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Smart Grids in the European Union

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

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Contents

Abstract

This annual CETO report provides an overview of technological trends and market issues on selected topics regarding the electricity grid and the “smart grid of the future”. The analysis this year focuses on grid infrastructure, since the physical grid assets are increasingly being recognized as fundamental enablers of the smart grid transition and a potential source of criticalities for an effective and timely decarbonization of the energy system. It builds on the last year’s assessment of High Voltage Direct-Current (HVDC) connections, and analyses Alternating-Current (AC) lines and cables, and power transformers. For each of these two topics, their current status is reported in terms of technology developments and trends, value chain analysis and global competitiveness.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform.

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

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Executive Summary

This report aims to provide an updated overview of the latest trends and developments for selected technologies that are key to the overall the Smart Grid sector. The focus of this year analysis is on grid infrastructure, which is increasingly recognized as one of the most important enablers of the smart grid paradigm and, more generally, of a swift and effective energy transition. Building on the analysis of High-Voltage Direct-Current (HVDC) connections, conducted in the 2023 CETO report (De Paola, Andreadou, & Kotsakis, 2023), this document focuses on two specific grid elements: Alternating-Current (AC) lines and cables, and power transformers.

Alternating-Current (AC) lines and cables

Electricity grids and in particular lines and cables have constituted the backbones of the power system for more than a century. However, in recent years the sector has been undergoing radical changes, with the increasing penetration of renewables sources and the electrification of key technologies such as transportation and heating. It is therefore of paramount importance that the grid is able to accommodate and enable new patterns of power generation and consumption, acting as a key enabler of the energy transition. In this regard, our analysis has shown the following:

- Electricity lines and cables are well-proven technologies that benefit from a clear standardisation process and extended supply chains.
- As of 2021, the total length of connections in the EU amounts to about 500,000 km for the transmission grid and almost 10,000,000 km for the distribution grid. Significant expansions are expected in the next 30 years. By 2050, the EU network will include almost 1,000,000 km (+100%) of transmission lines and 13,000,000 km of distribution lines (+30%). Moreover, over 7 million km of existing lines (including about 300,000 km of transmission lines) will have to be replaced by 2050.
- The cost of new grid projects varies significantly, depending on the type of asset (overhead line or underground cable), voltage level, number of circuits and location. For transmission lines, the median unitary cost can range from 0.26 M€/km for a 110-150kV, 2-circuit overhead line to 1.91 M€/km for a 220-225 kV, 1-circuit underground cable.
- The European share of patent applications for "Electrical machinery, apparatus, energy" (which includes also AC lines and cables) amounts to 7% of the total, a percentage that is quite similar to other regions (from 6% of the US to 9% of Japan). However, the European patent applications exhibit by far the largest increase (+18%) with respect to 2021 compared to all the other considered regions.
- The time ranges of typical recently commissioned projects indicate significant variability with respect to voltage levels and geographical region. In the case of the EU, low voltage lines are generally deployed in 2-4 years, with significantly higher times for high-voltage lines (4-7 years) and extra-high-voltage lines (5-13 years).
- The substantial grid expansions planned over the next decades will require a significant amount of copper and aluminium. The supply chains of these materials are expected to keep up in the short term; however, on the medium-long term, there are risks of disruption due to high demand and concentration of refined copper production.
- EU companies are currently holding a leadership position in the sector of wires and cable manufacturing. Some of the main European manufacturers include Prysmian group (Italy), NKT (Denmark) and Nexans (France), with the addition of Tele-Fonika (Poland) and Hellenic Cables (Greece) which also provide products for low-voltage levels.

