step, the coil will be edge-trimmed to remove cracked sides and ends. This step causes a yield loss of 0.5-2 wt%, with an average at 1.5 wt%. At the next annealing and pickling step, a yield loss of 0.5 wt% is incurred due to scale removal. At the cold-rolling step, yield loss is minimal at less than 0.025% (Labiapari, de Alcântara, Costa, & De Mello, 2015). This step forms primary recrystallization and produces thinner GOES (You & Park, 2018). Then the coil is trimmed again, annealed, and laser oriented to develop the desired grain orientation before being covered in a layer of coating. The total yield loss of the entire process is approximately 7.3%, with the highest loss at the hot rolling step.

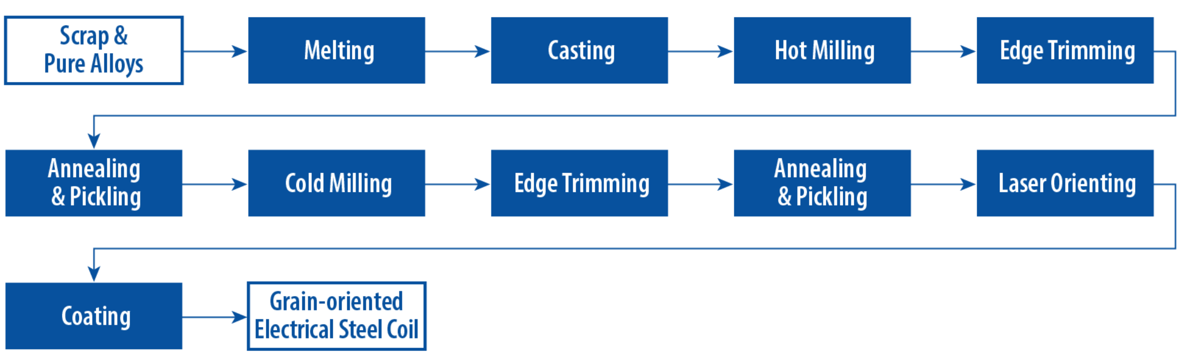

Figure 6. GOES manufacturing process (World of Steel, n.d.).

There are two grades of GOES: conventional oriented grade (CGO) and high-permeability grade (HI-B). Two major differences in the manufacturing processes of these two grades are in the inhibitor and primary recrystallization (Xia, Kang, & Wang, 2008). To produce HI-B grade, several inhibitor mixes can be used. Aluminum nitride is used as the main inhibitor on top of manganese sulfide. Antimony can also be coupled with manganese sulfide or nitride boron as inhibitors (You & Park, 2018). For CGO, only manganese sulfide is used. In addition, two-stage cold-rolling is used in CGO production whereas mostly one-stage cold-rolling is used in HI-B process. HI-B has a smaller total core loss (including hysteresis loss and eddy-current loss) thanks to lower hysteresis loss, but larger grain size leading to larger eddy-current loss compared to CGO (Xia et al., 2008). HI-B grade with domain-refined grade is highly demanded by LPT manufacturers because of its low core loss to reduce LPT weight.

2.1.2.3 Continuously Transposed Conductor

The manufacturing of CTC begins with typically an 8 mm rod in coil form (Dubey, 2017). Variations exist for the diameter of the rod depending on the application and manufacturing capabilities of the CTC producer. Next, the wire rod is drawn into smaller diameter wires depending on the CTC finished product requirements (Dubey, 2017). Then, the drawn wires are cold rolled to the correct size for the flat rolling step (Dubey, 2017). Following, these geometrical changes in shape of the wire, the flat, bare wire is annealed to become soft (Dubey, 2017). An enamel coating is then applied to wire in multiple, incremental steps and an optional epoxy coating is applied if specified by the product requirements (Dubey, 2017). Finally, the coated strips are transposed and covered by insulating paper and/or netting tape to create a ‘bundled’ set of transposed, flat copper wires (Dubey, 2017). This is the final product and is referred to as CTC at this point which is used to create the winding of an LPT.

2.1.2.4 Conservator System

The conservator system consists of several main components that facilitate the cooling of the transformer system. First, a steel tank is designed which houses excess oil in case of pressure change within the transformer which allows the oil inside the transformer to be maintained at a consistent level (U.S. Department of the Interior Bureau of Reclamation, 2005). Next, a polymer bladder system is designed and inserted within the conservator tank. The bladder is the connection to the outside environment and can adjust its volume based on atmospheric and transformer oil pressure (U.S. Department of the Interior Bureau of Reclamation, 2005). This prevents air contact with the transformer oil which can degrade the oil and insulation within the transformer. Finally, the third component is the oil (mineral oil, synthetic oil, etc.) which comprises of the remaining space within the conservator tank (U.S. Department of the Interior Bureau of Reclamation, 2005).

2.1.2.5 Tap Changers

A transformer tap changer is a component designed to change the output voltage of a transformer by changing the turns ratio between the primary and secondary winding. Two types of tap changers are commonly utilized in transformers today, on-load tap changers (LTC) and de-energized tap changers (DETC) (Waukesha, 2021). LTCs are designed to operate when the transformer is still under electrical load, while DETCs are designed for operation when the transformer does not have an electrical load. Generally, LTCs are preferred by industry due to continuous loading requirements of the transformers (Pitt, 2018). Industry engagement indicated that the main materials required for tap changer manufacturing are copper, insulating materials, mineral oil, and springs. Typical manufacturing sees the tap changer separated from the main assembly (core, windings, and tank) as to keep the mineral oil of the tap changer assembly separate from the main tank assembly. This is to prevent the degradation of the oil in the main tank assembly from the electrical arcing that occurs in the tap changer during voltage output changes.

2.1.2.6 Bushings

Bushings provide the electrical connection between a transformer and the electrical transmission network. Several different forms of bushings exist for a variety of transformer sizes and applications, but industry engagement has indicated that the most common type of bushing for LPTs is the oil-impregnated paper (OIP) bushings. OIP bushings are typically comprised of several main components, an air side insulator made from porcelain that protects the internals, a conductor typically made from copper or aluminum, insulating kraft paper, and an interior insulator comprised of mineral oil. The manufacturing process starts with the production of the condenser core. This component requires kraft paper to be wound around the central conductor (saVRee, 2021). During this process, additional layers of conductor are inserted into the kraft paper insulation at varying radii to help control the electric field passing through the conductor (saVRee, 2021). Next, the core is treated to remove moisture and gas levels using an autoclave or by putting the core under vacuum (saVRee, 2021). Then the core is inserted into a hollow, porcelain insulator with an expansion chamber at the top of the bushing to allow for oil pressure fluctuations (saVRee, 2021). Lastly, the bushing is impregnated with mineral oil and sealed with rubber gaskets (saVRee, 2021).

2.1.2.7 Insulating Material

Insulating material typically refers to cellulose derived materials used as solid insulation in the internals of the transformer. Outside of cellulose insulating materials, aramid materials (produced by DuPont under the trade name Nomex) (DuPont, 2021) have been reported to be used in LPTs. Common cellulose insulating material types include paper, crepe paper, and pressboard (transformer board) (Hitachi, 2021; Saha & Purkait, 2017). Cellulose possesses excellent electrical properties such as high dielectric strength and low dielectric loss which is essential for efficient transformer operation (Saha & Purkait, 2017). The most common insulating material in LPTs is pressboard. This material is manufactured by taking electrical grade unbleached kraft pulp and winding the wet sheets on a making roll. Once the specified thickness is achieved, the wet sheets are placed into a buffer storage before being dried and pressed in a “hot-press” machine (Krause, 2012).

2.1.3 End-of-Life Management of Large Power Transformers

Transformer life is primarily dependent upon the thermal degradation of the insulation system. Factors which affect transformer life are loading conditions, ambient temperature, and other environmental conditions such as moisture, corrosive atmosphere, and vibration (Jefferson Electric, 2010). When a transformer is operated under ANSI/IEEE ideal loading conditions specified by IEEE C57.96 (IEEE Standards Association, 2014a), its normal life expectancy is about 20 years or 180,000 hours. The IEEE C57.96 ideal loading conditions for transformer are:

- The transformer is continuously loaded at rated kVA (kilo Volt Ampere) and rated voltages.
- The average temperature of the ambient air is 86°F (30°C) and the maximum temperature does not exceed 104°F (40°C).
- The transformer can operate at rated kVA at altitudes greater than 1,000 meters (m) without exceeding temperature limits. For every 100 m above 1,000 m, winding temperature rises by 0.5% for natural cooling and 1% for forced-air cooling.

The exact number of in-use U.S. LPTs is not readily available. In order to estimate this number, data from Energy Visuals (Energy Visuals, 2014) were used with different filters. This dataset includes two interconnects: Eastern & Western. When capacity rating of 100 MVA and above was selected as the filter criterion, 5,075 LPTs and 1,724 LPTs were counted for the Eastern interconnect and Western Interconnect, respectively. When a voltage rating of 230 kV and higher was selected as the filter criterion, 3,530 and 1,370

LPTs were counted for the Eastern interconnect and Western Interconnect, respectively. These two counts give a range of 4,900 to 6,799 LPTs currently in-use in the United States.

The average age of installed LPTs in the United States is approximately 38 to 40 years. More than 70% of U.S. LPTs are aged more than 25 years (U.S. Department of Energy, 2014). Some units in the grid are more than 70 years old and still operating (U.S. Department of Energy, 2014). Using in-use LPTs of 6,799 units and an average lifetime of 40 years, there are at least ~170 EOL LPTs every year in the United States that require proper EOL management. Three potential EOL scenarios are possible for an LPT: recycling, disposal, and incineration (Hegedic, Tihomir, Dukic, & Draakovj, 2016). Approximately 73% of the weight of an LPT can be recycled and the remaining materials are disposed of or incinerated (Martin & Devaux, 2008). Generally, the disassembly of a transformer would follow the reverse path of its construction and assembly. As a first step, the dielectric liquid oil and polychlorinated biphenyl (PCB) contained in the transformer tank for cooling and insulation are drained out. Next, the dismantling and sorting of different materials are done. The main transformer materials are steel, oil, copper, pressboard, paper, wood, aluminum, plastics, and silica gel. Recyclability or disposal process of different transformer materials are summarized below:

- The core steel made of GOES accounts for 40% (Hegedic et al., 2016) of the transformer weight and can either be sent for reprocessing to be used in the production of smaller transformers or sent to a metal recycling company. According to stakeholders, core weight could range from 55,000 to 70,000 lbs.
- The winding copper, copper tubing, stranded copper cable weigh 16% (Hegedic et al., 2016) of a transformer and are sent to metal recycling companies for processing.
- The steel pipework and steel fabrications are 21% (Hegedic et al., 2016) of a transformer's total weight and are sent to metal recycling companies for processing.
- The weight of transformer oil is around 19% (Hegedic et al., 2016) and can be tested and reused in another transformer or sent for recycling in accordance with state laws and regulations.
- The amount of plastic (thermoplastic) is around 1% (Martin & Devaux, 2008) and can be recycled.
- PCB is toxic and requires incineration in specialized plants.
- The cooling ducts, kraft papers, pressboards, and gaskets are considered oil-contaminated wastes and should be disposed of in accordance with state laws.
- Silica gel can be disposed of at an approved landfill site.

2.1.4 U.S. capabilities and competitiveness

2.1.4.1 Production Capabilities

LPTs: The major transformer manufacturers with production capabilities in the United States by alphabetical order include Delta Star, Hitachi Energy, HICO, Hyundai Power Transformers USA, Niagara Power Transformer, Pennsylvania Transformer Technology, SPX Transformers (acquired by GE), and Virginia Transformers (formerly EFACEC) (U.S. Department of Commerce, 2020; U.S. Department of Energy, 2014). A map of these company's locations is shown in Figure 7.

- Delta Star has three transformer manufacturing locations including San Carlos, California, Lynchburg, Virginia and Saint-Jean-sur-Richelieu near Montreal, Quebec (Delta Star, 2021). This company can manufacture power transformers up to 200 MVA and 345 kV.
- Hitachi Energy, formerly known as Hitachi ABB, has one LPT facility in the United States in South Boston, Virginia with a maximum range of 230 kV and 150 MVA as indicated through stakeholder engagement. In addition, this company has a facility in Varennes, Quebec which can supply transformers for traditional and specialty applications (including HVDC) up to 765 kV and 1400 MVA. They also

operate a facility in Alamo, Tennessee that supplies transformer components such as bushings, LTCs, etc.

- Hyosung Heavy Industries (HICO) acquired Mitsubishi facility in Memphis, Tennessee in 2019 (Walton, 2019). They have capability up to 1000 MVA and 765 kV (Hyosung HICO, 2021).
- Hyundai Power Transformer has a manufacturing plant in Montgomery, Alabama with capacity up to 750 MVA and 500 kV (Hyundai Power Transformers USA, 2012).
- Niagara Power Transformer is in Buffalo, New York. Its base rating is 50 to 60 MVA with the top rating of 100 MVA and 138 kV (Niagara Power Transformer, 2021).
- Pennsylvania Transformer Technology can produce up to 600 MVA and 345 kV at its Canonsburg facility in Pennsylvania (Pennsylvania Transformer Technology, 2020).
- SPX Transformer Solutions plant is based in Waukesha, Wisconsin with capabilities up to 1200 MVA for autotransformers and 345 kV (SPX Transformer Solutions, 2021). In late 2021, SPX was acquired by GE Prolec, a subsidiary of a 50/50 joint venture between GE and a Mexico-based private company named Xignux (General Electric, 2021).
- Virginia Transformer Technology has two LPT facilities including Roanoke, Virginia and Rincon, Georgia which can manufacture liquid-type transformers up to 1400 MVA and 500 kV class (Virginia Transformer, 2017).

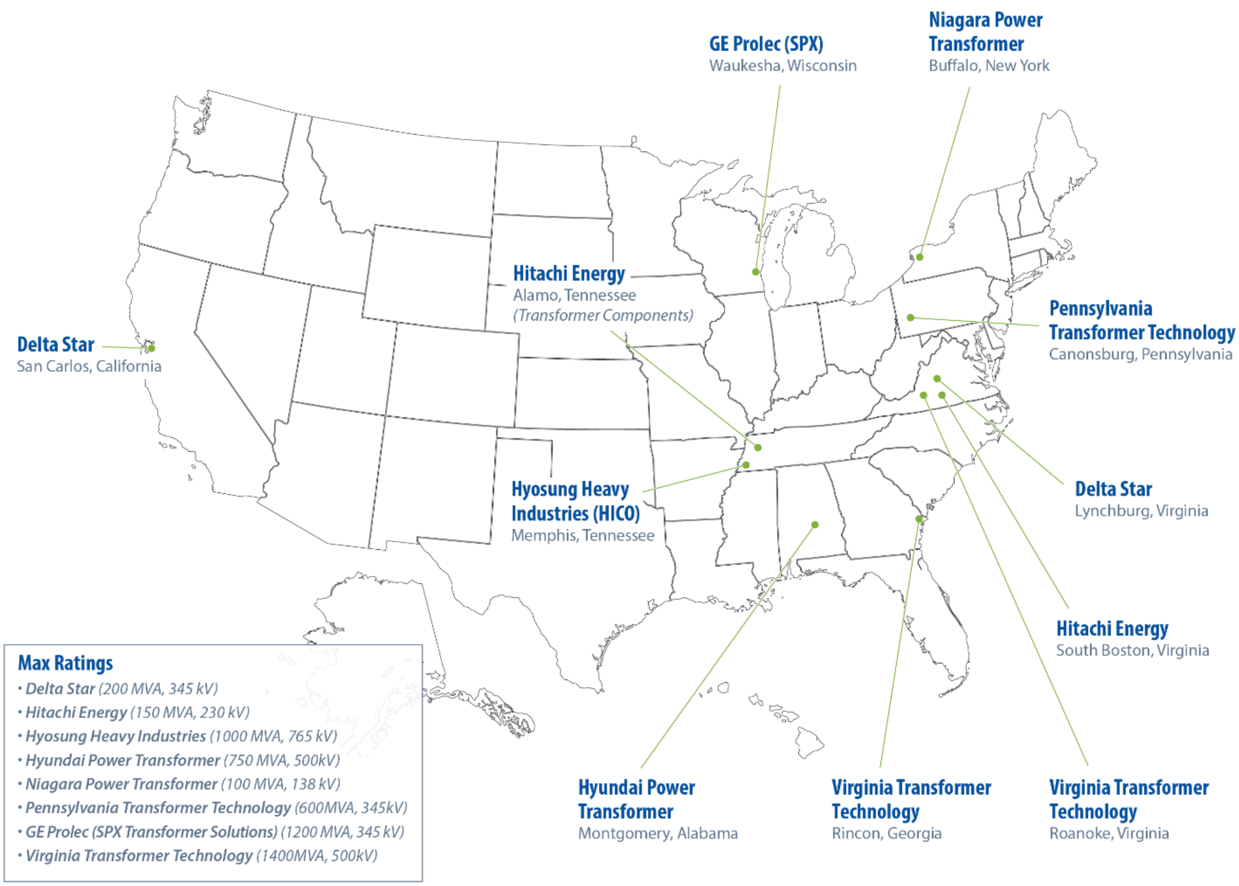

Figure 7. Map of U.S. large power transformer manufacturing facility.

The total production capacity of all U.S. LPT companies is not straightforward to estimate because each facility manufactures multiple products at the same time. In 2019, 137 LPTs were produced domestically while

617 units were imported and four units were exported (U.S. Department of Commerce, 2020). Based on the LPT capacity utilization of ~ 40% (U.S. Department of Commerce, 2020), a total capacity of ~343 LPTs/year was derived for domestic capacity. In 2020, out of $3 billion spent on "Power/distribution/specialty Transformers" imported into the United States with the North American Industry Classification System (NAICS) code 335311, 45% of these transformers came from Mexico, 15% from Canada, 7% from China, 5% from South Korea, 4% from Germany, and 3% from the Netherlands (USA Trade Online, 2021). Except for China, the remaining countries are friendly suppliers to the United States, which does not pose a supply chain risk. However, due to long LPT lead time, overseas shipping bears some risks due to potential disruptions as witnessed during the COVID-19 pandemic.

GOES: Both Allegheny Technologies Incorporated (ATI) and Cleveland-Cliffs (previously known as AK Steel) have the production capability. However, ATI shut down its GOES operation in 2016, leaving Cleveland-Cliffs with manufacturing facilities in Zanesville, Ohio and Butler, Pennsylvania as the sole GOES producer in the United States (U.S. Department of Commerce, 2020). The U.S. expenses for imports of commodities registered under "Flat-rolled Grain-oriented Silicon Electrical Steel", designated under Harmonized System (HS) code 722511, correspondingly saw a 155% increase from 2015 to 2018 (USA Trade Online, 2021). During 2019 – 2020, import of laminations accounted for approximately 88% of total consumption (U.S. Department of Commerce, 2020). In 2020, out of $29 million spent on GOES imports into the United States under the aforementioned HS code, 85% of imports came from South Korea, 6% came from Brazil, and 4% came from Russia (USA Trade Online, 2021). Two main complaints with domestic GOES are: (1) insufficient quantity and (2) insufficient quality including narrow width and heavy thickness. Both aspects point to the fact that Cleveland-Cliffs technology is outdated and unable to keep up with more stringent requirement from updated standards (U.S. Department of Commerce, 2020). Another factor that impacts their operation is competing with lower cost imported GOES. Recently, Big River Steel (BRS), a subsidiary of U.S. Steel based in Arkansas, entered the electrical steel sector targeting EVs with a nameplate capacity of 200,000 short tons/year of non-oriented electrical steel (NOES) (ArgusMedia, 2021). The BRS website indicates that their Flex Mill® has the infrastructure for additional equipment to produce GOES, including high-permeability grade or HI-B (Big River Steel, 2021).

CTC copper: According to stakeholder outreach there are three total manufacturers producing CTC in North America, but only two companies in the United States producing CTC copper wire. However, through literature review, instead of two, three potential U.S. companies were identified: (1) Sam Dong, (2) Essex Furukawa, and (3) REA. Sam Dong manufactures CTC at its Rogersville, Tennessee facility (Sam Dong, 2012). Essex Furukawa has multiple wire manufacturing facilities in the United States including Fort Wayne and Franklin in Indiana, and Franklin in Tennessee (Essex Furukawa, 2021), but it remains unclear if CTC can be produced at any of the domestic facilities. Lastly, REA has four domestic manufacturing facilities including Fort Wayne and Lafayette in Indiana, Guilford in Connecticut, and Ashland in Virginia (REA, 2021). Literature has shown that the Fort Wayne, Indiana location possesses the capability to produce CTC copper wire (Gorman, 2008). There has been an increase in imports of commodities registered under "Insulated Winding Wire Of Copper" category of HS code 854411 to the United States over the last 10 years; import expenses totaled ~$70 million in 2010 and ~$108 million in 2020, for a 55% increase (USA Trade Online, 2021). In 2020, out of $108 million spent on insulated copper winding wire imports into the United States under the aforementioned HS code, 38% came from Germany, 13% from Mexico, and 11% each from China and Vietnam (USA Trade Online, 2021). CTC supply was identified as a key concern of LPT manufacturers during industry engagement.

Cores: There has been a decline in the amount of domestic manufacturing of laminations and cores (in-house transformer companies and independent producers) in the past few years (U.S. Department of Commerce, 2020). The United States has become highly dependent on Canada and Mexico for core manufacturing. The imports of GOES laminations are approximately 88% with 95% of the imports coming from Canada and Mexico for both wound cores and stacked cores (U.S. Department of Commerce, 2020). The number of imports to the United States registered under "Stacked Cores for Incorporation into Transformer Parts" category of HS code 8504909638 increased from 50,267 units in 2016 to 842,929 units in 2021 through October – a nearly 1600% increase (USA Trade Online, 2021). In 2020, out of $12 million spent on stacked core imports into the United States under the aforementioned HS code, 47% came from Canada, 41% from Mexico, and 7% from Bulgaria (USA Trade Online, 2021). Stakeholder outreach has indicated that about half of the power transformer manufacturers cut the core laminations themselves, and all of them stack cores in-house. This indicates that all domestic LPT manufacturers mentioned in the previous section have some form of core production capability.

Conservator System: Industry engagement has indicated that conservator tanks are generally manufactured in-house by the LPT manufacturer. However, the geometry of the tank plays an important role in production. For example, round tanks for conservators are typically purchased by LPT manufacturers whereas other shaped tanks are made in-house. Literature review showed that there were no conservator bladder manufacturers in the United States, however, it remains unclear as to what capacity LPT manufacturers possess to produce their own bladders systems.

Tap Changers: Industry engagement and literature review has indicated that there are only a few domestic suppliers for tap changers in the United States:

- Hitachi Energy manufactures tap changers in its Alamo, Tennessee facility (ABB, 2017).
- Quality Switch, Inc. manufactures tap changers in Newton Falls, Ohio (Quality Switch Inc, 2022).
- SPX Transformer Solutions manufactures tap changers in Waukesha, Wisconsin (SPX Transformer Solutions, 2021).

Bushings: Industry engagement and literature review has indicated that there are only a few domestic suppliers for bushings in the United States:

- Hitachi Energy manufactures bushings in its Alamo, Tennessee facility (ABB, 2017).
- PCORE Electric manufactures bushings in its LeRoy, New York facility (Hubbell Power Systems, 2022).
- Fostoria bushings and Insulators Corporation manufactures bushings in its Fostoria, Ohio facility (Fostoria Bushings Insulators Corp, 2022).

Insulating Material: Industry engagement indicated that insulating material was a potential supply concern due to a lack of domestic manufacturing. Additional industry stakeholders and literature review showed that there are only a few domestic suppliers for insulating material for LPTs in the United States:

- Weidmann manufactures part of its product line at its Urbana, Ohio facility (Weidmann, 2022).
- Cindus Corporation manufactures insulating material in its Cincinnati, Ohio facility (Cindus Corporation, 2022).
- DuPont was reported by a stakeholder to manufacture its Nomex insulating material in the United States.