Power Transformers

Transformers are a fundamental part of the grid: they transform electricity to high voltage to facilitate transmission with minimal losses, whereas on the other hand they transform it to low voltage for local distribution grids covering commercial and residential needs. In the following, we give the main points for transformers, as follows:

- Transformers are under the Ecodesign Regulation 2019/1783, which amends the original Ecodesign 548/2014 Regulation. The Regulation for transformers covers the products with minimum power rating of 1 kVA and used in a network of 50 Hz. It should be also noted that this regulation is under review for energy efficiency issues, technological updates and market changes issues.
- Transformers can be categorised among: Small transformers, Medium transformers, Large power transformers, Liquid-immersed transformers, Dry-type transformers and Medium power pole mounted transformers.
- Only within the EU and Norway, according to available current data, it is estimated that there are around 4.5 million transformers installed. It is also foreseen that the number of transformers will be doubled by the year 2050, with annual additions of 172,000 transformers per year on average.
- Transformers play a key role in the power system and several materials are needed for their manufacturing. However, 50% of the materials required for their production is steel and out of this steel, 60% is the processed material of grain-oriented electrical steel, the so-called GOES. Other materials used in transformers include: aluminium, copper, transformer oil used for insulation, insulation material, paper, pressboard, plastic, porcelain and rubber.
- It is estimated that the global market of power transformers was worth 22.83 billion US dollars in 2022 and it is anticipated to grow until 2030 with an annual growth rate of 7.1%, reaching up to 38.91 billion US dollars. One of the drivers for the global market growth is expected to be the increase in transformers demand in the developed countries.
- China has been the leading exporter of transformers, especially to other emerging economies, whereas the United States is the main importer of transformers, mainly from Europe and Mexico.

1 Introduction

1.1 Scope and context

This document addresses the Clean Energy Technology Observatory Sub-Task A.2 and aims to provide an updated overview of the latest developments and trends in the Smart Grid sector. The analysis this year has focused on the topic of grid infrastructure, since the physical grid assets are increasingly being recognized as fundamental enablers and a potential source of criticalities for an effective and timely decarbonization of the energy system. Building up on the last year's focus on High Voltage Direct-Current (HVDC) connections, the present report analyses Alternating-Current (AC) lines and cables and power transformers. In regard to these two topics, the report presents their most relevant technological statuses and trends, analyses the key features and most timely issues of their value chains and assesses the market position and global competiteveness of EU companies.

1.1.1 Alternating-Current (AC) wires and cables

The topic recognizes the fundamental role that network infrastructure will play in the integration of renewables and in the support to an efficient operation of a decarbonized electricity grid. The study follows up on the analysis of HVDC technologies provided in (De Paola, Andreadou, & Kotsakis, 2023) by focusing instead on AC connections. The scope includes overhead electric lines and underground cables, both at transmission and distirbution level. The study does not consider emerging network technologies such as Flexible Alternating Currents Transmission Systems (FACTS), which will be the subject of future analyses.

1.1.2 Power Transformers

Transformers play a key role for the grid, as they transform electricity to high and low voltage to facilitate the transmission with minimum losses, whereas on the other hand they transform electricity to low voltage for local distribution grids covering commercial and residential needs. The scope here is to present the status of all kinds of transformers (large, medium and small) together with information about their technological level and i the materials needed for their construction. The study also assesses emerging issues and problems to be tackled for the European and global market and shows the trends with respect to investments and future development..

1.2 Methodology and Data Sources

The report structure broadly follows the CETO methodology that addresses three principal aspects:

a) Technology maturity status, development and trends

b) Value chain analysis

c) Global markets and EU positioning

The main sources utilised for the study include:

- Technical reports by public institutions and private entities
- Scientific review papers on technology state-of the-art
- ENTSO-E energy scenarios
- CORDIS database for Horizon 2020 and Horizon Europe research projects