The lack of domestic manufacturing is further reflected by an observed increase in U.S. import expenses for transformer insulating oils. The total value of "Insulating or Transformer Oils, not elsewhere specified" category under HS code 2710194545 imports to the United States increased from $323,535 in 2017 to ~$8 million in 2020, for a nearly 2400% increase (USA Trade Online, 2021). In 2020, out of $8 million spent on insulating or transformer oil imports into the United States under the aforementioned HS code, 92% came from Belgium, 6% from Canada, and 2% from Germany (USA Trade Online, 2021).

2.1.4.2 Workforce

A limitation associated with LPT production is the workforce. A major contributing factor is skill mismatch, meaning that worker's skill sets do not align with the needs of the industry. A 2020 U.S. Department of Commerce survey of 87 domestic LPT component manufacturers found that companies have difficulties hiring employees with necessary skill sets and qualifications for transformer manufacturing such as welding, coil winding, and transformer testing (U.S. Department of Commerce, 2020). They also claimed that few post-secondary institutions offer specializations in manufacturing engineering, power engineering, and electrical design engineering (U.S. Department of Commerce, 2020), perhaps due to a larger focus on other high demand areas, such as computer science and electronics. In addition, interviewed stakeholders indicated that they have not offered internships or cooperative education programs to raise awareness of the need for workers in the LPT manufacturing industry.

A lack of interest in transformer manufacturing and attaining the skills and specializations required to work in this industry appears to be exacerbating the skills mismatch issue further. In the same survey mentioned above, companies stated that they have difficulties attracting workers to the industry, such as young workers who are turned away by the remote locations of factories (U.S. Department of Commerce, 2020). This seems to be a prevalent problem in all parts of the LPT supply chain. As of present, companies (including but not limited to LPT manufacturers) are having problems attracting and retaining workers due to the COVID-19 pandemic. The U.S. Bureau of Labor Statistics reported that employment in all manufacturing sectors in the United States is down by 219,000 since February 2020 (U.S. Bureau of Labor Statistics, 2022).

Our own stakeholder engagement efforts provided two specific case studies that allow for a better understanding of issues faced by LPT manufacturers both large and small:

<u>Manufacturer 1</u> states that there are labor constraints associated with electrical and civil contractor availability as projects in both grid and electrical infrastructure increase. In addition, they cite a shortage of power engineering professionals.

<u>Manufacturer 2</u> has issues staffing its only large power transformer manufacturing plant, which makes order fulfillment challenging. This company has hiring difficulties caused by the low availability of skilled domestic engineers, the aging workforce, and the lack of early-career workers because universities are not offering appropriate education for transformer manufacturing. This producer also has difficulties recruiting employees who can comply with its strict drug testing policies designed to ensure that employees are fit for duty. They often end up sourcing their engineers from Canada, Mexico, and China for these reasons.

2.1.4.3 Manufacturing Costs

Detailed costs of LPTs are not available and vary by manufacturer depending on their cost structure. Below is some general information regarding LPT costs:

- Transformers are associated with a high initial cost due to strict production standards. The electrical components used in transformers are expensive for the manufacturer. Quality checks and automated manufacturing also make up a significant part of the expenses. High expenses lead to high product prices for customers (Global Market Insights, 2021).

- According to a 2020 U.S. Department of Commerce survey of 87 domestic manufacturers of LPT components, GOES accounts for about 25 percent of the total manufacturing costs for transformers, while labor accounts for 36 percent of costs on average (U.S. Department of Commerce, 2020). Since the U.S. labor rate is much higher compared to other countries, this factor puts the United States at a disadvantage.
- It is difficult to compare the price difference between domestic and imported LPTs. Stakeholder engagement suggested that for most utilities, the lifecycle cost is much more important than the upfront cost. They are willing to pay 15% more if the efficiency can increase by 0.5%. The price difference between LPTs manufactured in the United States vs. Mexico, Canada and Europe could be about 10%. LPT manufactured in the Asia-Pacific region could be 25% or more cheaper than domestic LPTs. Beyond the LPT prices, there are other factors that can contribute to the final purchasing cost including tariffs, exchange rates and transportation costs.

2.1.4.4 Market Competitiveness

Global Market: The largest global companies manufacturing LPTs include Hitachi Energy headquartered in Zürich, Switzerland; GE headquartered in Boston, United States; Siemens Energy AG headquartered in Munich, Germany; and Mitsubishi Electric headquartered in Tokyo, Japan (Global Market Insights, 2021).

The overall large power transformer market share in terms of revenue by global region in 2020 was as follows: Asia-Pacific (39%), Europe (24%), Middle East/Africa (17%), North America (15%), and Latin America (4.0%) (Global Market Insights, 2021).

U.S. Market: The U.S. market favors small power over large power transformer production domestically. In 2020, U.S. revenue for transformers with ratings less than or equal to 10 MVA was $4 billion. By comparison, revenues for transformers with ratings 61- 600 MVA and greater than 600 MVA were $772.5 and $571.0 million, respectively (Global Market Insights, 2021). Smaller transformers are more likely to be manufactured close to the end-user, which is why smaller distribution transformer manufacturers are more prevalent in the United States compared to LPT manufacturers (United States Domestic Transformer Manufacturers Coalition, 2021).

Foreign imports of power transformers to the United States with ratings greater than 10 MVA exceeded $1.1 billion in the most recent United States International Trade Commission report, with transformers over 60 MVA (medium to large power transformers) costing $832 million alone (United States Domestic Transformer Manufacturers Coalition, 2021). It is noted that these values can be considered as cost. Revenues from selling these imported transformers combined with domestic LPT revenues will make up the domestic market size of ~$2.6 billion.

2.1.5 Patent and Technology Landscape

318 published patent applications related to LPT were identified and analyzed for this report (PatSnap, 2021). The analyzed patent applications include applications with an application date after January 1, 2001 and publication date before December 1, 2021 which also contained the keyword “transformer” in the title or abstract and "large power transformer" or "large-scale power transformer" anywhere in the application but did not include “elimination of large power transformers” in the text.

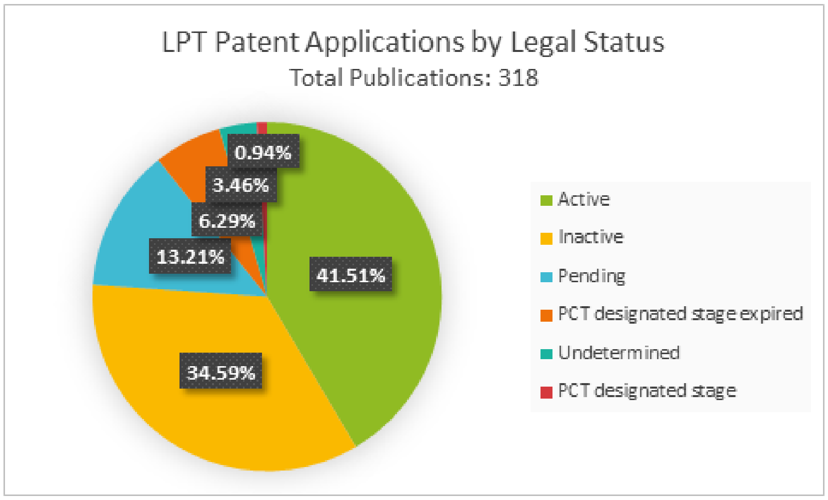

Figure 8. LPT patent application by legal status.

Figure 8 identifies the simple legal status for the analyzed applications. While ~42% of patents are active, 13% are pending, and ~35% are inactive. Active patent applications have been granted and were still within the patent term when these data were collected. Inactive applications have either expired or been abandoned, withdrawn, rejected, or invalidated. In this report, pending applications are those which have published and are currently under examination. Patent Cooperation Treaty (PCT) applications establish a priority date for patent protection and allow applicants additional time to select countries to pursue patent protection. The applications with the status of PCT designated stage are within the deadline for selecting countries to pursue patent protection. The applications with the status of PCT designated stage expired are past the deadline for selecting countries to pursue patent protection and have either entered the national phase procedures with each individual patent office or has not entered the national phase in any country. Undetermined applications do not have a confirmed legal status.

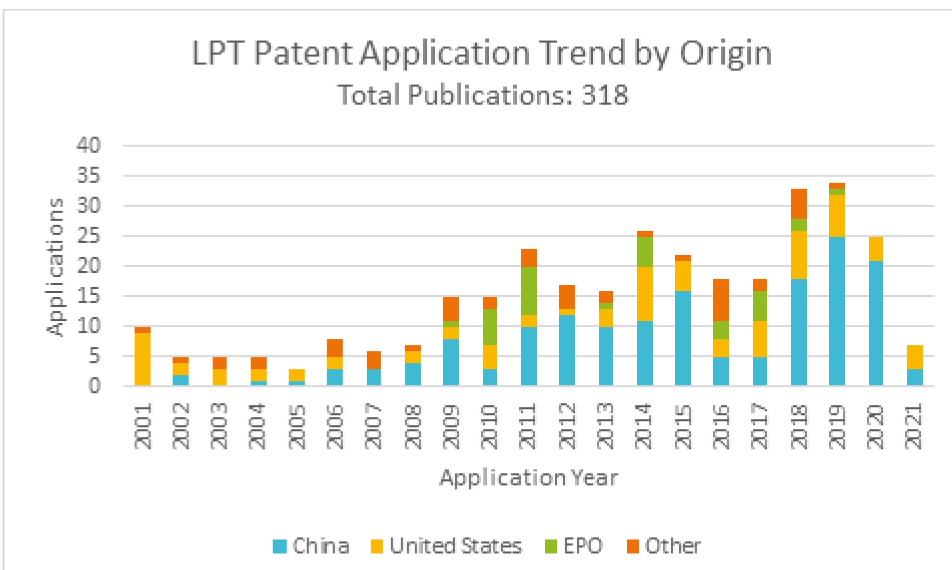

Figure 9. LPT patent application trend by origin.

Figure 9 shows the patent filing trend for each technology by the earliest patent application by filing location. The country which receives the first patent application could indicate that companies in that country either are innovating in certain technology area or wanting to capitalize the license first. 51% of the 318 original filings were in China, 25% of original filings were in the United States, and 10% of original filings were with the European Patent Office (EPO). This figure shows that most patents filed in the early 2000s were in the United States. However, after 2005 there is a strong growth in original filings in China. Historically, the Asia-Pacific region has had a larger LPT market than North America (Global Market Insights, 2021). The larger market size may be one reason companies are filing their first patent application in China. China is also home to companies who specialize in manufacturing LPTs including Baoding Tianwei Baobian Electric Company, commonly known as BTW. According to the analyzed data, BTW appears to have more patent applications related to LPTs than any other company.

The leading assignees for transformer patent applications are shown in Figure 10. BTW has the most patent applications in this area according to the analyzed data. Figure 10 shows BTW appears to use several different assignee names which make the list of the top ten assignees for LPT patents including Baoding Tianwei Baobian Electrical, Tianwei Baobian Qinhuangdao Transformer, Baoding Tianwei Group Co, and Baoding Baoling Transformer. Hitachi Energy appears to be the second leading company in patent applications for LPT, where Hitachi Energy uses assignee names ABB Schweiz AG and ABB Power Grids Switzerland AG (PatSnap, 2021).

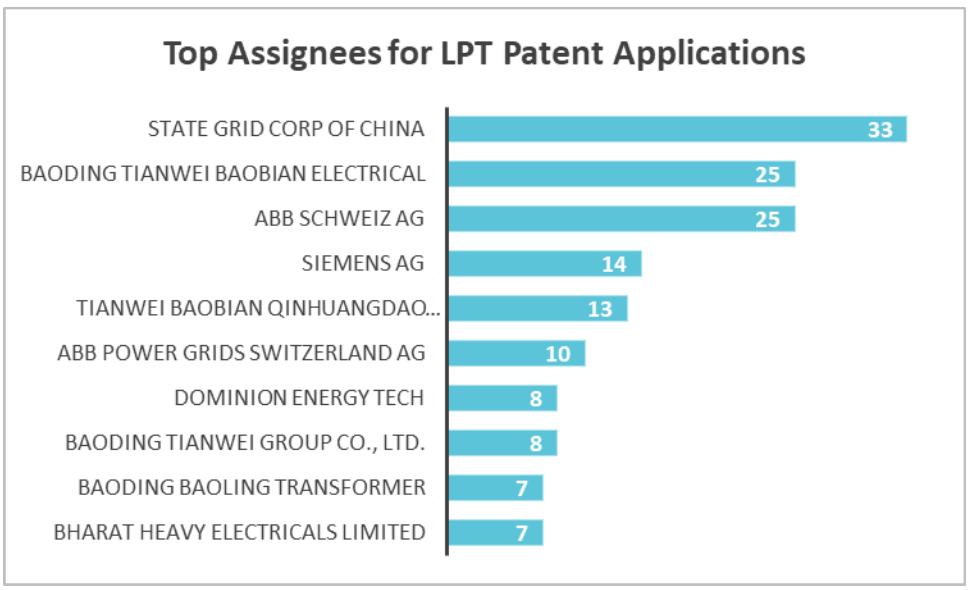

Figure 10. Top assignees for large power transformer patent applications.

2.1.6 Transformer Supply Chain Bottlenecks in the United States

Currently, there are two major bottlenecks in the LPT supply chain. The first one is in the U.S. GOES production capacity. The second one is in the testing capacity of LPT manufacturers.

As mentioned earlier, because the United States only has one GOES supplier, this company cannot meet all the demand of LPT manufacturers. From our conversation with stakeholders, all of them diversify their supply by sourcing both domestically and internationally. Some interviewees estimated that domestic supply meets about 20% of domestic demand, which agrees with a recent report (U.S. Department of Commerce, 2020). It is noted that this GOES supply could be used for producing all transformer types and not exclusive for LPTs. The same report indicated that all of the GOES used for LPT manufacturing is imported (U.S. Department of Commerce, 2020). In addition to limited production capacity, the domestic GOES producer also has challenges in attracting workers. This company offers a minimum wage of $13/hour and has reported that its GOES operations are not profitable due to more cost-competitive imports (U.S. Department of Commerce, 2020). Outside of the United States, there are 13 manufacturers of GOES in various countries, including China, Japan, France, Germany, India, Poland, Czech Republic, Russia, Brazil, and South Korea (U.S. Department of Commerce, 2020). Of those, only Japan, South Korea, and Germany can produce the GOES at the specifications outlined by current Department of Energy (DOE) standards (U.S. Department of Commerce, 2020).

Imports account for 82% of the consumption of LPTs in 2019. In 2020, there were six companies in the United States that produced LPTs with a capacity utilization of approximately 40% (U.S. Department of Commerce, 2020). These companies have consistently produced between 122 and 153 LPT units annually between 2015 and 2019 (U.S. Department of Commerce, 2020). U.S. companies typically face limitations with testing during LPT manufacturing due to a lack of test beds. Industry engagement has indicated that testing can take a week for LPTs and 24 hours for other transformer types. Test space can be a key limiting factor in LPT production capability when each facility/manufacturer only has 1 – 2 test beds to produce various ratings of power transformers. Regarding lead time for a LPT, stakeholders reported that on average, it takes 12 to 16 weeks to manufacture an LPT if all the materials are available. When the assembly is done, it takes one week to test and one week to prepare the LPT for shipping. Typically, transportation time could range from several days to one week for domestic customers. For international shipping, it could take up to 6 weeks. The biggest challenge in transportation is the last 5 – 10 miles from a town with a transportation hub to the substation. On average, transportation time over this distance takes one month, but it could be extended to three months. During COVID-19, both domestic and international logistic delays have been a concern. International shipping can take up to six months. Another source reported that it can take from 5 to 12 months for domestic producers and 6 to 20 months for non-domestic producers (U.S. Department of Energy, 2014). Logistics and transportation can cost from 3% to 20% of the total cost of an LPT (U.S. Department of Energy, 2014).

There are potential bottlenecks in component supply if the U.S. demand for LPTs were to increase significantly in the next 5 – 10 years to meet its carbon emission target. It has been observed that high-voltage bushings often have a long lead time of up to five months (U.S. Department of Energy, 2014). When the end-users request that porcelain for bushings to be sourced outside of China, there are limited sources available including U.S., Japan, and Poland. Stakeholders indicated that tap changers could also be a bottle neck. There are three domestic suppliers and one reliable supplier from Germany. However, German tap changers are much more costly and have a longer lead time.

2.2 High-Voltage Direct Current Converter Stations

2.2.1 Supply Chain Segments

The supply chain segments and sub-segments mapping for HVDC systems are shown in Figure 11, including raw materials, sub-components, and components forming elements of HVDC systems. The focus of this analysis is on supply chain considerations pertaining to HVDC converter stations and their components, primarily converters, DC switchgear (breakers), DC filters and AC switchyards. These four components require sub-components such as insulated-gate bipolar transistors (IGBTs), capacitors, inductors, arrestors, AC switches, resistors, and distributed transformers. Cables used in offshore HVDC systems require specialized manufacturing and are supplied by a separate sub-contractor (Hartel et al., 2017). This component could be a potential bottle neck in the future, but it is not being discussed in this study.

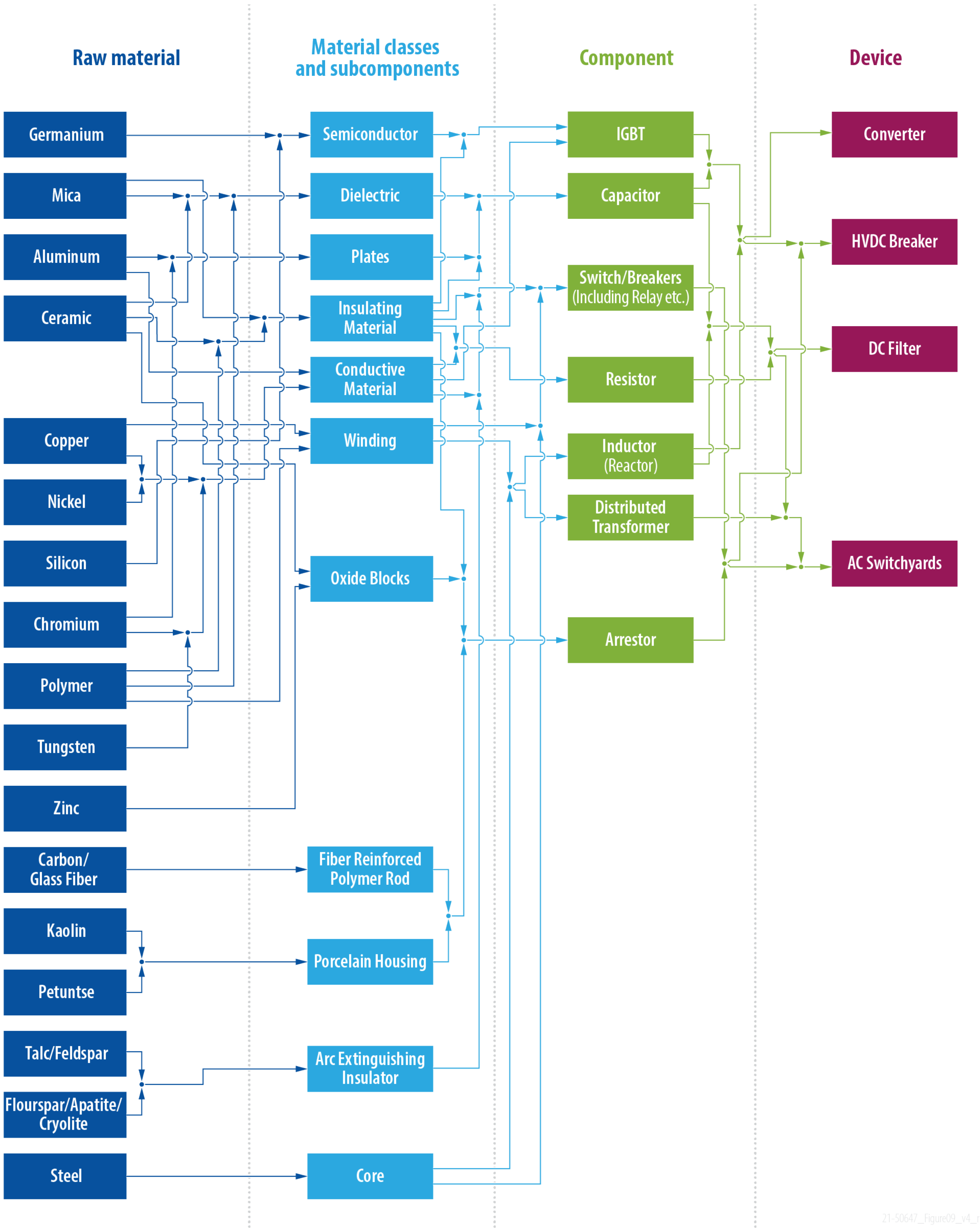

Figure 11. Supply chain segments and sub-segments for HVDC systems.

HVDC converters are mostly made up of thyristors and transistors, which use silicon metal (Si) as raw material. Although it is possible to use a variety of different materials for these types of devices, the process for Si is more mature, and less expensive than those for other materials. Si provides good thermal conductivity as well as a high-voltage and current capability (Bell, 2019). The semiconductor industry is highly globalized, with global trade in semiconductors and electronics involving cross-border design and manufacturing processes. Semiconductor firms headquartered in the United States were responsible for about 47% share, the largest among countries, of the $412 billion global market in 2019, as measured by sales (Platzer, Sargent Jr., & Sutter, 2020). The global market for dielectric materials, which is also globalized, reached close to $43.3 billion in 2016 and was expected to reach nearly $62.5 billion in 2021, with CAGR of 7.6% through 2021 (BCC Research, 2017).

2.2.2 Component-by-Component Break Down for HVDC Converter Station

Table 4 lists the typical key components for a HVDC converter station. Take the example of a 3 GW HVDC system, it typically has at least two DC transmission lines (e.g., +500 kV, -500 kV). It requires two sets of converters, one to five sets of AC switchyards depending on the AC out-going transmission lines and local grid connections inside the HVDC converter station. It also requires two sets of DC filters, three to five sets of DC switchgear (breakers) for maintenance/operation mode switching, up to two sets of DC switchgear (breakers) for cutting off the DC current per transmission line. The number of DC switchgear (breakers) depends on the high rated DC current breaker's technology progress. At present, most of the HVDC projects use DC switchgear (breakers) as a maintenance tool instead of cutting high DC current.

Table 4. A List of Typical Key Components (excluding transformer) in a HVDC Converter Station (Joseph, Ugalde-Loo, Liang, & Coventry, 2018).

Component	Type	Feature	Units in a Station
Converter	Voltage Source Converter (especially Modular Multilevel Converter)/Line-Commutated Converter	Key component to control Voltage/Current/Power	1 set per DC transmission line
AC Switchyard	-	Similar to AC substation	~1-5 sets depending on AC out-going local networks
DC Filter	-	Mitigate harmonics	1 set per DC transmission line
DC Breaker	For cutting DC current/ For maintenance	Key component to cut DC current	~3-5 sets for maintenance Up to one set per DC transmission line for cutting DC current

2.2.2.1 Converters

HVDC converters are divided into two categories: LLC and voltage source converters (VSC). MMC is an advanced version of VSC widely used for HVDC systems. MMC consists of tens to hundreds of converter modules aggregated together with high-power rating and flexible voltage, current, active power, and reactive power control capability. LCC is made with electronic switches that can only be turned on, thus having limited control capability. The difference between these technologies resides in the switching devices employed and how those switches are controlled. Table 5 summarizes these differences. Stakeholders indicated that the current thyristor technology used in LCC is suitable for long-distance, high capacity, and high-voltage systems. The transistors used in MMC are not able to handle as much of voltage and current as the LCC thyristors. Unless the transistor's ability to handle high-voltage and current can be increased, the VSC systems will lag behind LCC systems in terms of high-power density. It is also possible that matching performance of the two systems can be achieved in the next 5 to 10 years. Overall, the main advantage of VSC compared to LCC systems is its smaller footprint, reactive power control, lower risk of commutation failure and better connectivity to weak AC systems (Annakkage, 2015). On the other hand, LCC is more mature, economical, and has higher power capacity. Globally, most offshore HVDC projects are using MMC for wind farm or hydrogen co-production. For onshore HVDC projects, very long-distance and high-power projects prefer to use LCC, while multi-terminal, back-to-back or other application scenarios requiring grid control flexibility prefer MMC.

Table 5. Comparison of VSC/MMC and LCC.

Technology	VSC/ MMC	LCC
Semiconductor (control)	Consists of many modules with semiconductors and capacitors	Thyristor (turn on only)
Power control	Active/Reactive	Active only
AC Filters	No	Yes. Requires AC and DC harmonic filters for removal of distortion and harmonics
Black Start capability	Yes	No
Power Reversal	Done by changing the current direction	Done by reversing the voltage polarity

The HVDC converter (especially in LCC-HVDC systems) produces harmonics during the conversion process between AC and DC current, which can damage loads or reduce power transfer efficiency. To inhibit such interference and improve power quality, utilities specify the allowable harmonic level based on IEEE-519-2014 standard (IEEE Standards Association, 2014b). For MMC-HVDC systems, an advanced active or passive control strategy can be adopted to mitigate the DC side harmonics (B. Zhang & Nademi, 2020) such that a DC side filter is typically not required. Depending on the practical power quality and system operating circumstance, AC side filter might or might not be needed. For LCC-HVDC systems, filters are typically required on both AC and DC side. For AC side grid network distribution, switchyards are also needed for the local AC distributed grid and AC out-going transmission.

Figure 12 presents an example MMC-HVDC converter for wind farm integration. As shown in the green rectangle of Figure 12, MMC converter consists of six arms, where each arm includes an inductor and tens to hundreds of MMC sub-modules. On the AC side, every two arms connect to the AC grid as phase A, phase B, and phase C accordingly, while all three upper arms and three lower arms connect on the DC side, forming the DC terminal for long-distance DC transmission.

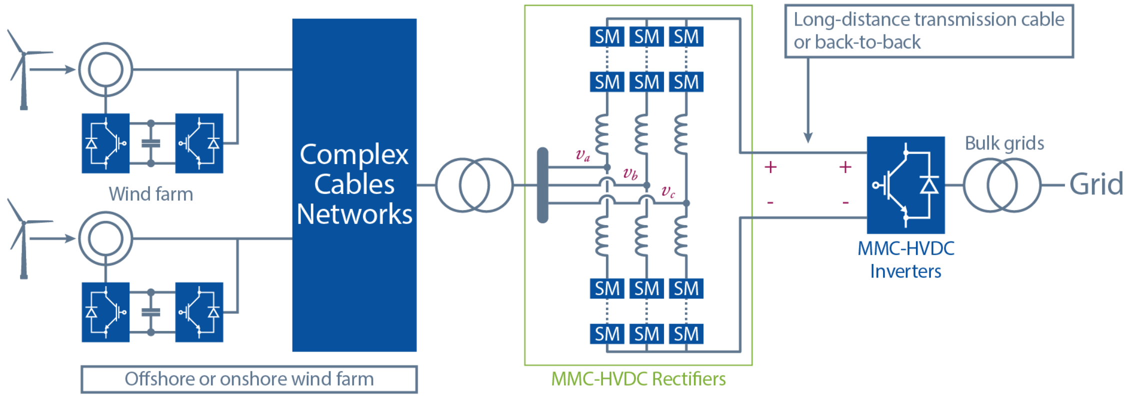

Figure 12. An example schematic of MMC-HVDC connecting wind farm and bulk grid.

2.2.2.2 DC Breakers (Switchgear)

Typically, there are two types of DC breakers (switchgear): one is used for maintenance or operation mode switching; the other one is used for cutting high DC current. Traditionally, the DC breakers are used for maintenance or operation mode switching. Because they operate at low voltage and current, the technology is mature without many operating or supply chain challenges. DC breakers used for cutting high DC current is a newer technology with applications in multi-terminal HVDCs.

The DC breaker used for cutting high DC transmission current when there is a grid failure. However, cutting DC current is very challenging from a technology standpoint compared to AC breaker. As a result, this component is still in the prototype research and development (R&D) stage. In 2020, Europe and Asia successfully performed some HVDC breaker (switchgear) prototype tests (Jia, Tang, & Shi, 2020; PROMOTioN, 2020). Globally, Hitachi Energy is the leading HVDC breaker manufacturer, successfully achieving 350 kV/20 kA DC current cutting in 2020 for the EU PROMOTioN HVDC project (PROMOTioN, 2020). In 2019, GE launched a medium voltage direct current (MVDC) breaker product with a goal to handle up to 100 kV voltage (GE, 2019). Stakeholders reported that Siemens Energy chooses to use more expensive inverters to avoid using DC breakers. In addition, for the U.S. market, demand for this component is very negligible and the trend will stay the same in the foreseeable future due to the lack of multi-terminal HVDC projects. Current HVDC suppliers do not anticipate that there will be a DC breaker plant in the United States.

2.2.2.3 AC Switchyard

An AC switchyard connects the AC transmission line with the HVDC converter station. Moreover, when there are any grid disturbances outside the HVDC converter station, a switchyard can protect the station. As shown in Figure 13, the typical components of an AC switchyard include an AC breaker, instrument transformer, AC filter, AC switch, and lightning arresters.

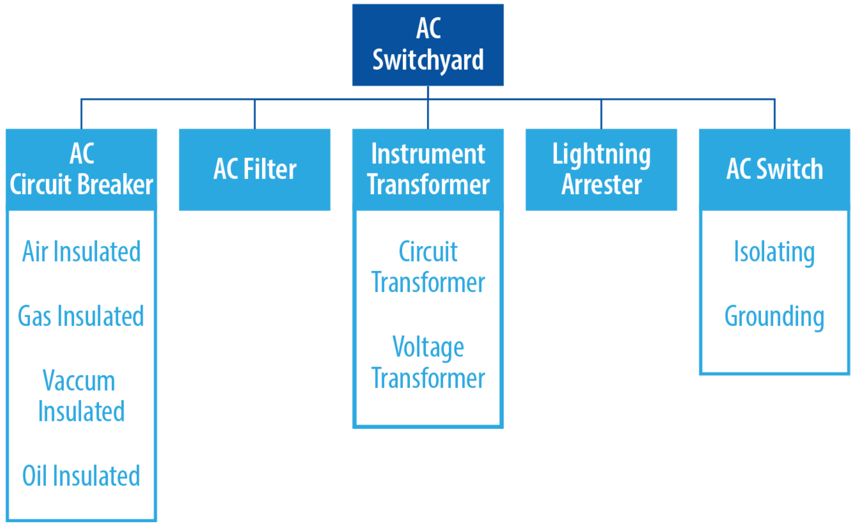

Figure 13. Different components of a typical AC switchyard of a HVDC converter station.

AC Circuit Breaker: AC circuit breakers are a crucial safety component of the switchyard, which helps protect electrical components from the damage caused by overload or short circuits. When too much current flows through the circuit, the breaker cuts off the power until the problem is fixed and it is reset. An AC breaker can be classified primarily as air, oil, gas, and vacuum type based on the quenching medium used to extinguish electric arc. A brief description is provided below.

Air Insulated: Air circuit breakers (ACB) operate with their contacts in free air (Jackson, 1997). When a fault occurs in a circuit, the first main contacts of ACB are separated and current of the circuit is shifted to another contact termed as arcing contact. The arcing contacts get disconnected, and the arc is pulled away from the contacts. Due to the electromagnetic effect, the arc moves upward along the arc runner until the arc breaks and the connection is split. Air acts as an insulator and forces the arc to extinguish as the contacts are pulled away from each other. It also prevents the arc from reforming after it is extinguished. In high-voltage applications, pressurized air serves as the dielectric because it has a higher dielectric constant value than atmospheric air (Seeger, Naidis, Steffens, Nordborg, & Claessens, 2005).

Vacuum Insulated: In this circuit breaker, a vacuum is used to extinguish the arc. It has good dielectric recovery character and can interrupt the high frequency harmonic current reliably (Matsui et al., 2006). These types of breakers are compact, can interrupt any fault current, have no fire hazards, have a higher dielectric strength, and require less power to control (Iturregi, Torres, Zamora, & Abarrategui, 2009).

Gas Insulated: Primarily sulfur hexafluoride (SF6) gas is used in a gas insulated switchgear (Koch, 2003). SF6 has an excellent insulating property and high electro-negativity (X. Zhang, Gockenbach, Liu, Chen, & Yang, 2013). Additionally, it is a colorless, odorless, non-toxic, and non-flammable gas (Koch, 2003). SF6 is 100 times more effective in arc quenching media than an air circuit breaker. Due to a combination of humidity and SF6 gas, hydrogen fluoride is formed (when the arc is interrupted) which can attack the parts of the circuit breakers. It should be noted that SF6 is the most potent greenhouse gas to date. Over a 100-year period, the global warming potential of SF6 is 22,800 times the equivalent amount of carbon dioxide (U.S. EPA). Recently the Advanced Research Project Agency-Energy (ARPA-E) of U.S. DOE funded $9.4 million to technology projects focused on removing SF6 from the U.S. power grid (Advanced Research Project Agency-Energy, 2021).

Oil Insulated: Oil is used in this type of circuit breaker as the insulator, preferably mineral oil. It has good insulating properties compared with air. When the fault occurs, the contacts of the breaker will open beneath the oil. Once the arc is struck among the two contacts of the breaker then the heat of the arc will dissolve the surrounding oil & separates into a significant volume of gaseous hydrogen at high pressure. This highly compressed gas bubble around, and arc prevents re-striking after the current reaches zero crossings of the AC cycle (Flurscheim, 1982). The main features of this circuit breaker are low cost, reliability, and simplicity.

AC Filter: An HVDC converter station often requires AC filters. The purpose of AC filters is to mitigate voltage distortion and reduce telephone interference in the connected AC network (Gunnarsson, Jiang, & Petersson, 2009). In addition, the AC filters also play a vital part in reactive power support. In most HVDC projects the primary decisive factor for the AC filter design is the requirement on telephone interference.

Instrument Transformer: Instrument transformers provide measurements of high voltages and current of the power circuit. There are primarily two types of instrument transformers–current transformer and voltage transformer.

Current Transformer: A current transformer is connected in series and utilized for the transformation of higher value currents into lower values. It is utilized in an analogous manner to that of AC instruments, control apparatus, and meters. These have lower current ratings and are used for maintenance and installation of current relays for protection purposes in the switchyard (Anderson, 2016).

Voltage Transformer: A voltage transformer (also known as potential transformer) is similar in characteristics to a current transformer but is utilized for converting high voltages to lower voltages for protection of the relay system and for lower rated metering of voltage measurements (Kaczmarek & Szczęsny, 2008).

Lightning Arrester: The purpose of a lightning arrester is to protect substation equipment from high voltages and to limit the amplitude and duration of the current's flow. These are meant for diversion of current to the earth if any current surge appears such as a lightning strike and hence protect insulation as well as conductors of the system from damage (Furukawa, Usuda, Isozaki, & Irie, 1989).

AC Switch: AC switches are used to isolate a circuit from the rest of the system and to de-energize it completely to ensure safety of the maintenance people during maintenance or testing of any equipment. AC switches include isolating and grounding switches which are described below briefly.

Isolating Switch: An isolating switch is a manually operated mechanical switch which separates a part of the system from the rest for safe maintenance works (Csanyi, 2014). Isolating switches are used to open a circuit under no load. Its main purpose is to isolate one portion of the circuit from the other and is not intended to be opened while current is flowing in the line (Olovsson & Constantinescu, 2004).

Grounding Switch: Grounding switches are mechanical switching devices for earthing parts of a circuit. Generally, these switches are interlinked with isolating switches. The main purpose of these switches is to discharge any charges remaining in an isolated circuit through ground. When an isolating switch opens the circuit, the grounding switch is kept closed and when an isolating switch closes the circuit, the grounding switch is kept open (Suzuki, Mizoguchi, Shimokawara, Murayama, & Yanabu, 1984). This ensures extra safety of the maintenance personnel during maintenance and routine checking.

2.2.2.4 DC Filters

The HVDC converter produces harmonics during the conversion process between AC and DC current (W. Zhang & Asplund, 1994). The harmonics can propagate into both the AC and the DC transmission lines and cause electromagnetic interference. To inhibit such interference, filters are installed. Many offshore MMC-HVDC projects do not include DC filter to save space, while most LCC-HVDC onshore projects still need DC filters. As a result, interviewed stakeholders indicated that DC filter is not a technically critical component in an HVDC system. The filters consist of capacitors, inductors, and resistors. They are designed to allow through currents at specified frequencies and to divert unwanted harmonic currents into the resistor, where they are dissipated as heat, safely and reliably. Inductors and capacitors are selected and matched to achieve this over the range of operating frequencies (Cressall Resistors, 2021).

The basic principle of the HVDC capacitors is to convert AC into DC via converters, which transfer the DC to the receiving end of the converter. The converter then converts DC to AC and sends it to the receiving end of the AC system (Precision Reports, 2020). There are different types of capacitors, which include electrolytic (aluminum and tantalum), ceramic, and film capacitors. Differences among those types are summarized in Table 6.

Table 6. Comparison of different capacitors (NIC Components Corp., n.d.).

Capacitor type	Advantage	Disadvantage
Electrolytic (aluminum/tantalum)	High capacity Surge voltage DC resistant Self-healing Open failure mode Low cost Stability: voltage	Polarized Low voltage rating for tantalum capacitors Limited surge resistance Short failure mode
Ceramic	Non-polarized Small size Transient resistant Low cost	Limited capacity range Short failure mode Large voltage coefficient and aging
Film	Non-polarized Transient resistant Stability over a wide range of voltage & temperature	Large size Higher cost Limited soldering heat

Resistors may be used for three reasons: to control the percentage of harmonics to be filtered, to dissipate the heat corresponding to those harmonic currents, or to lower the risk of voltage surge due to parallel resonance problems also known as current spikes (Hilkar, 2021). These harmonics are generated inside the system by the connection of a greater number of electronic power converters. These resistors act as a very high frequency low-pass filter in conjunction with resistors and capacitors.

Filter reactors or inductors are used to obstruct the flow of higher frequencies, help reduce harmonics in the systems, and provide current limiting (Magnetic Specialties, 2021). Reactors oppose rapid changes in current, to limit spikes caused by current pulses (Captech, 2015). They are installed on both the DC and AC sides of the HVDC converter. There are two main types of inductors: air-core reactors and iron-core reactors. Differences between these types are summarized in Table 7.

Table 7. Comparison of Iron and Air-Core Reactors, adapted from (NEPSI, n.d.).

Technical parameters	Iron-core reactors	Air-core reactors
Saturation	Yes	No
Stray magnetic field	Low	High
Space requirement	Low, compact	Large
Number of turns in the winding	Low	High
Enclosure	Simple	Difficult due to eddy-current heating from stray magnetic field

2.2.3 Manufacturing Process

2.2.3.1 Converters

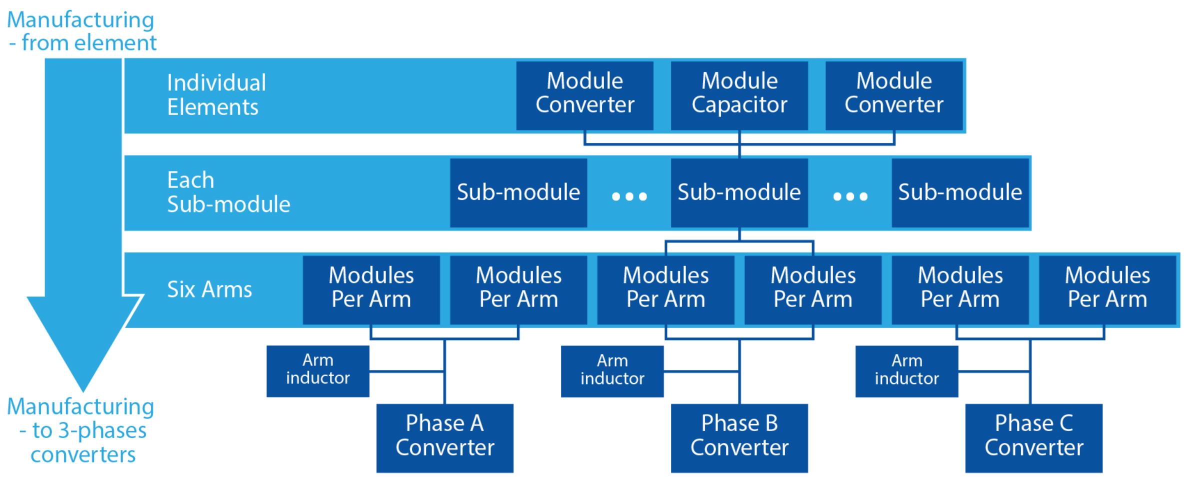

Figure 14. Manufacturing process of MMC-HVDC converter.

As shown in Figure 14, the manufacturing process of MMC-HVDC converter starts from individual module capacitor and module converters, and ends with assembling three phases of MMC converters (GE, 2016; Hitachi Energy, 2021b; Siemens, 2016).

- Step 1: Sub-modules in a half-bridge topology are assembled using two converters and one modular capacitor (GE, 2016; Siemens, 2016).
- Step 2: Tens of sub-modules are assembled to make arms. Within each arm, a voltage balancing strategy is needed to ensure internal voltage balancing among tens of sub-modules.
- Step 3: Two arms plus the arm inductor are used to form a single phase of the converter. Because the common mode currents potentially exist in both upper and lower arms for each phase, a control strategy or physical filters to mitigate the circulating current (common mode currents) are required.
- Step 4: Three phases of MMC converters are assembled. At this final step, voltage control, current control, power control and protection strategies are integrated.

2.2.3.2 DC Breakers

Currently, HVDC breakers are still at the R&D stage with prototypes being developed. Globally, Hitachi Energy is the leading HVDC breaker manufacturer. In 2020, Hitachi Energy successfully achieved 350 kV/20 kA DC current cutting for EU PROMOTioN HVDC project (PROMOTioN, 2020). In 2019, GE launched a MVDC breaker product with a goal to handle up to 100 kV voltage (GE, 2019).

2.2.3.3 AC Switchyard

The primary components of an AC switchyard are AC circuit breaker, AC filter, instrument transformer, lightning arrester, and AC switch. The components, sub-components, and raw materials required in the manufacturing process are discussed below.

AC Breaker

The main components of an AC breaker are an external casing, electrical contacts, operating mechanism, and quenching medium (EATON, 2021).

- The external casing of an AC breaker is made of steel, glass polyester, and thermoset composite resin (EATON, 2021). The key materials required to manufacture glass polyester and thermoset composite resin are silica, limestone, thermonatrite, natron, and natural gas (Brügging, Rüter, & Kaminsky, 2000; Khoun, Centea, & Hubert, 2010).
- The electrical contacts are made of copper, tungsten, and silver (Nasrallah, Brikci, & Perron, 2022).
- The operating mechanism is generally made of copper, iron, and steel.
- Based on the type of the breaker, mineral oil, SF6, or air can be used as a quenching medium (EATON, 2021).

AC Filter

- The AC filters are basically a circuit consisting of resistor, inductor, and capacitor (Circuit Globe, 2021; Gavrilović, 2003). The manufacturing processes of these components are skipped here and discussed in detail under section 2.2.3.4.

Instrumentation Transformer

The major components of an instrumentation transformer are the core, winding, and bushing (Hurst, 2021).

- GOES is used to manufacture the transformer core (Commodity Inside Limited, 2020).
- The coil winding is made from CTC similar to LPT's coil (Global Info Research, 2022).
- Bushings are primarily made of porcelain (Csanyi, 2012). Composite insulating materials can also be used as an alternative to porcelain, but it is expensive.

Lightning Arrester

The primary components of lightning arresters are fiber-reinforced polymer (FRP) rods, porcelain housing, silicone rubber shade, and metal oxides block (Siemens Energy, 2020).

- To manufacture FRP rods, aramid, carbon, or glass are primarily used as fibers, and epoxy or vinyl ester are commonly used as a matrix (Reeve, 2021).
- For porcelain housing, kaolinite and petuntse are the key materials used in the production process (Edwards, 2020).
- Silicone rubber shade is made of silicon dioxide, carbon, hydrogen, and oxygen (Mazurek, Vudayagiri, & Skov, 2019).
- Metal oxides blocks are produced from silicon dioxide, carbon, zinc, and oxygen (Meidensha, 2021).

AC Switch

The core components of AC switches are base, support insulator, earth-fixed contacts, blade assembly, and terminals (SS Power, 2021).

- Both drive and non-drive bases are mainly made of galvanized steel (SS Power, 2021).

- The support insulator is manufactured from porcelain which is primarily produced from kaolinite, petuntse, silica, feldspar, and China stone (Edwards, 2020; Kelun, 2004).
- The earth-fixed contacts are made of silver-plated copper fingers fitted to an aluminum casting (SS Power, 2021).
- The main components of male and female blade assemblies are aluminum tubes welded to aluminum housing, and earth-fixed contacts (SS Power, 2021).
- The terminals are manufactured from tinned copper tubes (SS Power, 2021).

2.2.3.4 DC Filters

The filters consist of capacitors, inductors, and resistors. Figure 15 through Figure 20 display the main steps in manufacturing inductors, capacitors (ceramic, film, aluminum) and resistors, respectively of DC filters in HVDC systems. These components can be connected in a parallel or series manner to make a DC filter. DC harmonic filters are used to either control the percentage of harmonics to be filtered and dissipate the harmonic currents as heat or to lower the risk of amplification due to parallel resonance problems. Resistors, commonly called grid stoppers, act as a very high frequency low-pass filter in conjunction with inductors and capacitors (NIC Components Corp., n.d.).

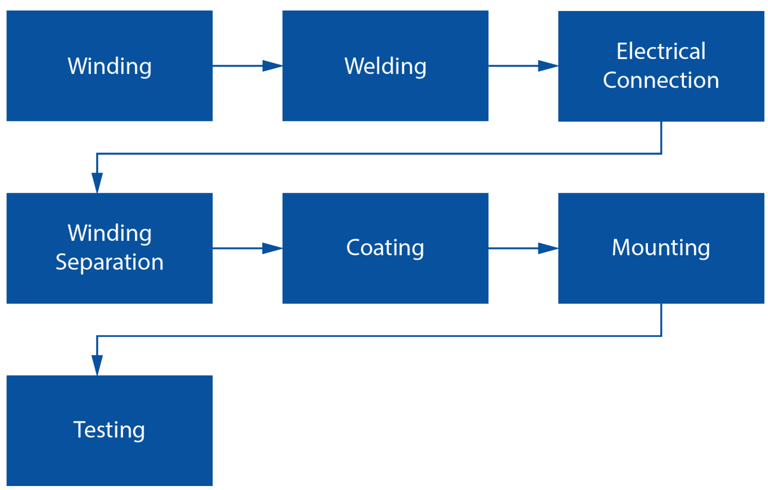

Figure 15. Air-core reactor manufacturing process, adapted from (Caverly et al., 2017).

Figure 15 shows the manufacturing process of an air-core reactor. First, several concentric cylindrical windings are electrically connected by welded connections to aluminum cross arms (spiders). These cross arms are located at both the top and bottom of the cylindrical windings. Next, external terminals are connected to the cross arms to complete the circuit. The windings used are typically specialty cables or individual aluminum wires insulated with insulating tapes. Concentric cylindrical windings are radially separated from each other by duct sticks, made from composite materials. These duct sticks form the air ducts which are necessary for the cooling of the winding. Next, a coating is applied to the surface of the windings to improve durability. The reactor is mounted on several base insulators and mounting brackets. Lastly, final tests are conducted (Caverly et al., 2017).