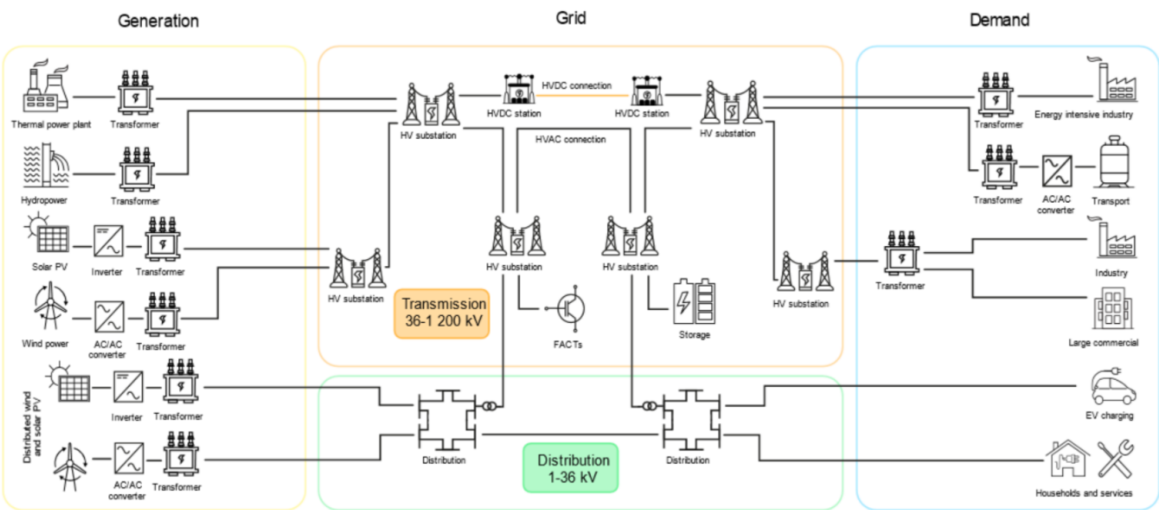
Additional information, both in the form of qualitative assessments and quantitative data, has been obtained through contacts with external stakeholders, including industry associations (T&D Europe, Europacable, Eurelectric, Euractiv) and technical experts (Transformers Magazine).

2 Alternating-Current (AC) lines and cables

Electricity grids are a fundamental element of the global energy system and will play an even larger role as the electrification of key sectors such as transportation and heating progresses. This chapter focuses on the electric lines and cables that connect the different components of the grid, as shown graphically in ***Figure 1***.

There are currently 80 million km of existing power lines in the world, operating at voltage levels ranging between 35 kV and 800+ kV (transmission network) or below 35 kV (distribution network). Most of the existing lines operate in alternating current (AC), which has been historically preferred for its low losses and relative simplicity of voltage transformation. However, the increasing penetration of inverter-based generation (particularly wind and solar) has led to a growing use of High-Voltage Direct Current (HVDC) technology, which has been analysed in detail in (De Paola, Andreadou, & Kotsakis, 2023).

Figure 1. Key technology components of electricity grids



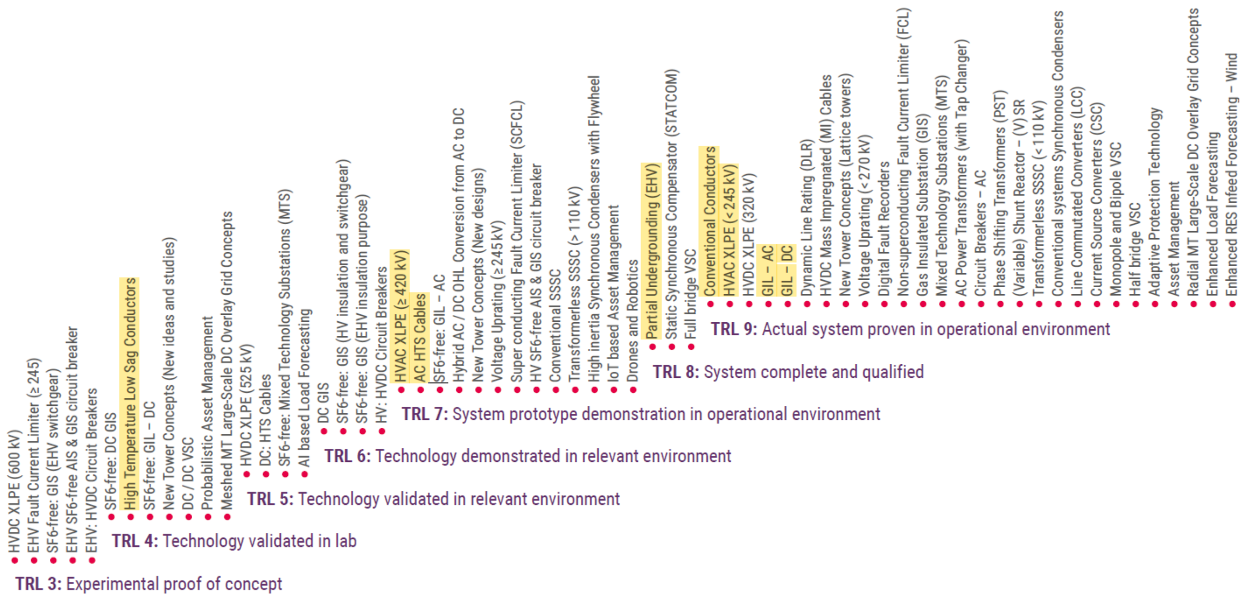
Source: (IEA, 2023a)