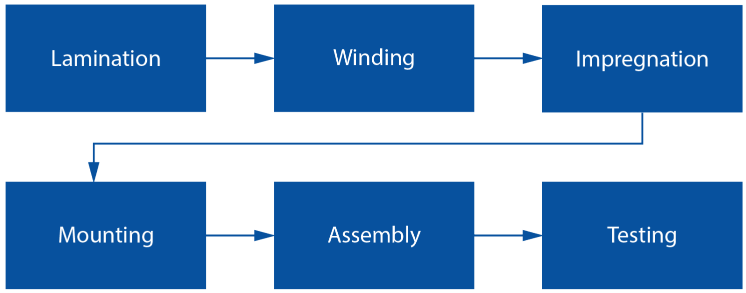

Figure 16. Iron-core reactor manufacturing process, adapted from (Hans Von Mangoldt Aachen, 2011).

Figure 16 shows the manufacturing process of iron-core reactor. First, laminations of iron are manufactured to create the core of the reactor. Next, copper winding is wrapped around the iron-core. Then, impregnation of the complete unit under high vacuum and overpressure is performed to protect the components. Finally, the units are mounted on insulators, assembled before final testing.

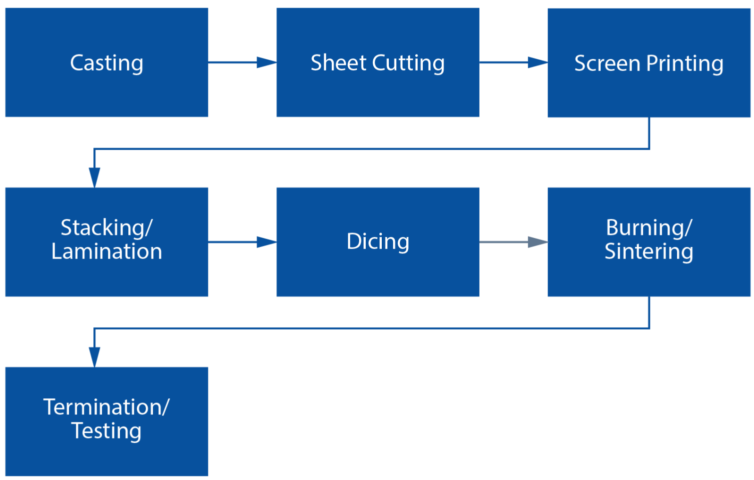

Figure 17. Manufacturing process of ceramic capacitor, adapted from (Pan & Randall, 2010).

Figure 17 shows the manufacturing process of a multilayer ceramic capacitors in DC filters. Ceramic capacitors can also be found in a disk construction orientation. However, this construction is outside the scope of this report. First, a ceramic powder is mixed with solvents, dispersant, binder, and plasticizers to form a homogeneous suspension, which is then cast into a thin, continuous sheet to be cut. This wet sheet is dried to form a flexible tape to which an electrode paste is applied in a process called screen printing. This electrode paste provides the conductive material to which electricity flows through the capacitor. The printed tape is then stacked with multiple layers during the lamination process. Next, the capacitors are cut and diced; and the capacitors undergo a process known as burnout to remove the organics from the different layers in the capacitor. Next, they are sintered to consolidate the layers of ceramic and inserted electrodes into a dense body. The final step is to apply metal terminations to make electrical connections to the internal electrodes exposed on opposite ends. At this point, the completed product contains multiple layers of dielectric with layers of electrode inserted between the stacked dielectric (Pan & Randall, 2010).

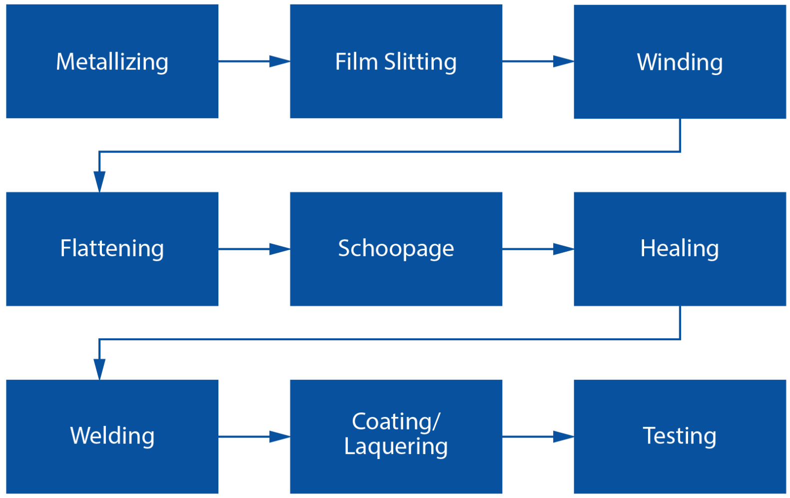

Figure 18. Manufacturing process of film capacitor, adapted from (Components101, 2020).

Figure 18 shows the manufacturing process of film capacitors in DC filters. The plastic film is extracted to the desired thickness as this sets the desired capacitance value. Next, the film is metallized with either aluminum or zinc and rolled into a large "mother roll". This roll is then put through slitting, winding, and flattening processes to tailor the roll to the desired electrical characteristics. Once the capacitor gets its desired shape and size, the projecting electrodes are subjected to a metallizing process called schoopage which is where metals such as zinc, aluminum, or tin are used to protect the protruding electrodes. Next, the terminals of the capacitor are welded on the end metal contact layers of the schoopage. After attaching the terminals, the capacitor body is dipped into a protective coating to create an exterior body. Final tests are then conducted on the capacitor (Components101, 2020).

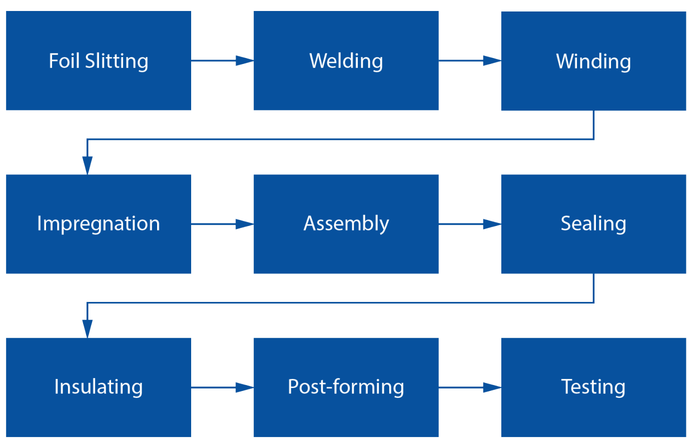

Figure 19. Process flow diagram for production of aluminum electrolytic capacitors, adapted from (Panasonic, 2018).

Figure 19 shows the manufacturing process of aluminum capacitors in DC filters, specifically radial aluminum electrolytic capacitors with non-solid electrolyte, which handle higher voltage. The production process starts with mother rolls. The anode foil on the mother roll and the cathode foil are cut to the required width. The rolls are fed to an automatic winder, which makes a wound section, in consecutive operations, including terminal welding and winding. The wound section is soaked with electrolyte under vacuum impregnation. The impregnated winding is then built into an aluminum case, and mechanically tightly sealed by curling. Thereafter, the capacitor is provided with an insulating shrink sleeve film. Post-forming and testing ensue (Panasonic, 2018).

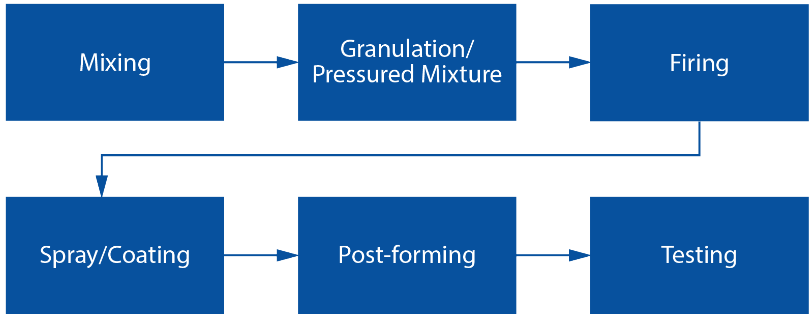

Figure 20. Resistor manufacturing process, adapted from (Hill Technical, 2005).

Figure 20 shows the manufacturing process of grid resistors, a subset of the larger category of resistor. Grid resistors are made of large matrices of resistive metal strips which are joined between two electrodes (Agnihotri, 2021). These metal strips are manufactured using a specific mixture of clays, alumina, and carbon (Hill Technical, 2005). The materials are mixed, granulated, and pressed into a specific shape. This pressed mixture is then fired to sinter or weld the mixture together creating a bulk resistive material. Typically, aluminum is then flame sprayed onto the flat surfaces of the resistor to provide reliable electrical contact, and an anti-track coating is applied to the edges to improve dielectric withstand. Lastly, final tests are conducted.

2.2.4 U.S. capabilities and competitiveness

2.2.4.1 Production Capabilities

The United States does not have HVDC manufacturing capability. Leading global HVDC suppliers such as GE, Hitachi Energy and Siemens Energy are present in the United States, but their manufacturing plants are based in Asia and Europe. Compared to Europe and Asia, the United States is lagging, mostly due to insignificant demand, which results in a lack of investment in the United States.

2.2.4.2 Market Competitiveness

Geographically, China and Europe are the two key global players in HVDC demand. This is largely attributed to the HVDC projects used to transport bulk energy over the large geographical areas of these countries (Alassi et al., 2019). It is estimated that by 2022, the total global HVDC transmission capacity will be over 400 GW, with about 52 percent of this capacity being transmitted within Asia (Alassi et al., 2019). The largest number of HVDC projects is in Europe, but internal European HVDC capacity accounts for only 22 percent of the global HVDC projects due to smaller geographical distribution compared to Asia (Alassi et al., 2019).

The top three global HVDC suppliers include GE Grid Solutions, Hitachi Energy, and Siemens Energy (Alassi et al., 2019). Their manufacturing facilities are based in Asia and Europe where significant demand resides. Stakeholder engagement estimated that there are 350 HVDC systems in operation worldwide. This demonstrates that the market is relatively small but highly competitive. Because manufacturing of key components of the converter station are non-existent in the United States, the United States does not have a competitive edge compared to other countries.

2.2.4.3 Manufacturing Costs

Due to the small and competitive HVDC market, manufacturing costs are not available. Most of the HVDC cost is based on the installation project timeline. Stakeholder engagement provided the cost breakdown as shown in Figure 21.

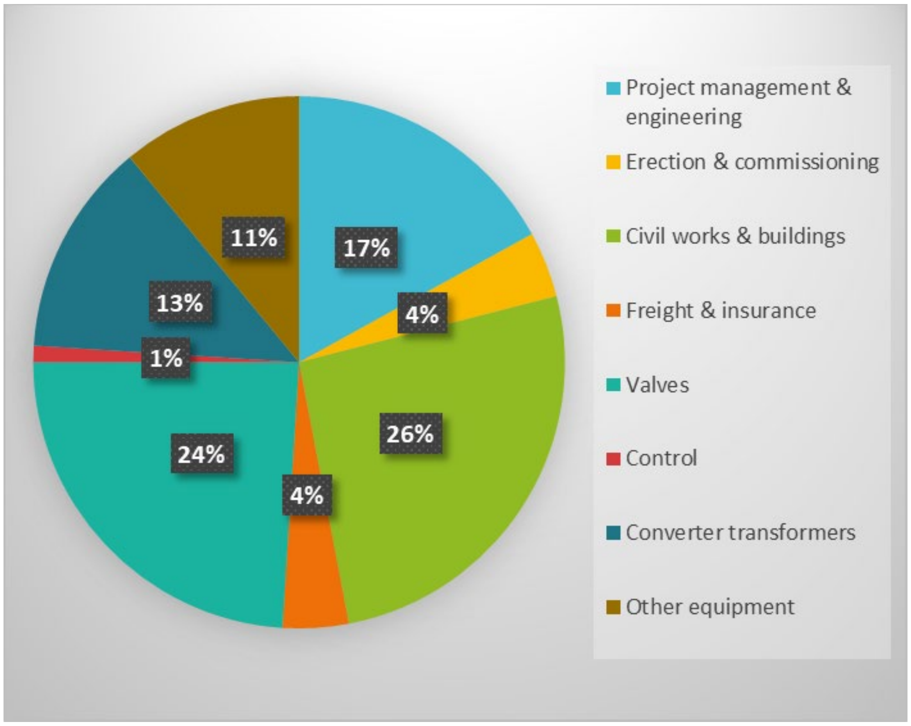

Figure 21. Cost breakdown of an HVDC project.

The cost of HVDC transmission systems depend on various factors, including but not limited to power capacity being transmitted, submarine or land-based transmission type, environmental factors, and access/cost of equipment such as costly converter stations (U.S. Energy Information Administration, 2018). Previous work done by the National Renewable Energy Laboratory (NREL) for a system with 100-mile transmission, 500-kV HVDC bi-pole line, built on flat terrain in a rural area, utilizing its Jobs and Economic Development Impact (JEDI) model, estimated the average cost per mile of installing HVDC transmission lines in the United States (U.S. Energy Information Administration, 2018). Results showed that total capital costs were about $9.17 million/mile. Converter stations (including all required equipment and labor) would cost $367 million per station and two stations are required at each end of the HVDC line.

2.2.4.4 Other Competitiveness Factors

Due to the lack of HVDC manufacturing capability in the United States, the workforce faces similar skills mismatch issues to LPT manufacturing in terms of designing and testing HVDC systems. Problems with workforce availability become a barrier for projects requiring more than 50% of project cost dedicated to supporting local businesses, according to stakeholder engagement. Leading manufacturers and service providers, with a small number of projects in the United States, often hire experts from Europe and send workers there to be trained as a short-term solution.

2.2.5 Patent and Technology Landscape

2.2.5.1 HVDC Converter

1,909 published patent applications related to HVDC converters were identified and analyzed for this report (PatSnap, 2021). The analyzed patent search results include applications with a filing date after January 1, 2001 and publication date before December 1, 2021 which contained these keywords in the title or abstract: 1) converter, rectifier, or inverter, and 2) HVDC, high-voltage DC, or high-voltage direct current, while also including one of these keywords anywhere in the application: grid, utility, utilities, power system, power transmission system, power transmission, transmission line, or power transmission network.

Figure 22 identifies the simple legal status for the analyzed applications. About 46% of patents are active, 11% are pending, and ~29% are inactive.

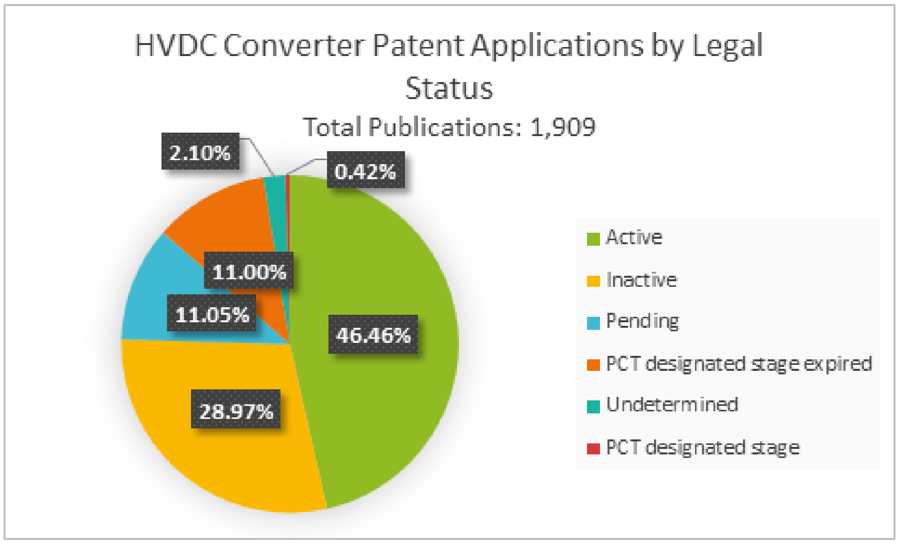

Figure 22. HVDC converter patent applications by legal status.

Figure 23 shows the patent filing trend for each technology by the earliest patent application and shows where it was filed (PatSnap, 2021). The country which receives the first patent application could indicate that either companies located in that country are innovating in this area or wanting to capitalize the license first. The HVDC market is largest in China and Europe, hosting major HVDC manufacturing plants of leading global HVDC suppliers such as GE, Hitachi Energy and Siemens. That is why a significant portion of patent applications are filed in those jurisdictions. Most patents were filed between 2009 and 2018. Chinese patent filings have increased dramatically since 2013.

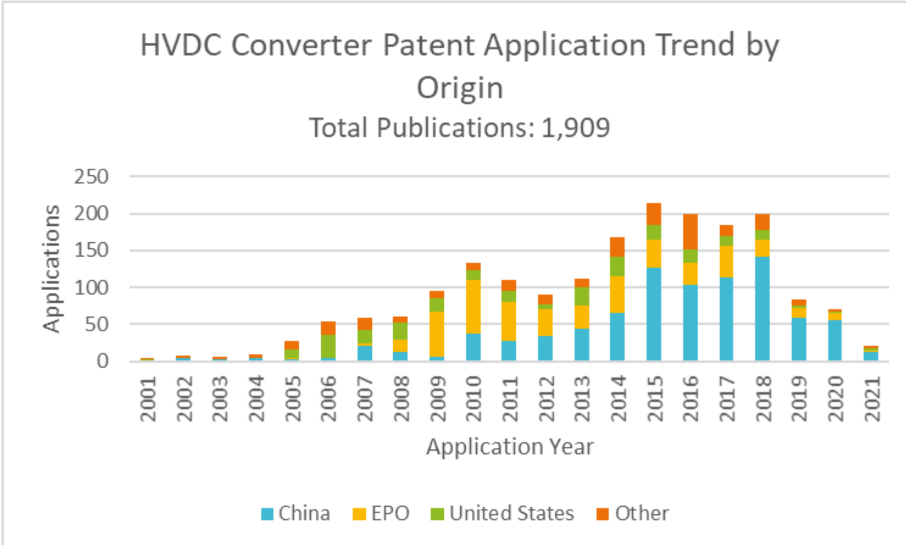

Figure 23. HVDC converter patent application trend by origin.

The leading assignees for patent applications related to HVDC converters are shown in Figure 24. This list uses the assignee name from the patent application. Using assignee names ABB Schweiz AG and ABB Power Grids Switzerland AG, Hitachi Energy appears to have the most patent applications in this area (PatSnap, 2021). Correlating with the higher HVDC market demand in China, many of the top assignees of patent applications related to HVDC converter are based in China as shown in Figure 24.

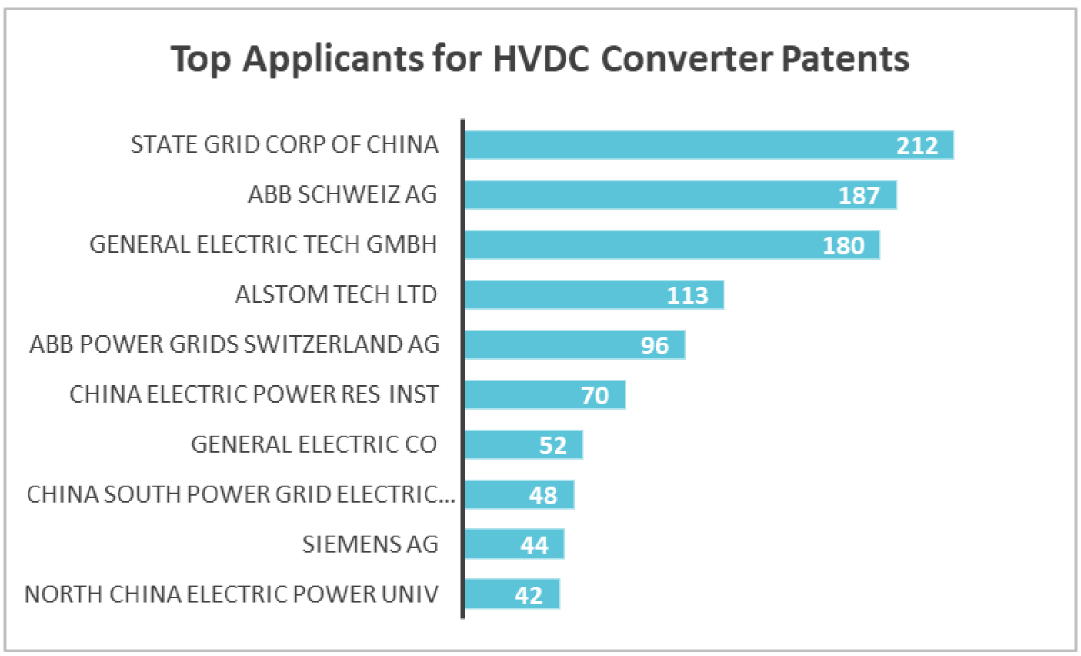

Figure 24. Top applicants for HVDC converter patents.

2.2.5.2 DC Switchgear (Breakers)

764 published patent applications related to DC switchgear were identified and analyzed in this report (PatSnap, 2021). The analyzed patent search results include applications with a filing date after January 1, 2001, and publication date before December 1, 2021, where the title or abstract contained 1) DC or direct current and 2) breaker or switchgear, while also including HVDC, high-voltage DC, or high-voltage direct current anywhere in HVDC or high-voltage direct current anywhere in the application and excluding patents mentioning the keyword battery to return more relevant results.

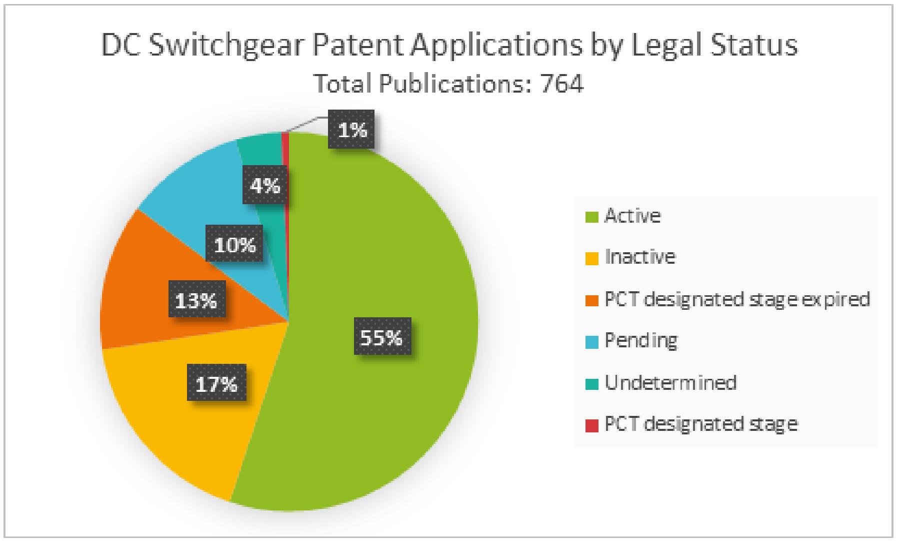

Figure 25. DC switchgear patent applications by legal status.

Figure 25 identifies the simple legal status for the analyzed applications. Approximately 55% of filed patents are active, 13% are pending, and 17% are inactive.

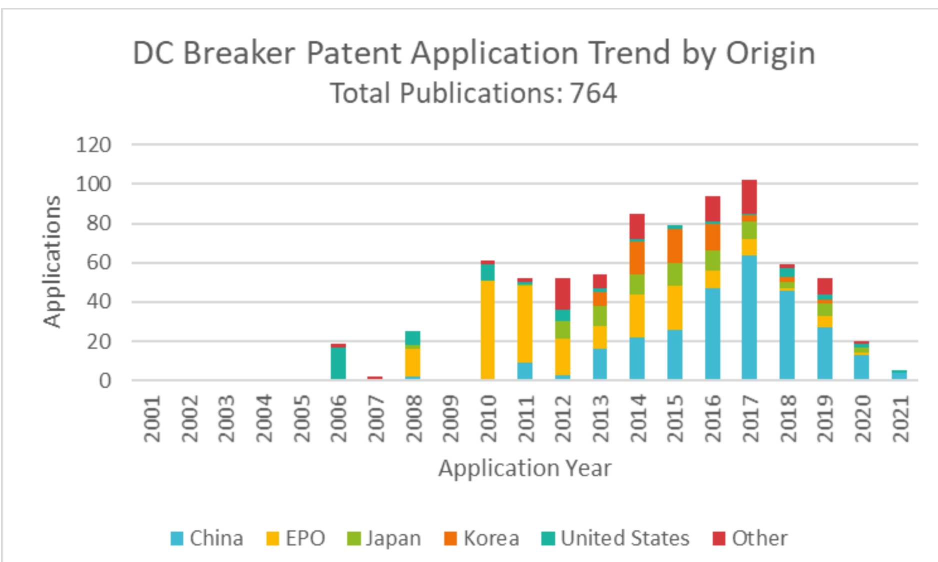

Figure 26. DC switchgear application trend by origin.

Figure 26 shows the patent filing trend for each technology by the earliest patent application and shows where it was filed. The EPO dominated the DC switchgear patent landscape from 2008 to 2012. Since 2013, the number of Chinese patent applications related to DC switchgear have significantly increased while European filings have decreased.

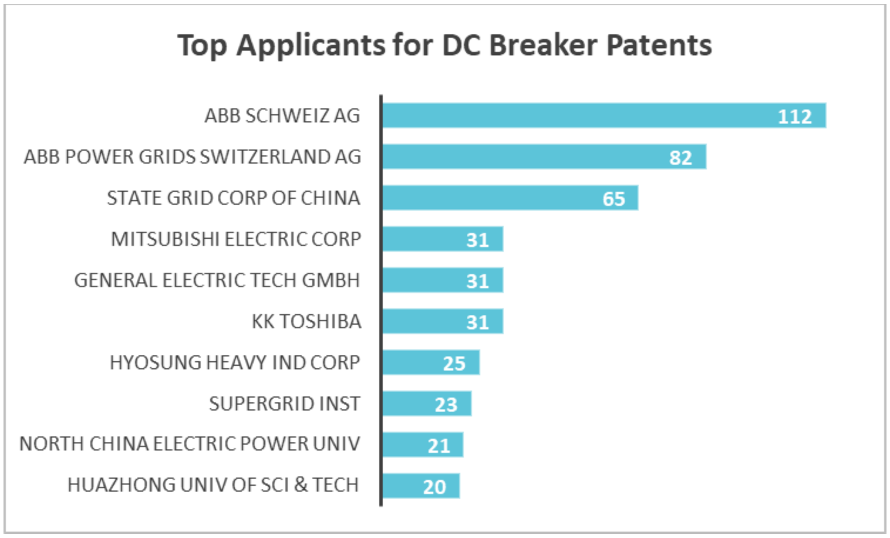

Figure 27. Top applicants for DC switchgear patents.

The leading assignees for patent applications related to DC switchgear are shown in Figure 27. Using assignee names ABB Schweiz AG and ABB Power Grids Switzerland AG, Hitachi Energy appears to have the most patent applications which indicates that this company has been a leader in HVDC breaker innovations over the last 20 years.

2.2.5.3 AC Switchyards

138 published patent applications related to AC switchyards were identified and analyzed for this report (PatSnap, 2021). The analyzed patent search results include applications with a filing date after January 1, 2001, and publication date before December 1, 2021, where the title or abstract contained the keyword switchyard.

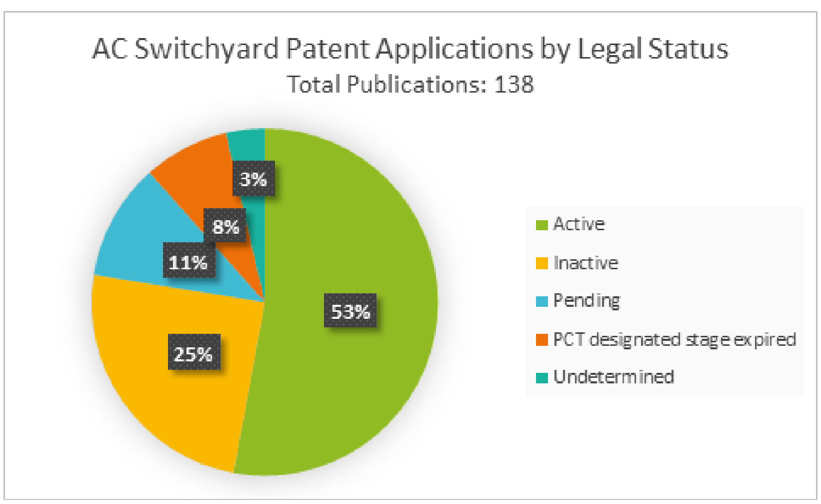

Figure 28. AC switchyard patent applications by legal status.

Figure 28 identifies the simple legal status for the analyzed applications. Approximately 53% of patent applications are active, 25% are inactive and 11% are pending.

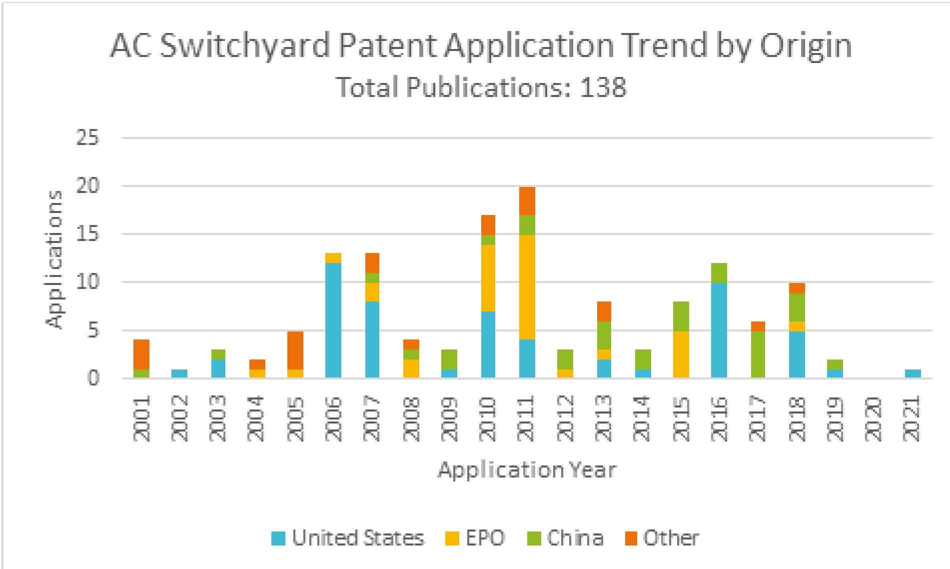

Figure 29. AC switchyard patent application trend by origin.

Figure 29 shows the application trend by the earliest patent application and shows where it was filed. The United States, EU, and China has been taking turn although China is somewhat behind. Overall, the United States has a significant footprint in this field.

Figure 30 shows the leading assignees for patent applications related to AC switchyards. Using assignee names ABB Schweiz AG and ABB Power Grids Switzerland AG, Hitachi Energy appears to have the most patent applications in this area.

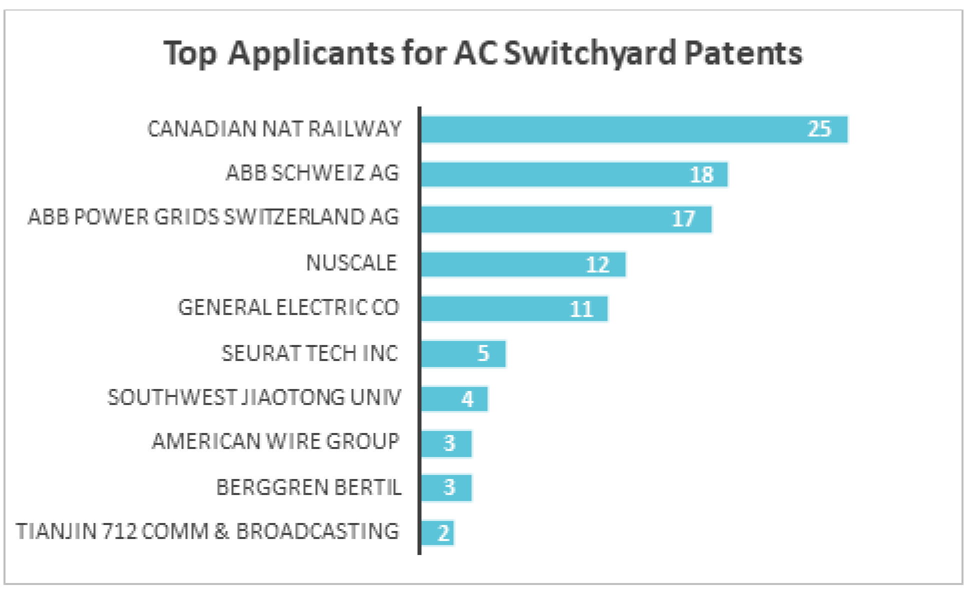

Figure 30. Top applicants for switchyard patents.

2.2.5.4 DC Filters

102 published patent applications related to DC filters for use with HVDC systems were identified and analyzed for this report. The analyzed patent applications include applications with a filing date after January 1, 2001 and publication date before December 1, 2021 (PatSnap, 2021) which contained 1) filter in the title, 2) DC or direct current and 3) HVDC, high-voltage DC, or high-voltage direct current within the title or abstract, and included at least one of the following keywords anywhere in the application: grid, utility, utilities, power system, power transmission system, power transmission, transmission line, or power transmission network.

Figure 31 identifies the simple legal status for the analyzed applications. Approximately 64% of filed patterns are active, ~24% are inactive and ~10% are pending.

Figure 32 shows the patent filing trend for each technology by the earliest patent application and shows where it was filed. China has dominated this technology area since 2003. The higher application numbers for that jurisdiction could be correlated with China having the largest HVDC market.

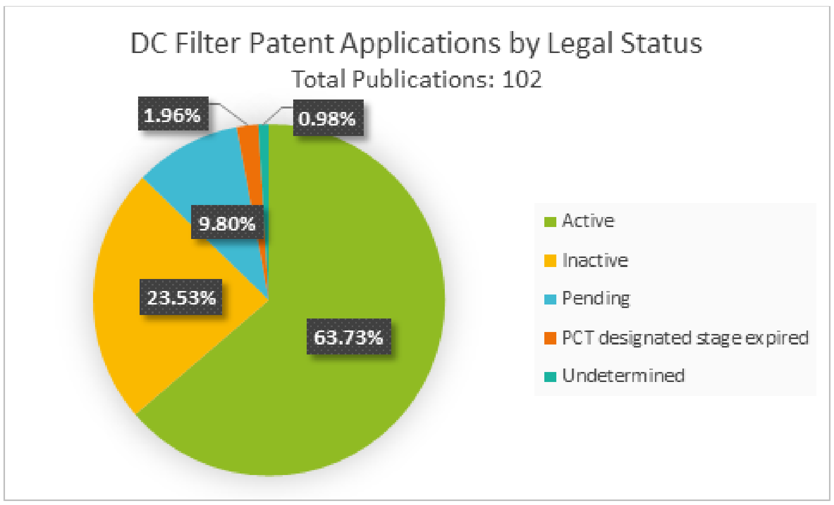

Figure 31. DC filter patent applications by legal status.

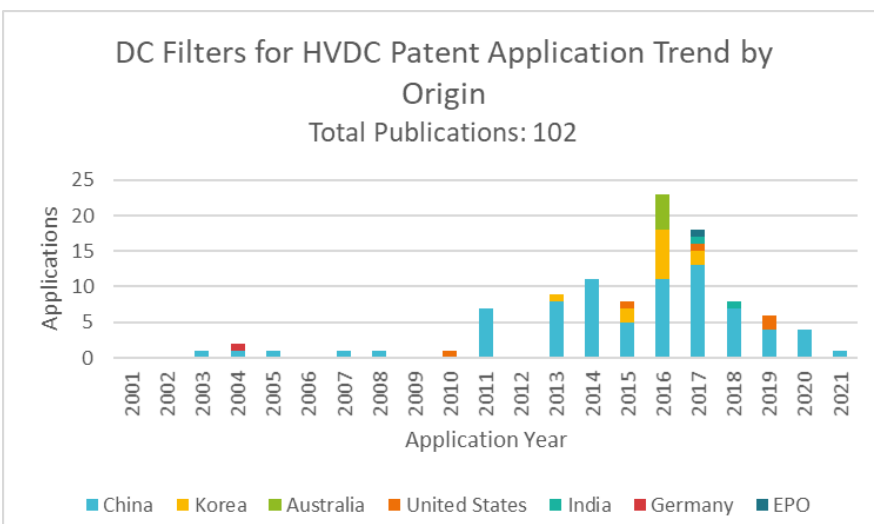

Figure 32. DC filters for HVDC patent application trend by origin.

Figure 33 shows the leading assignees for patent applications related to DC filter. State Grid Corp of China appears to have the most patent applications in this area.

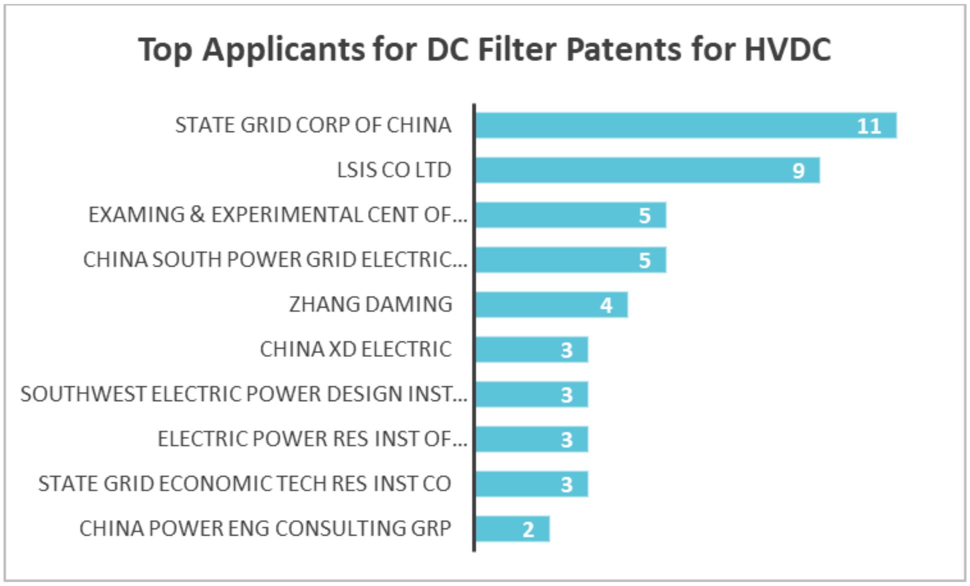

Figure 33. Top applicants for DC filter patents.

2.2.6 HVDC Supply Chain Bottlenecks

Because HVDC system manufacturing in the United States does not exist, discussion on supply chain bottlenecks is not relevant. Stakeholders raised concerns about lacking HVDC demand in the United States caused by a complex permitting process involving many stakeholders to approve. A detailed discussion on permitting is beyond the scope of this report. Investors have not felt the security to invest in HVDC manufacturing given the current U.S. market condition and legal framework. In addition, lacking collaboration among Regional Transmission Organizations (RTOs), uncertain cost recovery, and insufficient workforce training programs are major barriers to grow U.S. HVDC demand. These challenges are discussed in more detail in Section 4.4.1.

Globally, one apparent bottleneck is the semiconductor supply. HVDC converter station's four key components including converters, DC switchgear (breakers), DC Filters, AC Switchyard rely on seven main sub-components, including IGBTs, AC switch/breakers, transformers, capacitors, inductors, resistors, and arrestors. In some cases, semiconductor components require a lead time of one year (Vakil & Linton, 2021). In 2021, the world's largest semiconductor company holding 54% market share, Taiwan Semiconductor Manufacturing Company, was unable to catch up with demand (Y. N. Lee, 2021). The major issue with the chip industry is the lean production practice where cost cutting is highly emphasized and maintaining inventory is deemphasized. With a lean inventory, chip manufacturers cannot cope with unanticipated demand. In October 2020, a fire at Asahi Kasei Microdevices semiconductor factory in Japan caused supply shortages for multiple products including analog-to-digital converters, oscillators, and frequency control applications (TTI Inc., 2020). Adding more complexity to the picture is the shortage of fiber glass used for printed circuit boards due to a fire at Nittobo's plant in Japan in July 2020 (Drysdale, 2021).

Another bottleneck for the global HVDC supply chain is competing demand from other applications. IGBT's and semiconductors are used in renewable inverters, battery energy storage system inverters, variable-frequency drives, static synchronous compensator, rectifiers, static frequency convertors (Han, Liang, Kang, & Qiu, 2020; Kennedy, 2002; Pelczynski, Heremans, & Schwed, 1999; Rideout, 1978). HVDC transformers are subject to the overall demand for power and distribution transformers (used by almost all industries and sectors) (Allied Market Research, 2019; Global Market Insights, 2021) and impacted by the key materials required to manufacture them (subject to global electrification demand putting pressure on NOES and copper). Capacitors and inductors are used in many utility, solar, data centers, transportation, and industrial applications (J.-H. Lee, Liang, & Chen, 2013; Powers, 2015; Soltani & Beheshti, 2021; Yan, Moss, Ngo, Mei, & Lu, 2017). Switches and breakers are also in demand by utilities, renewables, data centers, transportation, and various industrial applications (Almutairy, 2016; M&M Research, 2021; Research Nester, 2017). Overall, due to climate change initiatives and decarbonization commitments, there are many industries and sectors that are looking to electrification as a means of solving these challenges, putting increased pressure on the capacity of the industry to serve the grid related needs.

3 Supply Chain Risk Assessment

Due to variance in available supply chain data, two methodologies were used to evaluate the supply chains. A qualitative assessment was performed for both the LPT and HVDC supply chain, while the quantitative assessment was performed for only the LPT supply chain. This difference in methodology selection was due to the availability of data between the two supply chains stemming from the respective maturity of manufacturing capability in the United States. Because LPT manufacturing is more mature, there was more information available for quantitative analysis. In addition, only a short list of segments from the qualitative LPT assessment is considered for the quantitative assessment.

3.1 Risk Assessment Methodology

3.1.1 Qualitative Risk Assessment Methodology

A two-step approach was developed to identify supply chain vulnerabilities and weaknesses for the electric grid. The first step used an evaluation metric to identify vulnerable or weak U.S. supply chain segments. The supply chain was divided into key components of the final product. Each supply chain segment was qualitatively evaluated by answering yes, no, or maybe based on seven criteria as followed. For components or materials without domestic manufacturing, not applicable (N/A) will be used without further explanation.

1. Significant domestic manufacturers: number of domestic manufacturers is considered significant if there are at least three manufacturers or domestic supply meets at least 50% domestic demand.

2. Significant domestic demand: if the market value is of at least $1 billion, the domestic demand is significant.

3. Projected significant domestic demand: if the projected annual compounded demand growth rate is greater than or equal to 2% over a period of 5 years, projected domestic demand is considered significant.

4. Significant global market: if the market value is of $10 billion dollars or more, the market under evaluation is considered significant.

5. Projected significant global demand: if the projected annual compounded demand growth rate is greater than or equal to 3% over a period of 5 years, projected global demand is considered significant.

6. Cost-competitive among U.S. manufacturers: this criterion can be evaluated based on one of the following three metrics, depending on data availability. The simplest metric is the diversity of domestic

producers. If there are at least three domestic producers, the market is competitive. The next metric is market share. If no single company has more than 50% of the domestic market share, the market is considered competitive. The last metric is directly based on the cost/selling price. If the same grade products produced/offered domestically are within ±10% cost/selling price, it is considered competitive.

7. Cost-competitive between U.S. manufacturers and global manufacturers: this criterion can be evaluated based on one of the following two metrics, depending on data availability. If no single producer has more than 15% of the global market share, the market is considered competitive. Alternatively, if the same grade products produced in the United States are within ±15% cost/selling price compared to products manufactured elsewhere, it is considered competitive.

The second step detailed an explanation to support the score with accompanied data wherever available. Market dynamics and relevant technology information are discussed to explain the cause of a specific weak link in the supply chain. To help inform this process, industry outreach to companies in the LPT and HVDC market was performed. Questions centered around the seven criteria, but also covered topics like workforce, manufacturing lead time, shipping lead time, cybersecurity, etc. Three HVDC companies, nine transformer/LPT manufacturers, two companies with GOES manufacturing capability, two transformer recyclers, one data company and two trade associations were contacted for stakeholder engagement. Interviews were conducted with 14 individuals from five companies. Followed-up emails were exchanged after the interviews for further clarification.

3.1.2 Quantitative Risk Assessment Methodology

For the qualitative assessment, an evaluation metric table was developed with numeric scoring. Listed below are the metrics that were evaluated as well as the associated scoring system. This process was performed for each supply chain segment of the LPT supply chain. The goal was to determine the segment with the highest risk and elements contributing to high-risk scores. It is important to note that the analyzed supply chain segments differed slightly between the qualitative and quantitative analysis. During preliminary assessment and evaluation of the qualitative table, the segments for the quantitative assessment were identified. Additionally, the quantitative analysis focused on large market supply chain segments and segments of concern confirmed by the current state of industry engagement. Evaluation metrics include:

1. Number of domestic manufacturers: Number of domestic manufacturers was calculated by counting the domestic manufacturers. The lower the number of domestic manufacturers is, the higher the risk score becomes.

   A. Number of domestic manufacturers ≤ 1; risk score equals 3.

   B. 1 < Number of domestic manufacturers < 3; risk score equals 2.

   C. Number of domestic manufacturers ≥ 3; risk score equals 1.

2. Import reliance: Import reliance was measured by the percentage of a product that was imported to meet the demand for the supply chain segment. If the import reliance could not be calculated through data sources, the quantity of stakeholders that raised import reliance as a concern for a supply chain segment was used. The more the United States relies on import, the higher the risk score becomes.

    A. Method 1

        i. Import reliance > 75%; risk score equals 3.

        ii. 75% ≥ Import reliance ≥ 25%; risk score equals 2.

        iii. Import reliance < 25%; risk score equals 1.

    B. Method 2

        iv. Number of concerned stakeholders ≥ 3; risk score equals 3.

        v. 1 < Number of concerned stakeholders < 3; risk score equals 2.

        vi. Number of concerned stakeholders ≤ 1; risk score equals 1.

3. Number of friendly foreign manufacturers: Number of friendly foreign manufacturers was calculated by counting the manufacturers from western Europe, Korea, Japan, Australia, New Zealand, Canada, and Mexico.

    A. Number of friendly manufacturers ≤ 1; risk score equals 3.

    B. 1 < Number of friendly manufacturers < 3; risk score equals 2.

    C. Number of friendly manufacturers ≥ 3; risk score equals 1.

4. Lead time: Lead time was measured by counting the quantity of stakeholders that raised lead time as a concern for a supply chain segment. The more concern regarding lead time is raised, the higher the risk score gets.

    A. Number of concerned stakeholders ≥ 3; risk score equals 3.

    B. 1 < Number of concerned stakeholders < 3; risk score equals 2.

    C. Number of concerned stakeholders ≤ 1; risk score equals 1.

5. Technology/Material substitution options: Technology/material substitution options were measured by counting the number of possible alternative technologies or materials for a supply chain segment. If a material/component has more substitution options, the risk score is lower.

    A. Number of technology/material substitution options < 1; risk score equals 3.

    B. 1 < Number of technology/material substitution options < 3; risk score equals 2.

    C. Number of technology/material substitution options ≥ 3; risk score equals 1.

6. Supply competition due to other application demand: This metric aimed to measure factors beyond the industry of interest that could limit supply. One way to measure that is by looking at competing demand from other applications that could reduce supply for the LPT supply chain. Ideally, this metric is quantified based on application market share. When supply is limited, the top applications are most likely to be prioritized whereas the applications with lowest demand share might not have any allocation. In the case of LPT supply chain, the competing application is even more complicated because the competing demand is not directly on the same material, but a different material that can be produced from the same facility. As a result, the score was formulated by counting the quantity of stakeholders that raised supply competition as a concern for a supply chain segment.

   A. Number of concerned stakeholders ≥ 3; risk score equals 3.

   B. 1 < Number of concerned stakeholders < 3; risk score equals 2.

   C. Number of concerned stakeholders ≤1; risk score equals 1.

7. U.S. ability to compete with non-domestic sources: The U.S. ability to compete with non-domestic sources was measured by counting the quantity of stakeholders that raised concerns with the U.S. prices, quality, and quantity (caused by limited production capacity) in comparison to non-domestic sources.

   A. Number of concerned stakeholders ≥ 3; risk score equals 3

   B. 1 < Number of concerned stakeholders < 3; risk score equals 2

   C. Number of concerned stakeholders ≤1; risk score equals 1

3.2 Large Power Transformer Risk Assessment Results

3.2.1 Qualitative risk assessment results

Table 8 displays the results of the seven qualitative criteria described in Section 3.1.1 for LPTs. The major components of LPTs were identified to be steel, copper, bushings, conservators, and tap changers. These categories were further broken down into SC segments. Steel components consist of raw steel, GOES and core assembly. Copper components mostly consist of CTC wire, and copper winding assembly. The conservator was broken down into two components: the tank and the bladder. Bushings and tap changers were not further broken down into raw materials. The final row in Table 8 discusses each of the criteria for the entire LPT assembly. Explanations for relevant supply chain segments with a 'no' assessment are provided below. For all the 'maybe' assessments, insufficient data was found to support a 'no' or a 'yes' answer.

3.2.1.1 Raw Steel

Insignificant projected global demand: Raw steel does not have significant projected global demand. Data collected for the raw steel market has not shown projected global demand to exceed 3% per year over a period of five years. One source reported a global demand growth rate value of 1.4% from the years 2015 to 2035 for the steel market (Accenture Strategy, 2017), while another source reported a global demand growth rate of 2.5% for the years 2020 to 2027 (Market Research Future, 2021). Additionally, the World Steel Association reported a growth rate of 4.5% for 2020 and forecasted 2.2% growth for the year 2022 (World Steel Association, 2021). These sources showed that raw steel demand growth rate can fluctuate from one year to the next but the growth trend for longer term (five years or so) is not consistently 3% or higher per year.

3.2.1.2 GOES

Insignificant domestic manufacturers: Only one domestic manufacturer has been identified that can produce GOES, however, the manufacturer cannot produce the grades required for LPT core manufacturing.

Insignificant projected domestic demand: There is not anticipated to be a significant projected domestic demand for GOES. Data were unable to be obtained for the United States specifically, however, it is an appropriate assumption that GOES demand would be in line with the reported GOES projected global demand growth rate of 1.6% (360 Research Reports, 2019). This is less than the required 2% per year growth rate to determine significance.

Insignificant global market: A value of $6.6 billion was obtained for the global GOES market in 2019, which is less than the $10 billion market requirement (360 Research Reports, 2019).

Insignificant projected global demand: There is not a significant projected global demand for GOES. One data source reported that GOES is expected to grow at a rate of 1.6% for the years 2019 to 2024 (360 Research Reports, 2019).

Uncompetitive cost among U.S. manufacturers: Due to the lack of domestic manufacturers of GOES, it was deemed that there was a lack of cost competitiveness within the U.S. market. With Cleveland-Cliffs being the only GOES manufacturer currently, there is simply not enough competition to create a competitive market.

Uncompetitive cost between U.S. and global manufacturers: It was assumed that U.S. manufacturers were not cost-competitive with global manufacturers of GOES because data showed that 88% of GOES was imported in 2019 (U.S. Department of Commerce, 2020). Additionally, industry engagement has indicated that U.S. manufacturers cannot produce GOES at the highest specifications required for LPT production. This indicates a lack of competition between the U.S. GOES manufacturers and the global GOES manufacturers.

Table 8. Evaluation results for LPT supply chain.

SC segments to meet final product demand	Significant domestic manufacturers	Significant domestic demand	Projected significant domestic demand	Significant global market	Projected significant global demand	Cost-competitive among U.S. manufacturers	Cost-competitive between U.S. manufacturers vs. global manufacturers
Raw steel	Yes	Yes	Yes	Yes	No	Yes	Yes
GOES	No	Yes	No	No	No	No	No
Assembled cores	Yes	Yes	Yes	No	Yes	Yes	No
Refined copper/ scrap	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CTC	Yes	Maybe	Yes	Maybe	Yes	Yes	Maybe
Copper windings	Yes	Maybe	Yes	No	Yes	Maybe	Maybe
Bushings	Yes	No	Yes	No	Yes	Yes	Maybe
Conservator tank	Yes	No	Yes	No	Yes	Yes	Yes
Conservator bladder	No	No	Yes	No	Yes	N/A	N/A
Tap changer	Yes	No	Yes	No	Yes	Yes	Yes
Insulating material	Yes	No	Yes	No	Yes	Yes	Maybe
LPTs	Yes	Yes	Yes	Yes	Yes	Yes	No

3.2.1.3 Large Power Transformer Core

Insignificant global market: There was not a significant global market for large power transformer cores. The data indicated that the market size was approximately $5.3 billion for all transformer cores in 2018 (Research and Markets, 2020). From this data, it is sufficient to state that the LPT core market is a portion of this value yielding a result under the $10 billion requirement.

Uncompetitive cost between U.S. and global manufacturers: It was assumed that the LPT cores supplied by the United States were not competitive with global manufacturers due to the amount of imports (54%) required as compared to domestic supply (U.S. Department of Commerce, 2020).

3.2.1.4 Continuously Transposed Conductor Copper Wire

Unclear significance of domestic demand: CTC copper wire for LPTs could be approximated by using the data point that ~23% of the total cost of an LPT is from copper (U.S. Department of Energy, 2014) and applying that data point to the U.S. LPT market value (Market Research Future, 2021). This yields a value of ~ $601 million. Additionally, another approach was to obtain data for magnetic power cables. This data point showed a value of ~ $25.2 billion in 2019 for energy and industrial applications (Parkhi, 2020). However, the limitation to this data point is that it is not disclosed if the wire in this application consists of only CTC copper wire.

Unclear significance of global demand: It was unclear what the global market size was for CTC copper wire. Applying the same value of ~23% (U.S. Department of Energy, 2014) to the global LPT market value of $15 billion, the derived CTC market value is ~ $3.5 billion. But if the global power transformer of $44 billion is used (Market Research Future, 2021), the estimated CTC market value is at $10 billion, which could be significant.

Unclear cost competitiveness between U.S. and global manufacturers: It was unclear how the cost for domestic and global manufacturers of CTC copper wire compared to each other. Without accurate pricing data and a better representation of the market shares of individual CTC copper wire manufacturers, it is difficult to make any determination.

3.2.1.5 Copper Windings

Unclear significance of domestic demand: It is unclear if the domestic market demand exceeds $1 billion for LPT copper windings. Information through comprehensive literature review indicated a possibility that manufacturing of these windings occurred at the LPT manufacturing stage. However, it was not possible to fully determine if there were external winding manufacturers for LPT manufacturing.

Insignificant global market: One methodology reported in the previous section yielded a value of CTC copper wire for LPTs at ~ $3.5 billion (Market Research Future, 2021; U.S. Department of Energy, 2014). It is unlikely that the value addition required for producing copper windings would exceed $10 billion in global market value.

Unclear cost competitiveness among U.S. manufacturers: There were insufficient data to indicate if the U.S. manufacturers of copper winding were cost-competitive. However, under the assumption that there was vertical integration of the LPT manufacturers to produce transformer copper windings, there were more than three domestic manufacturers of transformer copper windings.

Unclear cost competitiveness between U.S. and global manufacturers: There were insufficient data to indicate if the U.S. manufacturers of transformer copper windings were competitive with global manufacturers.

3.2.1.6 LPT Bushings

Insignificant domestic demand: It was unclear what the domestic demand for LPT bushings quantity yielded. However, the global demand for LPT bushings showed a value of $426 million for all transformer bushings (Precision Reports, 2021) indicating that domestic demand for LPT bushings would be less than this value and therefore less than $1 billion.

Insignificant global market: There was an insignificant global market for LPT bushings with a reported value of $426 million for all transformer bushings (Precision Reports, 2021). This is significantly under the threshold of $10 billion.

Unclear cost competitiveness between U.S. and global manufacturers: It was unclear what the relationship between cost was between U.S. and global manufacturers of LPT bushings. Without accurate pricing data and a better representation of the market shares of LPT bushing manufacturers, it is difficult to make any determination.

3.2.1.7 Conservator Tank

Insignificant domestic demand: It was assumed to be unlikely that the domestic conservator tank market for LPTs was more than $1 billion. This was based on the total domestic LPT market being valued at $2.6 billion (Market Research Future, 2021) making it unlikely that a steel tank would represent over ~60% of the LPT market value.

Insignificant global market: It was assumed to be unlikely that the conservator tank market for LPTs was in excess of $10 billion. This was based on the total LPT market being valued at $15 billion (Global Market Insights, 2021) making it unlikely that a cylindrical, steel tank would represent over ~60% of the LPT market value.

3.2.1.8 Conservator Bladder

Insignificant domestic manufacturers: The data compiled for transformer conservator bladders showed that there were zero manufacturers in the United States. However, it should be noted that it is unclear if the bladder manufacturing has been vertically integrated within the LPT manufacturers business structure.

Insignificant domestic demand: With copper and GOES representing half of the cost of an LPT, it is unlikely a polymer bladder would exceed 1 billion in a $2.6 billion U.S. market (Market Research Future, 2021).

Insignificant global market: It was determined to be unlikely that the conservator bladder market exceeded $10 billion when the total LPT market was only valued at $15 billion in 2020 (Market Research Future, 2021).

3.2.1.9 Tap Changers

Insignificant domestic demand: It is unlikely that with a U.S. market value of $2.6 billion for LPTs (Market Research Future, 2021) tap changers would be worth more than $1 billion.

Insignificant global market: It was assumed to be unlikely that the tap changer market for LPTs exceeded $10 billion. This was based on the total LPT market being valued at $15 billion (Market Research Future, 2021) making it unlikely that the tap changer component would represent over ~60% of the LPT market value.

3.2.1.10 Insulating Material

Insignificant domestic demand: With the global market evaluated at ~ $1 billion (360 Market Updates, 2021), it is sufficient to estimate the domestic demand at a value lower than $1 billion.

Insignificant global demand: The total global market value for insulating paper for electrical applications was estimated at ~ $1 billion (360 Market Updates, 2021) indicating that the global market demand was significantly less than $10 billion.

Unclear cost competitiveness between U.S. and global manufacturers: It was unclear what the cost competitiveness may be between insulating material manufacturers. Without adequate pricing information between domestic and non-domestic manufacturers, it is difficult to make any determination.

3.2.1.11 Large Power Transformers

Uncompetitive cost between U.S. and global manufacturers: It was determined that U.S. manufacturers could not compete with global manufacturers in terms of cost for LPTs. This information was inferred from the quantity of LPTs imported, 82%, and the lack of LPT production capacity utilization (U.S. Department of Commerce, 2020). The U.S. manufacturers only utilized approximately 40% of their production capacity in 2019 indicating that they cannot compete with global manufacturers on price (U.S. Department of Commerce, 2020). Interviews with domestic LPT manufacturers indicated that most of their sales were from within the

United States and that countries such as China, India, Taiwan, and Korea could manufacture transformers 25% or more cheaper than domestically produced transformers. LPTs manufactured in Canada, Mexico and Europe are about 10% less expensive than their counterparts manufactured in the U.S.

3.2.2 LPT Quantitative Assessment Results

The quantitative assessment of the LPT supply chain can be seen in Table 9. The results indicate that the scoring of the supply chain segments at risk, in descending order, are GOES, LPTs, bushings, CTC, tap changers, regular copper, and insulating material. Within the GOES supply chain segment, highest risk scores come from four aspects, including (1) single domestic supplier, (2) no material substitution for GOES used in LPT, (3) potential supply limit due to competing demand from EV application using NOES that can be produced from the same facility as GOES, and (4) the U.S. inability to compete with imported products regarding quantity, prices, and quality. LPT highest supply chain risk scores come from three aspects, including (1) high import reliance, (2) long lead times, and (3) no alternative technology for LPTs. Bushing high risks scores mostly come from high import reliance and long lead time. CTC's highest risk is from not having a substitution to be used for LPT manufacturing. Tap changer's highest risk stems from long lead time. Regular copper and insulating materials have the lowest supply chain risk. It is important to emphasize that the pandemic lengthened lead times for all materials/commodities considered. Stakeholders cited examples of lead time comparison before and after COVID-19 as follows: 5 weeks vs. 12 weeks for GOES, 8 weeks vs. 18 weeks for CTC, 4 weeks vs. 12 weeks for regular Cu sheet, and 6-week increase for tap changers. It is unclear whether longer lead times of 6 – 10 weeks compared to pre-COVID-19 are a "new" normal or the supply chains will get back to normal when the pandemic is over. If the supply chains can bounce back, the quantitative risk listed here will be less severe.

Table 9. Quantitative risk assessment table for different segments of the LPT supply chain.

Risk Metrics	Supply Chain Segments						
	GOES	Refined Copper	CTC Wire	Bushings	Insulating Material	Tap Changers	LPTs
Number of domestic manufacturers	3	1	2	1	1	1	1
Import reliance	2	2	2	3	2	2	3
Number of friendly foreign manufacturers	1	1	1	1	1	2	1
Lead time	2	1	2	3	1	3	3
Technology/material substitution options	3	2	3	2	1	1	3
Limited supply due to other application demand	3	2	1	2	1	1	1
U.S. ability to compete with non-domestic sources	3	1	1	1	2	1	1
Total risk score	17	10	12	13	9	11	13

3.2.3 Large Power Transformer Weakest Links Overview

The weakest links (components and products) identified in the qualitative and quantitative risk assessment were GOES and LPT manufacturing. In the qualitative assessment, weak links could be identified by examining the domestic demand and its supply competitiveness. Categories that had significant domestic demand yet had no domestic manufacturers or an unclear amount of domestic manufacturers or lacked or had unclear cost competitiveness were deemed as weak links. In the quantitative assessment, weak links were identified simply by the total risk score.

3.2.3.1 GOES

GOES 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.

Currently, Cleveland-Cliffs (formerly AK Steel) is the only GOES producer in the United States. With outdated technology and processes, this company is unable to meet the highest specifications required for LPTs by DOE efficiency standards (U.S. Department of Commerce, 2020). When GOES cannot meet higher tolerance and lower loss requirements, LPT manufactures must design larger LPTs which are less cost-competitive and lower performance compared to imported LPTs made from higher quality GOES. GOES is a very competitive market. In 2016, ATI withdrew from this market (360 Research Reports, 2021) and focused on other lower grade or NOES. Recently, U.S. Steel announced its plan to build a 200,000 short tons/year capacity line for NOES at its BRS facility in Arkansas (ArgusMedia, 2021).

The GOES market size in 2020 was estimated at $6.6 billion with a CAGR of < 2% for the next five years (360 Research Reports, 2021). In addition to transformers, GOES is used in power generators, electric motors, reactors and magnetic amplifiers, magnetic sealers, electromagnetic devices for accelerators, mutual inductors, and TV and radio transformers (Baosteel, 2014). In recent years, EVs are a major demand growth driver for electrical steels (Eckard, 2020). If demand for this sector is high, supply of GOES to other sectors will decrease to cater to the EV sector. As reported by stakeholder engagement, global GOES manufacturers have begun replacing part of their GOES production volume with NOES. POSCO, a major global steel maker based in Korea, doubled its NOES annual production capacity from 80,000 tons to 160,000 tons in 2017 (H.-s. Lee, 2017) and planned to build a new factory with 300,000-ton NOES production capacity in 2021 (Hwang, 2021). In parallel, POSCO also planned to cut GOES production to improve its profitability (H.-s. Lee, 2017).

The lack of substitution makes the GOES supply risk worse. Although amorphous steel has gained popularity within the smaller transformer market (Grandview Research, 2018), stakeholders indicated that this material is very delicate to handle, more expensive than GOES and can only be used in distribution transformers. Demand of amorphous steel is declining based on recent customer preferences. As a result, this material will not play a major role in reducing GOES supply constraint.

3.2.3.2 LPT Manufacturing

LPT manufacturing is another weak link in the LPT supply chain caused by high import reliance, long lead time and lacking substitution technologies. Currently, the domestic manufacturers are not able to meet domestic demand and they have under 40% capacity utilization (U.S. Department of Commerce, 2020). It is noted that most transformer manufacturers produce a range of ratings which might include both LPTs and non-LPTs. This strategy of diversifying products might complicate the capacity utilization estimate. Low LPT capacity utilization means that demand for other non-LPT is higher compared to LPT. U.S. companies typically face limitations with testing during LPT manufacturing due to a lack of test beds. Industry interviews have indicated that testing an LPT can take a week while lower rating transformers only take 24 hours. If a facility or manufacturer only has 1 to 2 test beds, their LPT output will limit their non-LPT output significantly. As a result, some manufacturers made a choice to focus on lower rating LPTs. In 2019, 82% of LPTs used in the United States were imported (U.S. Department of Commerce, 2020). Although there are 6 to 8 LPT manufacturers, giving the impression that this market is competitive, the high import rate suggests that LPTs produced domestically are not cost-competitive. This is caused mainly by worker's skill mismatch, high tariffs on imported GOES material, and currency exchange rates according to industry interviews. The issue is exacerbated by lower foreign labor rates, government subsidy and foreign dumping at artificially lower prices (U.S. Department of Commerce, 2020).

Long lead time is also another factor contributing to a high LPT supply risk score. Stakeholders reported that on average, it takes 12 to 16 weeks to manufacture an LPT if all the materials are available. When the assembly is done, it takes one week to test and one week to prepare the LPT for shipping. Typically, transportation time could range from several days to one week for domestic customers. For international shipping, it could take up to 6 weeks. The biggest challenge in transportation is the last 5 to 10 miles from a town with a transportation hub to the substation. On average, transportation time over this distance takes one month, but it could be extended to three months. During COVID-19, both domestic and international logistic delays have been a concern. International shipping can take up to six months. Beyond stakeholders, another source reported that it can take from 5 to 12 months for domestic producers and 6 to 20 months for non-domestic producers to deliver an LPT (U.S. Department of Energy, 2014).

Most LPT producers are vertically integrated. At the very least, they produce cores and windings for LPTs in-house. For companies with a global presence, they would source core materials from countries with lower prices so that their final LPT products are cost competitive. Domestic LPT manufacturers do not have that advantage due to high tariffs rates on imported GOES and a lack of domestic GOES manufacturing capability. Domestic manufacture interviews revealed a significant decrease in foreign sales citing the GOES tariffs and currency exchange rates as the most significant factors. Tariffs on GOES have made domestic transformer manufactures less competitive globally because manufacturers in countries without tariffs incur less material cost. Also, some domestic LPT manufacturers highly rely on the foreign manufacturers of GOES, up to 100% (U.S. Department of Commerce, 2020).

The last supply chain risk comes from lacking substitution for LPTs. LPT is a mature technology at current state of technology and the grid will continue to rely on this device type to build critical infrastructure. Lacking substitute is not necessarily a bad thing, but it suggests that when there is a bottleneck in this supply chain, there needs to have mitigation measures. These measures could include ways to reduce lead time bottlenecks (both in manufacturing and transportation), reduce material density used in LPTs, and reduce import reliance.

3.3 High-Voltage Direct Current System Risk Assessment Results

3.3.1 HVDC Qualitative Results

Table 10 displays the results of the seven criteria described in Section 3.1 for HVDC supply chain. The major components of HVDC stations were identified to be converters, DC breakers (switchgear), DC filters, AC switches/breakers, IGBTs, capacitors, inductors, and surge arrestors. Explanations for relevant supply chain segments with a 'no' assessment are provided below. For all the 'maybe' assessments, insufficient data was found to support a 'no' or a 'yes' answer.

Table 10. Evaluation results for HVDC supply chain.

Component/product	Significant domestic manufacturers	Significant domestic demand	Projected significant domestic demand	Significant global market	Projected significant global demand	Cost-competitive among U.S. manufacturers	Cost-competitive between U.S. manufacturers vs. global manufacturers
Converter	No	No	Yes	Yes	Yes	N/A	N/A
DC breakers (switchgear)	No	No	Maybe	No	Yes	N/A	N/A
DC filters	No	No	Yes	Yes	Yes	N/A	N/A
AC switchyard	No	No	Yes	Yes	Yes	N/A	N/A
AC switch/ breaker	Yes	Maybe	Yes	No	Yes	Yes	Yes
IGBT	No	No	Yes	Yes	Yes	N/A	N/A
Capacitor	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Inductor	No	Yes	Yes	Yes	Yes	N/A	N/A
Arrestor	Yes	No	Yes	No	Yes	Yes	Yes

Because of a small number of HVDC projects in the United States, demand for converters, DC breakers, DC filters, AC switchyard and IGBTs is almost non-existent. This leads to no significant domestic manufacturers for those components. Leading global suppliers such as Hitachi Energy, GE, and Siemens Energy have a U.S. presence in other areas, but their HVDC facilities are in Asia and Europe. It is noted that although AC switches/breakers, capacitors and arrestors have sufficient U.S. supply currently, the final assembly is done in the United States using imported parts, according to interviews.

3.3.1.1 DC Breakers

Insignificant domestic demand: The United States does not have significant demand for DC breakers due to lacking multi-terminal HVDC projects.

Insignificant global market: HVDC breaker (switchgear) is still not widely utilized in practical HVDC projects due to technological limitations.

3.3.1.2 HVDC Inductors (Reactors) and Capacitors

Insignificant domestic manufacturers: Leading global suppliers such as Hitachi Energy, GE, and Siemens Energy have U.S. presence in other areas, but their HVDC facilities are in Asia and Europe.

3.3.1.3 AC Switch/Breaker

Insignificant global market: The total size of the global switch market for all voltage categories was $9.8 billion in 2018 (Allied Market Research, 2018) and breakers for high-voltage in 2019 was evaluated at $2 billion (Gaurav, 2020). Consequently, the global market of high-voltage switches is insignificant.

3.3.1.4 Arrester

Insignificant global market: The size of the global market of arresters (include all voltage categories) was only $2.4 billion in 2020 (Grand View Research, 2021). As a result, the market size for high-voltage arresters is not significant.

3.3.2 HVDC Weakest Links Overview

The global HVDC market was approximated at $8.2 billion in 2018 with projections to reach $12.3 billion by 2024 (Markets and Markets, 2019). From 2010 to 2017, the United States only represented 6.7% of the total HVDC global transmission capacity (Alassi et al., 2019). The manufacturing of critical components at a converter station for HVDC systems is almost non-existent in the United States. Major companies such as GE, Hitachi Energy and Siemens Energy have production capability based in Europe or Asia where the demand is. Without a significant domestic demand, HVDC manufacturers lack incentive to establish U.S. based manufacturing facilities.

As the world seeks to adopt more carbon-neutral energy sources, demand for HVDC devices will increase and procuring these devices with no domestic manufacturing may be more challenging. There may be a higher risk of failed projects due to delays associated with a heavy dependance on foreign markets and limited global production capacity. Additionally, industry interviews revealed offshore wind is expected to be a fast-growing HVDC market, but a limited number of undersea cable laying vessels (only seven in the world) could also create bottlenecks for projects (Cowan, 2021). Despite this increase in demand from the U.S. offshore wind market, manufactures are skeptical it will generate enough business to justify building manufacturing plants in the United States. The lack of U.S. electrical grid investment into HVDC projects is the main driver stunting domestic manufacturing capabilities.

4 U.S. Opportunities and Challenges

4.1 U.S. Opportunities in LPTs

4.1.1 Prioritization in the Short, Medium, and Long Terms

Short-term efforts should be focused on improving the domestic capabilities (quantity and technological prowess) of GOES production. With only one GOES producer in the United States, the United States is highly vulnerable to supply chain disruptions. The current domestic GOES producer has stated that GOES production is not profitable due to competitive products from other countries (U.S. Department of Commerce, 2020). Regardless of LPT manufacturing capabilities, without domestic GOES production capabilities, LPT manufacturers will be dependent on foreign sources. In 2020, 85% of imported GOES came from South Korea, 6% from Brazil and 4% from Russia (USA Trade Online, 2021). Although the largest supplier is from South Korea – a friendly country – their recent move of expanding production capacity of NOES to serve the EV sector and reduce GOES production for transformers causes concerns for LPT manufacturers of upcoming GOES supply shortage. BRS was acquired by U.S. Steel and has invested in top-notch technology (ArgusMedia, 2021). Their current product is NOES, serving the EV market. Interviews indicated that this company has an intention to invest in the GOES business but still undecided due to domestic demand uncertainty. If the company has support to ensure guaranteed domestic demand or capital subsidy in the form of tax credits, tax breaks or low interest loans, similar to the American Recovery and Reinvestment Act (ARRTA) of 2009 mentioned in Section 4.3, to upgrade their manufacturing capability using the most advanced technology, their GOES operation will reduce the U.S. vulnerability significantly. A positive thing stakeholders indicated was that diversifying supply sources has been their major strategy to reduce global supply chain risks. As a result, they will always procure GOES from domestic manufacturers despite higher prices. This base demand from domestic LPT manufacturers would help facilitate new capacities.

Medium-term efforts should be focused on decreasing the import quantity of LPTs and increasing the capacity utilization of the domestic LPT manufacturers in the United States. Literature indicated that imports account for 82% of the consumption of LPTs in the United States (U.S. Department of Commerce, 2020). Over 70% of imported power transformers are from friendly countries, which does not pose a supply chain risk. However, as mentioned above, long LPT lead time due to overseas transportation could be a major bottleneck due to potential disruptions as witnessed during COVID-19. In 2010, there were six companies in the United States that produced LPTs with a capacity utilization of approximately 40% (U.S. Department of Commerce, 2020). These companies have consistently produced between 122 and 153 LPT units annually between 2015 and 2019 (U.S. Department of Commerce, 2020). Reliance on foreign countries for LPT supply leaves the bulk power system vulnerable due to the aging LPT infrastructure in the United States. The average age of installed LPTs in the United States is approximately 38 to 40 years, and the suggested lifespan of a transformer is 20-25 years. Currently, more than 70% of U.S. LPTs are aged more than 25 years (U.S. Department of Energy, 2014). Additionally, growth of electricity demand due to electrification and decarbonization efforts would translate into an increased need for domestic LPT manufacturing.

Another medium-term focus is workforce training. At a high level, the United States need to promote the energy industry in high school, college, and university curricula to draw a larger and more diverse group into the professional fields of power and electrical engineering. Craft labor is a national problem that could benefit from some early education exposure and programs blended into the schools to allow for hybrid learning and exposure to a multitude of career options. Apprenticeships in collaboration with industry can provide technical certificates to address the industry needs. Partnerships with industry to gain additional funding for local trade schools can be helpful to creating a broader labor pool. Incentives to offset increasing wages and skill gaps may be of assistance.

Long-term efforts should be focused on R&D to improve efficiency, improve modularity, and lower domestic manufacturing costs of LPTs and related materials. First, advanced manufacturing of hollow transformer cores show promise to solve GOES shortages and reduce transformers weight. Hollow or porous transformer cores require less material to manufacture and thus could ease up limited material supplies from a transformer manufacturers perspective. Currently, hollow cores have managed to match the performance of NOES, but additional research is needed to match the performance of laminated GOES cores (Plotkowski et al., 2020). Further research into this technology could spark new domestic manufacturing capabilities of novel GOES products. Second, modular controllable transformer (MCT) offers some opportunities. MCT leverages three smaller transformers, which has the added advantage of increased system reliability (Kandula, Divan, Jinsiwale, & Mauger, 2018). A back-to-back converter is used to enable the transformers to accommodate a wide variety of substation environments by adjusting impedance, power flow, and voltage. The main drawback of this strategy is that it would require more real-estate with a substation. The real-estate issue could be lessened by leveraging work done by GE on designing a truly universal transformer, which does not require a separate back-to-back converter (Ndiaye, 2019). This universal transformer takes up the same space as its traditional transformer counterparts (Kellner, 2021). The universal transformer can adjust its short-circuit impedance such that it is able to accommodate a wide range of substation locations. This universal transformer could be leveraged to reduce the number of spare transformers inventory needed by utilities and thus reduce demand on a limited GOES supply. Third, flexible LPTs allow the implementation of a system to select transformer leakage impedance while simultaneously holding constant the configured voltage ratio (Ndiaye, Betancourt Ramírez, Avila Montes, Jiang, & Elasser, 2019). This is accomplished through multiple low voltage side transmission class taps to make the transformer flexible (Ndiaye et al., 2019). Increased R&D

could help the U.S. supply by reducing the demand for spare LPTs and increasing the manufacturing capacity of LPTs by reducing the amount of custom design required per LPT.

4.2 U.S. Opportunities in HVDC Supply Chain

4.2.1 Prioritization in the Short, Medium, and Long Terms

Short-term efforts should be focused on increasing the domestic HVDC demand. HVDC is a key transmission technology supporting the 30 GW of offshore wind deployment by 2030 (Department of Energy, 2021). Near-term growth in HVDC projects supporting connection of offshore wind is expected. From a national grid perspective, at some point, offshore wind will need to connect with the rest of the grid on land, which would require onshore HVDC systems as the backbone not only for delivering energy to distant users but also improving grid resilience, security, and flexibility.

Medium-term efforts should be focused on increasing R&D investment and workforce training. Areas of R&D investment include grid interconnection, cost feasibility, grid stability, harmonics, power quality, grid control and resilience, HVDC grid maintenance, and life cycle management. HVDC equipment such as the HVDC breaker (switchgear) and HVDC converter also needs further R&D support to accelerate commercialization. Additionally, it is important to train the workforce for design, installation, maintenance, and eventually manufacturing, especially focusing on >100 kV high-voltage power system/equipment with on-site experiences. During this time frame, there might be growth in HVDC demand. However, foreign friendly suppliers can be utilized for HVDC component sourcing.

Long-term efforts should be focused on increasing the domestic HVDC component manufacturing in the United States. Once demand is substantial, it will make the business case for manufacturers to locate their facilities in the United States to reduce distribution and related costs. Additionally, supply chain vulnerabilities can be reduced by increasing domestic production of HVDC components. One such example is semiconductors. Using the U.S. domestic manufacturer GE as an example, the IGBT manufacturers for GE are still mainly from Europe because of the high demand of European HVDC markets and the completeness of the EU supply chain. It is important to support U.S. domestic downstream semiconductor manufacturing serving HVDC systems through demand stimulation, tax breaks during production ramp-up period, and other policy means that do not violate World Trade Organization fair-trade agreement similar to ARRTA of 2009.

Stakeholders also suggest another long-term strategy for a National Transmission Plan. This plan should identify corridors that have priority for developing transmission projects. This will help reduce the number of stakeholders required to approve a transmission project. One example cited by stakeholders is that a multi-country HVDC project in Europe only requires half of the stakeholders needed for an HVDC project that spans two U.S. states. Due to a reduced number of stakeholders, Europe can bring certainty of construction to award projects. In addition, if RTO collaboration challenges are not solved, it is very likely that large-scale onshore U.S. HVDC demand will stay stagnant for the next decade. A National Transmission Plan could also be leveraged to identify which existing transmission HVAC lines could better benefit the bulk power system by being converted to HVDC lines. The process of converting existing HVAC lines to HVDC would be simpler and faster compared to constructing new HVDC lines. This conversion would also increase transmission capacity, reduce system losses, and improve overall system stability.

4.3 Existing Programs and Policies to Address Supply Chain Risk and Vulnerabilities

Energy Act of 2020: The Energy Act of 2020 was signed into law on Dec. 27, 2020 (Viola, McDonald, & Lane, 2021). This legislative package authorized $2.3 trillion in spending, however, not all of it was directly allocated for energy efforts (Viola et al., 2021). Many different highlights exist for DOE programs with allocation of funds going to topics such as renewable energy, energy storage, carbon capture, critical minerals, nuclear energy, financing and technology transfer, industrial emissions reduction, and grid modernization (Viola et al., 2021). Title VI describes enhancing the efficiency and productivity of industrial and manufacturing technology for many sectors such as aluminum, cement, and steel relevant to the HVDC and transformer markets. Title VII promotes R&D for critical materials (e.g., rare earth elements and minerals) recycling. HVDC products may contain rare earth elements in them. Transformer manufacturing is also dependent on mineral supply chains.

Steel and Aluminum Tariffs: In March 2018, the United States imposed tariffs on steel (25%) and aluminum (10%) from most countries, along with tariffs on other imported goods. The tariffs caused trade disputes with India, China, the European Union, Canada, Mexico, and many other nations. Many of these nations retaliated with tariffs of their own starting the trade wars of 2018 and 2019. Eventually Mexico, Canada, Argentina, Brazil, South Korea, and Australia were exempted from these tariffs (Horsley, 2018). Steel and aluminum tariffs could be viewed as either an opportunity or a challenge depending on the stakeholders. This creates an opportunity for the only domestic GOES producer. However, from an overall LPT supply chain, increased material cost makes the final LPTs less cost-competitive compared to countries without the tariffs.

Trade Adjustment Assistance (TAA) Program: this program was established under the Trade Adjustment Assistance Reauthorization Act of 2015. This Act aids workers affected by foreign trade. Benefits include financial aid to training, job search and relocation allowances, income support and other reemployment services (U.S. Department of Labor, n.d.).

American Recovery and Reinvestment Act (ARRTA): This Act was passed in 2009 after the Great Recession in 2008. Section 48C outlined tax credits for manufacturing facilities of clean energy products such as electric grids and storage for renewables, equipment for energy conservation and other advanced energy property designed to reduce greenhouse gas emissions (Congress, 2009).

Small and Medium-Sized Business Initiative: The Office of the U.S. Trade Representative (USTR) has implemented this initiative to support U.S. small and medium enterprise's ability to increase export opportunities (United States Trade Representative, 2021). USTR supports this initiative by improving information availability, leveraging new technology applications, and empowering local export efforts (United States Trade Representative, 2021). Additional offices and agencies assisting in the effort include the U.S. Small Business Administration and the U.S. Departments of Agriculture and Commerce (United States Trade Representative, 2021).

America's Seed Fund: The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs support startups and small businesses to partner with R&D organizations for commercialization (U.S. Small Business Administration, 2022). These programs are competitive awards-based with three phases. Phase one is to establish technical merit, feasibility, and commercial potential. Funding amount varies from $50,000 to $250,000 for six-month SBIR or one-year STTR awards. Phase two is to continue phase one efforts. Funding amount is $750,000 for two years. Phase three is for small businesses to pursue commercialization resulted from phase one and two achievements. Funding for SBIR program comes from Federal agencies with R&D budgets above $100 million. Funding for STTR program comes from Federal agencies with R&D budgets above $1 billion. Eleven federal agencies are participating in the SBIR program, with five of those agencies participating in the STTR program (U.S. Small Business Administration, 2022).

Energy policy Act of 2005: This Act was signed by President Bush in 2005 to address energy production in the United States. Federal power of eminent domain may be used to acquire electric transmission rights-of-way in areas designated as congested by the Secretary of Energy. Tax reductions are provided to domestic energy production and energy efficiency (Congressional Research Service, 2006).

4.4 Challenges That Prohibit Realizing These Opportunities

4.4.1 Overall Challenges

In LPTs, significant investment would be required to upgrade the current GOES producer's facility to output the higher grades of GOES required for current DOE energy standards to increase energy efficiency. Additionally, increasing diversity of domestic GOES supply is challenging with only one current GOES producer without significant investment. Foreign competition is a major challenge to GOES and LPT production as companies in other countries benefit from subsidies and government protection (U.S. Department of Commerce, 2020). Lastly, LPT manufacturers reported continuing labor challenges with an aging workforce and difficulty attracting and retaining younger workers (U.S. Department of Commerce, 2020). Workforce concerns continue to be an issue confirmed by stakeholder engagement as LPT manufacturers often see gaps between existing and necessary skills in prospective employees. This is true for shop floor labor and engineering labor. These companies believe that power system engineering is not in high demand as other fields within electrical engineering such as electronics and computer science. Even within the field of power systems engineering, more research and education focus has been on microgrid and other forms of renewable energy than transformer design and manufacturing.

In HVDC projects, stakeholders raised concerns about collaboration among RTOs. For large transmission projects, RTOs need to work together to exchange data and technical details. However, RTOs do not necessarily have incentives to pursue transmission projects beyond their regions. If an RTO is interested in a transmission project, they face obstacles in obtaining data from utility companies in another RTO. Another aspect related to RTO is lacking HVDC expertise. Similar to the case of LPT, there are very few people trained in HVDC systems in the United States. For projects that require interconnect, without proper expertise, the uncertainty of a project gets higher, with longer delays in technical design, installation, and operation.

Another concern is cost recovery of an HVDC project. Like a tollway project, HVDC projects can only recover cost by getting new users who are willing to pay more to get better services. Since utilities are managing cost well to reduce energy cost, it is hard for a new HVDC project to compete. As a result, forecasting the demand and build a new customer base seems to be difficult.

4.4.2 Current Policies in Other Countries

4.4.2.1 China's Subsidies on Steel

China's subsidies on steel have led to steel production which exceeds market demand (United States - China Economic and Security Review Commission, 2020). In 2020, the crude steel production increased in China by 5.2% compared to 2019, with a total production of 1,053 Mt while other countries cutback on production in response to market demand. The United States reduced crude steel production by 17.2% compared with 2019, which sums to 72.7 Mt for 2020 (World Steel Association, 2021). The European Union, India, and Japan also decreased production in 2020 by over 10% in response to market demand (World Steel Association, 2021). While businesses in other countries respond to declining market demand, China increases production and uses subsidies to offer lower prices for steel.

Additionally, government incentive programs have led to an increase in global capacity for manufacturing crude steel despite decreasing steel production and demand. Specifically, China's foreign investments in Southeast Asia are contributing to additional capacity development which is unbalanced by regional demand (OECD, 2021). Investments by local companies and foreign investors, including China, are expected to result in more than 60 Mt in total excess capacity in Southeast Asia by 2026, where demand is estimated to eventually reach that capacity level in 20 years (OECD, 2021). Globally, the gap between steelmaking capacity and crude steel production is also increasing from 568.7 Mt in 2019 to 624.9 Mt in 2020 (OECD, 2021).

China began steel capacity swap program in 2015 establishing grants for replacing old steelmaking facilities with new equipment. A hold was placed on the program in 2020 when some steel mills were found taking advantage of the program to expand production capacity. A revised swap scheme has been proposed to fix the loophole in the previous program and continue upgrading China's steelmaking facilities (OECD, 2021).

4.4.2.2 China's Semiconductor Incentives

Higher labor costs and fewer government incentives make the United States less attractive for establishing new semiconductor manufacturing facilities. China's incentives programs have led to increased semiconductor manufacturing capacity while the U.S. global capacity share is declining (Varas, Varadarajan, Goodrich, & Yinug, 2020). China's incentives for building new semiconductor manufacturing facilities can cover 30-40% of costs during the first 10 years of operation while U.S. incentives are estimated to cover only 10-15% of costs (Varas et al., 2020). Israel, South Korea, Taiwan, and Singapore government incentives cover 25-30% of initial costs (Varas et al., 2020). Due to China's incentive programs, China is expected to have the most growth in semiconductor manufacturing capacity over the next decade, growing from about 15-24% of the global capacity share (Varas et al., 2020).

5 Conclusion

In this report, we studied supply chain issues and opportunities of LPTs and HVDC systems, two crucial elements of the U.S. electric grid. Both elements are currently facing complex challenges with a strained or virtually non-existent domestic manufacturing. Over 90 percent of the power consumed by the nation passes through LPTs making it one of the most critical components of the power grid. The need to modernize and increase the capacity of the power grid is growing due to increased energy demand, aging infrastructure, grid resilience and security requirements and global and national clean energy goals. HVDC transmission is a new technology and potentially can play an important role for the United States to achieve 100 percent carbon-free electricity by 2035, and net zero economy by no later than 2050.

As part of supply chain mapping, we investigated different supply chain segments, including raw material manufacturers, component manufacturers, transformer manufacturers, end-users, recyclers and re-manufacturers. By analyzing the latest available data and U.S. manufacturer's engagement, we identified the supply chain bottlenecks of the United States.

The key findings for the LPT supply chain can be summarized as below:

- The weakest links (components/products) identified in the risk assessment were GOES and LPT manufacturing.
- EVs are a major demand growth driver for electrical steel. Although the EV industry uses NOES, the manufacturing capacity of GOES could significantly be impacted since both GOES and NOES come from the same manufacturing facilities.
- Regardless of LPT manufacturing capabilities, without improving domestic GOES production capabilities, LPT manufacturers will be dependent on foreign sources.
- The U.S. manufacturers of LPTs are not competitive compared to the global manufacturers because of multiple issues including workforce skill gaps, high capital investment, lacking test space, and unstable material costs.

The key findings for the HVDC supply chain can be summarized as below:

- Leading HVDC suppliers are present in the United States. However, their manufacturing plants are based in Asia and Europe where most demand resides.
- The semiconductor required for manufacturing HVDC converters are not manufactured in the United States, either.
- As the world seeks to adopt more carbon-free electricity, demand for HVDC devices will increase, and procuring these devices with no local manufacturers will be more challenging and make the United States heavily dependent on foreign markets and politics.
- Lacking RTO collaboration and unclear cost recovery prospects for HVDC projects cause slow demand growth. Currently, demand for HVDC in the U.S. is much lower compared to Asia and Europe.

We expect that this study would be a useful document to understand the opportunities and vulnerabilities of the LPT and HVDC supply chains and assist in prioritizing the short-, medium-, and long-term strategies to make the supply chains more competitive, secured, and reliable.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

6 Appendix: Additional Patent Data

This appendix contains additional patent data and charts. Patsnap was used as a tool to search 126 databases and find relevant applications.

Section 1: Large Power Transformers Patent Data

Dataset Information:
Query: ((("large power transformer" OR "large-scale power transformer") AND TA:(transformer) AND (APD:[20010101 TO *]))) NOT ("elimination of large power transformers")
Data Grouping: One document per application
Stemming: On
Data Range: Searched from 126 databases and found 318 applications

318 published patent applications related to LPTs were identified and analyzed for this report. The analyzed patent applications include applications with an application date after January 1, 2001, and publication date before December 1, 2021, which also contained the keyword "transformer" in the title or abstract and "large power transformer" or "large-scale power transformer" anywhere in the application but did not include "elimination of large power transformers" in the text.

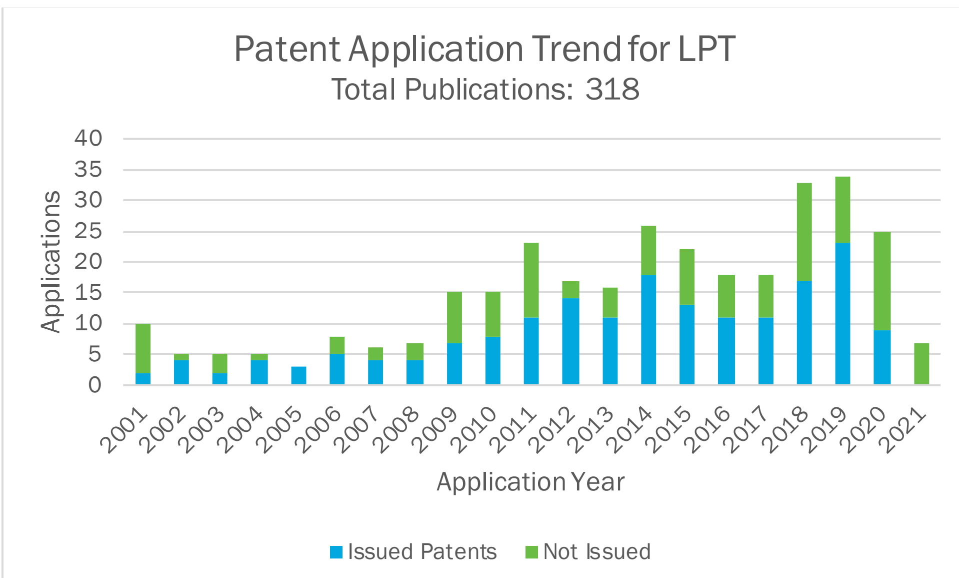

Figure A 1. Patent application trend for LPTs.

This figure shows the patent application and patent issuance trend for LPTs since 2001. Lower application numbers are expected in this figure during 2020 and 2021, because not all applications have published. Many of the unissued patents are being prosecuted, and it can take many years before a patent application issues.

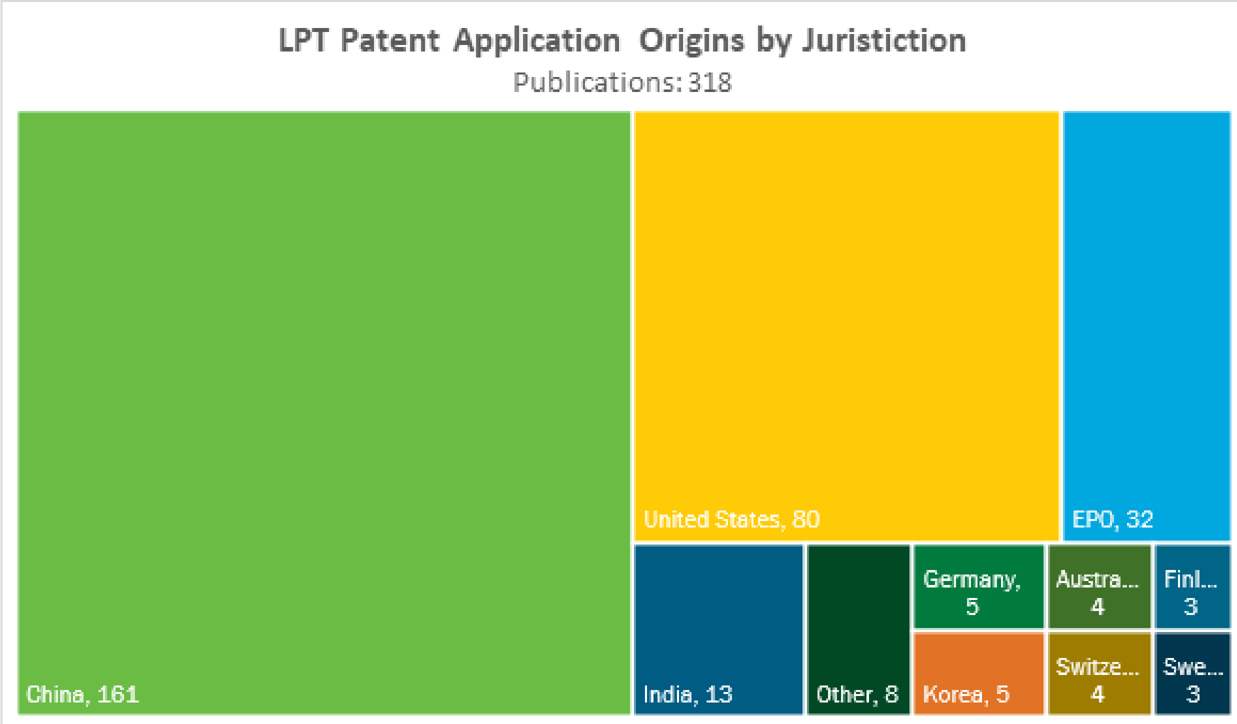

Figure A 2. LPT patent application origins by jurisdiction.

This figure shows the country in which the earliest application was filed for each technology. This data could indicate that either companies located in these countries are innovating in this area or that these are the countries which companies want to first capitalize in. 50.63% of original filings were in China, 25.16% of original filings were in the United States, and 10.06% of original filings were with the EPO.

Section 2: HVDC Patent Data

HVDC Converter:

Dataset Information:
Query: (TA:(("high-voltage direct current") OR ("high-voltage dc") OR hvdc)) AND TA:(converter OR rectifier OR inverter) AND (grid OR utilities OR ("power system" OR "power transmission system" OR "power transmission" OR "transmission line") OR ("power transmission network") OR utility) AND (APD:[20010101 TO 20211201])
Data Grouping: One document per application
Stemming: On
Data Range: Searched from 126 databases and found 1,909 applications

1,909 published patent applications related to HVDC converters were identified and analyzed for this report. The analyzed patent search results include applications with an application date after January 1, 2001, and publication date before December 1, 2021, which contained these keywords in the title or abstract:
1) converter, rectifier, or inverter, and 2) HVDC, high-voltage dc, or high-voltage direct current while also including one of these keywords anywhere in the application: grid, utility, utilities, power system, power transmission system, power transmission, transmission line, or power transmission network.

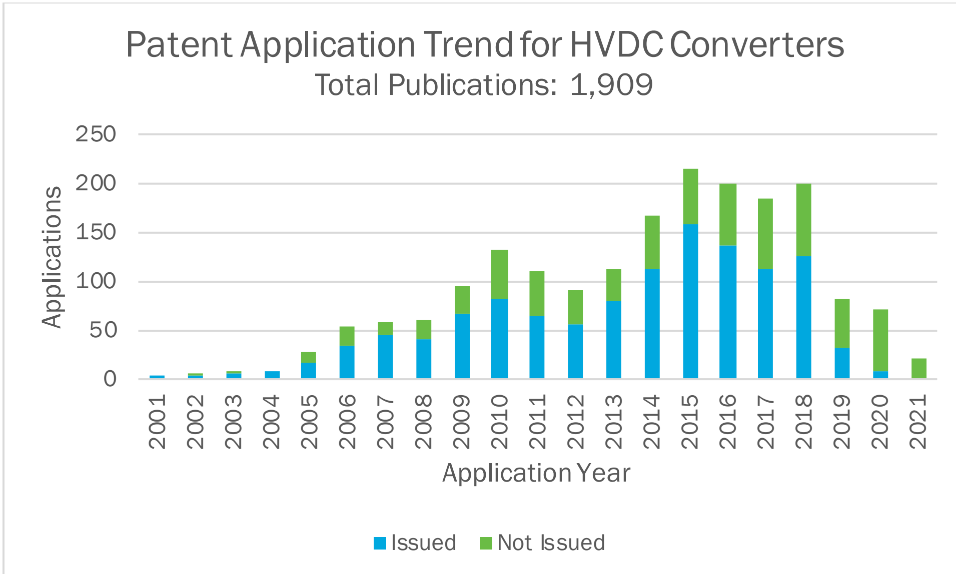

Figure A 3. Patent application trend for HVDC converters.

This figure shows the patent application and patent issuance trend for HVDC converters since 2001. Lower application numbers are expected in this figure during 2020 and 2021, because not all applications have published. Many of the unissued patents are being prosecuted and it can take many years before a patent application issues.

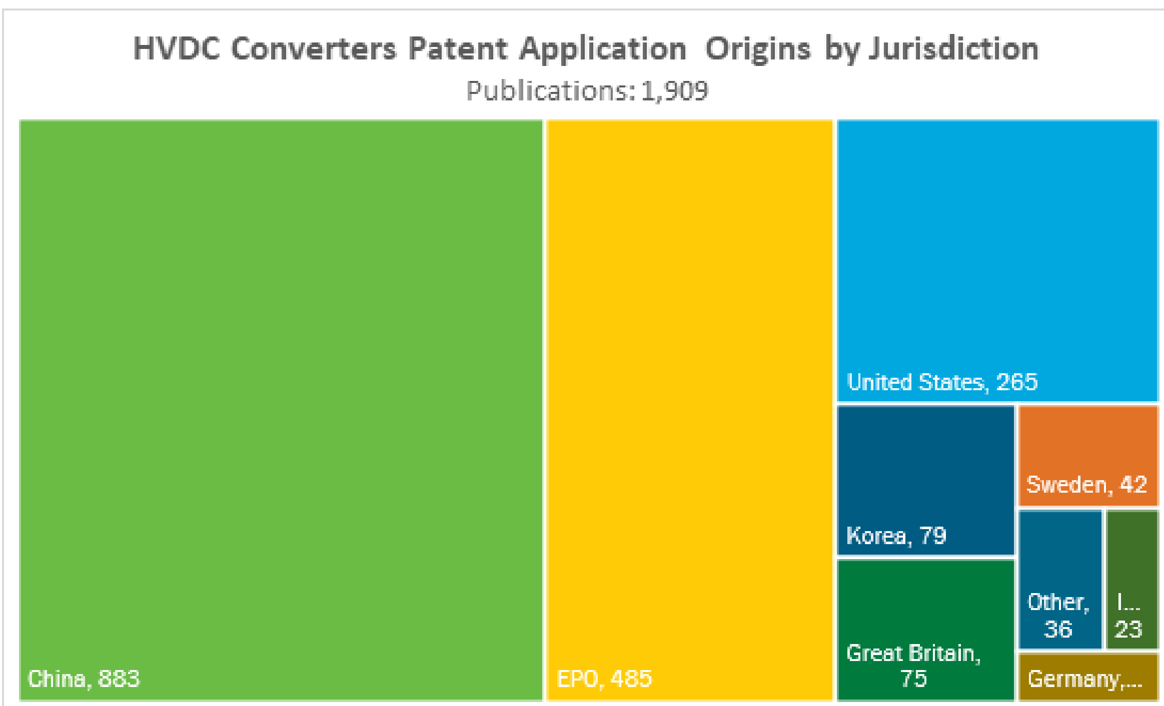

Figure A 4. HVDC Converter patent application origins by jurisdiction.

This figure shows the country in which the earliest application was filed for each technology. This data could indicate that either companies located in these countries are innovating in this area or that these are the countries which companies want to first capitalize in. Countries with less than ten patents are included under Other. 46.25% of original filings were in China, 25.41% of original filings were with the EPO, and 13.88% of original filings were in the United States.

DC Switchgear (Breakers):

Dataset Information:
Query: (((TA:((dc OR "direct current") AND (breaker OR switchgear))) AND (hvdc OR ("high-voltage dc") OR ("high-voltage direct current")) AND (APD:[20010101 TO 20211201])) NOT (battery))
Data Grouping: One document per application
Stemming: On
Data Range: Searched from 126 databases and found 764 applications

764 published patent applications related to DC switchgear were identified and analyzed in this report. The analyzed patent search results include applications with an application date after January 1, 2001, and publication date before December 1, 2021, where the title or abstract contained 1) DC or direct current and 2) breaker or switchgear, while also including HVDC, high-voltage dc, or high-voltage direct current anywhere in the application and excluding patents mentioning the keyword battery to return more relevant results.

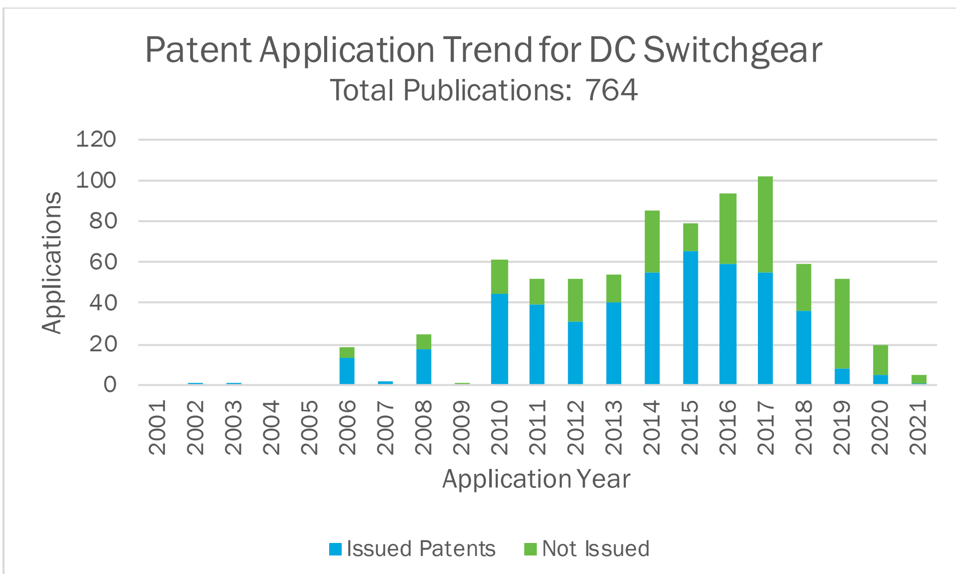

Figure A 5. Patent application trend for DC switchgears.

This figure shows the patent application and patent issuance trend for DC switchgear (breakers) since 2001. Lower application numbers are expected in this figure during 2020 and 2021, because not all applications have published. Many of the unissued patents are being prosecuted and it can take many years before a patent application issues.

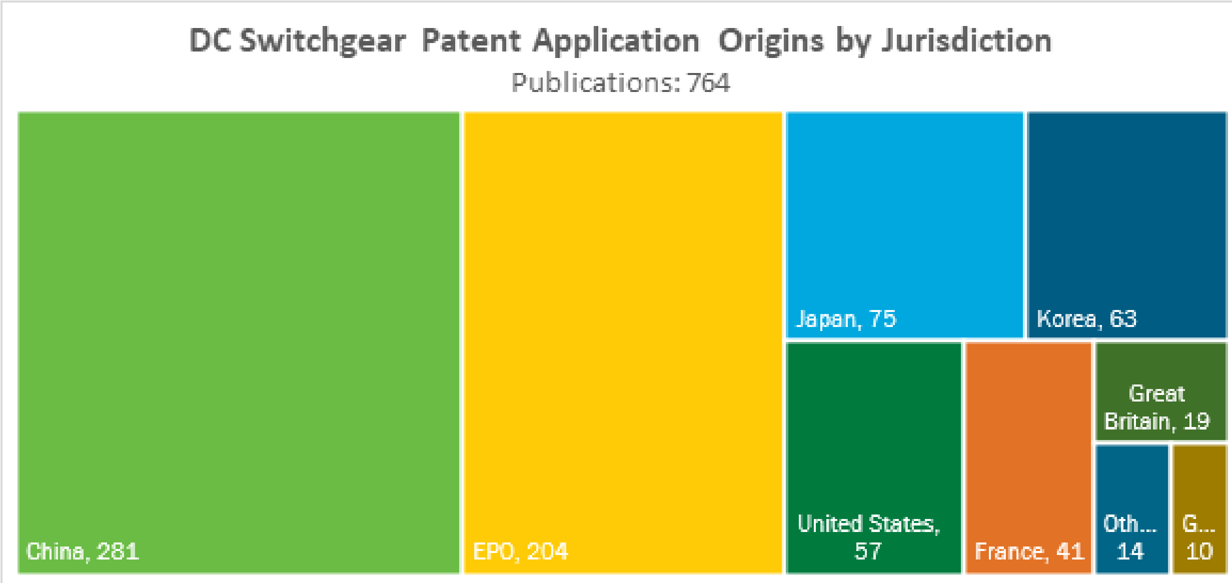

Figure A 6. DC switchgear patent application origins by jurisdiction.

This figure shows the country in which the earliest application was filed for each technology. This data could indicate that either companies located in these countries are innovating in this area or that these are the countries which companies want to first capitalize in. Countries with less than ten patents are included under Other. 36.78% of original filings were in China, 26.70% of original filings were with the EPO, 9.82% of original filings were in Japan, 8.25% of original filings were in South Korea, and 7.46% of original filings were in the United States.

DC Filters:

Dataset Information:
Query: ((TA:(("high-voltage" OR “high-voltage dc” OR hvdc) AND ("direct current" OR dc))) AND TITLE:(filter) AND (grid OR utility OR utilities OR ("power system" OR "power transmission system" OR "power transmission" OR "transmission line") OR ("power transmission network"))) AND (APD:[20010101 TO 20211201])
Data Grouping: One document per application
Stemming: On
Data Range: Searched from 126 databases and found 102 applications

102 published patent applications related to DC filters for use with HVDC were identified and analyzed for this report. The analyzed patent applications include applications with an application date after January 1, 2001, and publication date before December 1, 2021, which contained filter in the title, DC or direct current and HVDC, high-voltage dc, or high-voltage direct current within the title or abstract, and included at least one of the following keywords anywhere in the application: grid, utility, utilities, power system, power transmission system, power transmission, transmission line, or power transmission network.

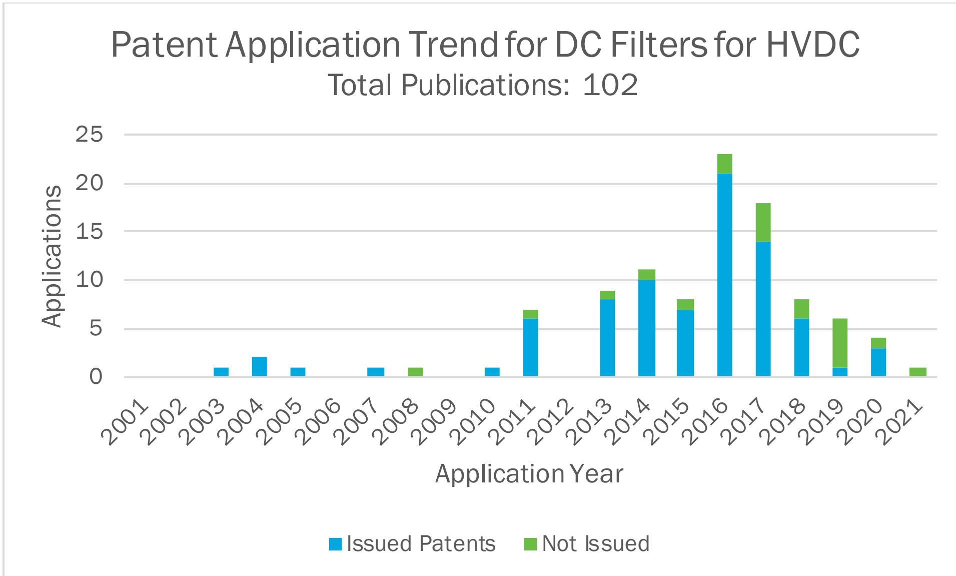

Figure A 7. Patent application trend for DC filters for HVDC systems.

This figure shows the patent application and patent issuance trend since 2001 for DC filters for use with HVDC. Lower application numbers could be expected in this figure during 2020 and 2021, because not all applications have published. Many of the unissued patents are being prosecuted and it can take many years before a patent application issues.

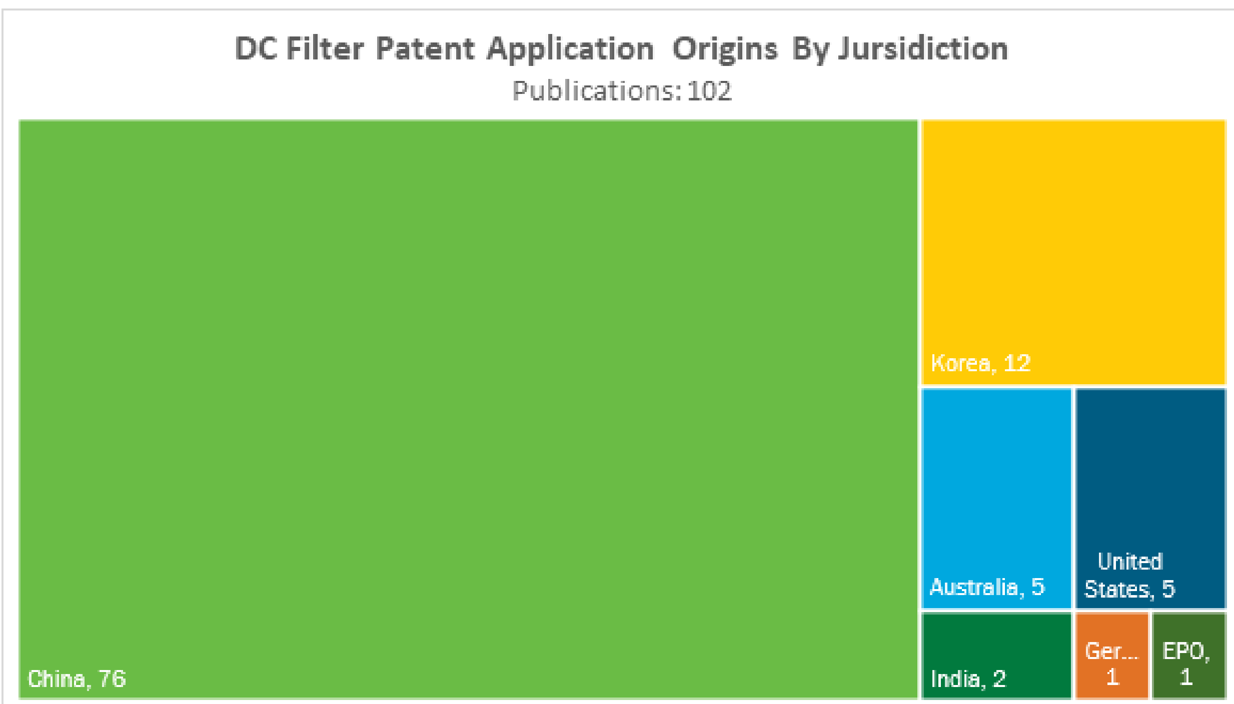

Figure A 8. DC filter patent application origins by jurisdiction.

This figure shows the country in which the earliest application was filed for each technology. This data could indicate that either companies located in these countries are innovating in this area or that these are the countries which companies want to first capitalize in.

AC Switchyards:

Dataset Information:
Query: (TA:(switchyard) AND (APD:[20010101 TO 20211201])) AND (PBD:[* TO 20211201])
Data Grouping: One document per application
Stemming: On
Data Range: Searched from 126 databases and found 138 applications

138 published patent applications related to AC switchyards were identified and analyzed for this report. The analyzed patent search results include applications with an application date after January 1, 2001, and publication date before December 1, 2021, where the title or abstract contained the keyword switchyard.

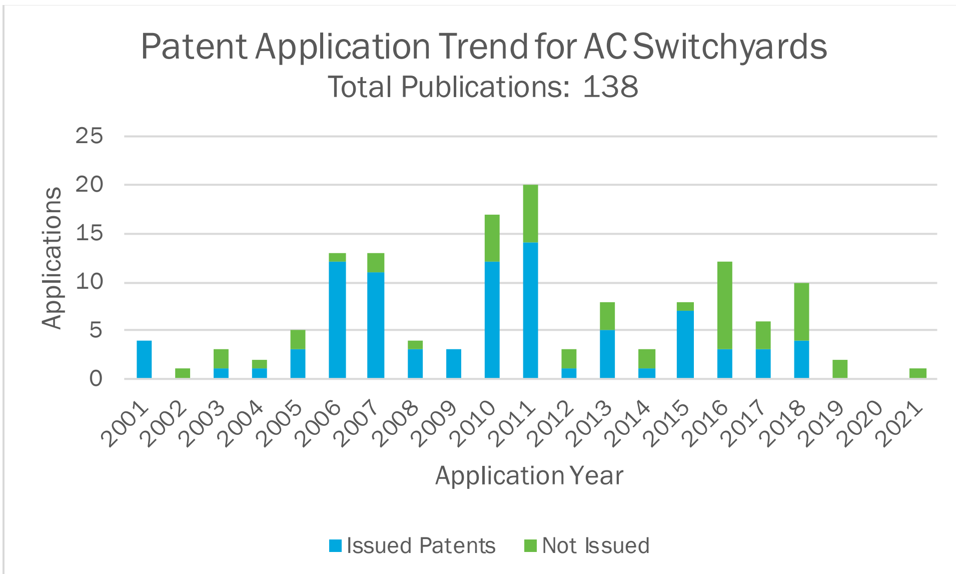

Figure A 9. Patent application trend for AC siwtchyards.

This figure shows the patent application and patent issuance trend for AC switchyards since 2001. Lower application numbers are expected in this figure during 2020 and 2021, because not all applications have published. Many of the unissued patents are being prosecuted and it can take many years before a patent application issues.

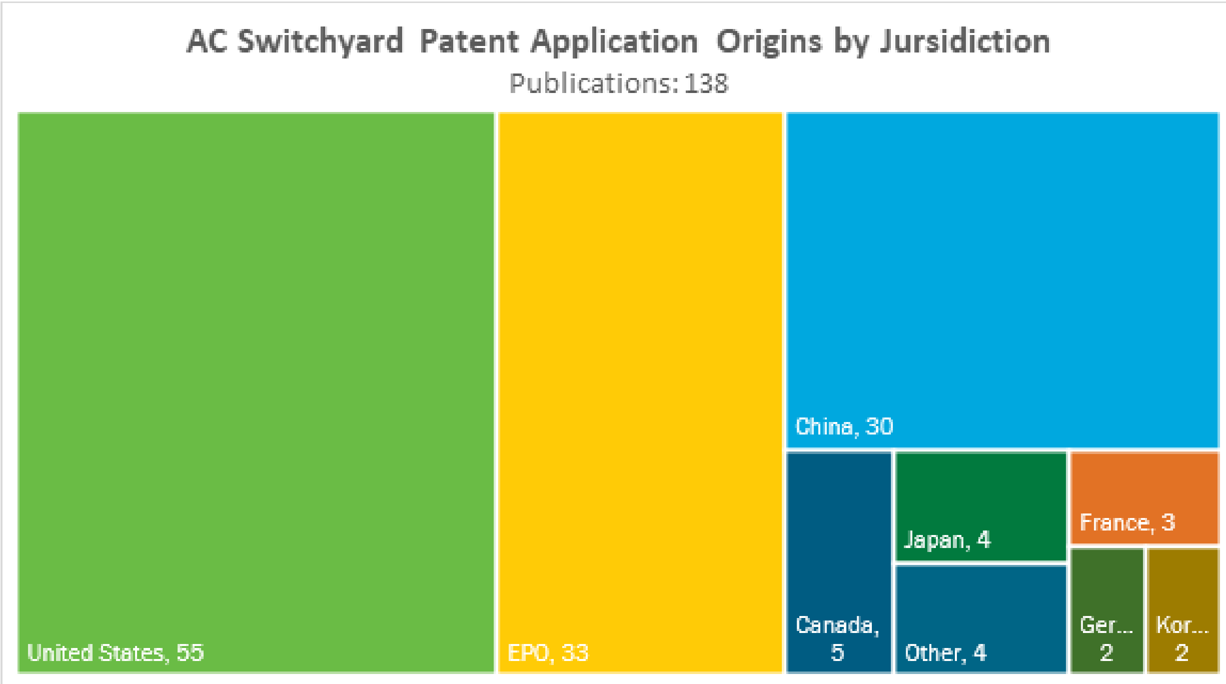

Figure A 10. AC switchyard patent application origins by jurisdiction.

This figure shows the country in which the earliest patent application was filed. This data could indicate that either companies located in these countries are innovating in this area or that these are the countries which companies want to first capitalize in. Countries with only one patent are included under Other. 39.86% of original filings were in the United States, 23.91% of original filings were with the EPO, 21.74% of original filings were in China.

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