2.1 Technology development and trends

2.1.1 Technology readiness level

The Technology Readiness Level of line and cable technologies, with a particular focus on transmission applications, is summarized in ***Figure 2***. The most relevant technologies (highlighted in yellow in the figure) include: Gas Insulated Lines (both AC and DC), conventional conductors, High-Voltage Cross-linked Polyethylene (XLPE) cables, partial undergrounding, High Temperature Superconductors (HTS) cables, and High Temperature Low Sag conductors.

Figure 2 Technology Readiness Level (TRL) of line and cable technologies at transmission level



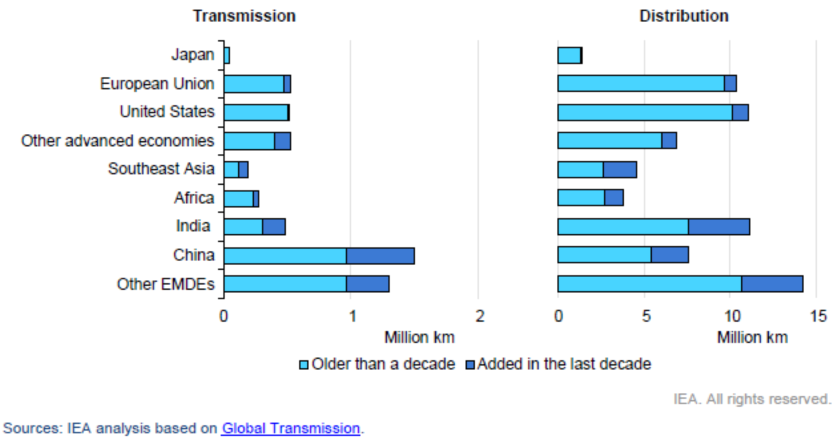
Source: ENTSO-E

The bulk of the existing overhead lines is currently constituted by aluminium conductors, a well-proven century-old technology which benefits from a clear standardisation process and an extended supply chain (ENTSO-E, 2024). In recent years, underground cables are seeing a rapid diffusion, as a result of the reduced visual impact that facilitates public acceptance of new projects albeit at increased cost. Compared to overhead lines, which can benefit from the heat dissipation and insulation of air, underground cables require additional insulation layers. The main technology in this regard is represented by Cross-linked Polyethylene (XLPE) cables, which are already seeing widespread use for voltage levels below 245 kV and are at a prototype demonstration stage for voltage levels of 420kV and above. Alternative approaches, such as Gas-Insulated Lines (GIL), are mostly used in particular cases with high capacity requirements and narrow spaces limitations, while the use of High-Temperature Superconductor (HTS) cables, based on special superconducting materials that are cooled down to extremely low temperatures (e.g., -180 °C), is currently at a prototype demonstration stage.

2.1.2 Installed capacity and production

Some of the latest available data regarding the current installed capacity of cables is provided by (IEA, 2023b) and summarized in ***Figure 3***.

Figure 3: Electricity transmission and distribution lengths by age and country/region, 2021



Source: (IEA, 2023b)

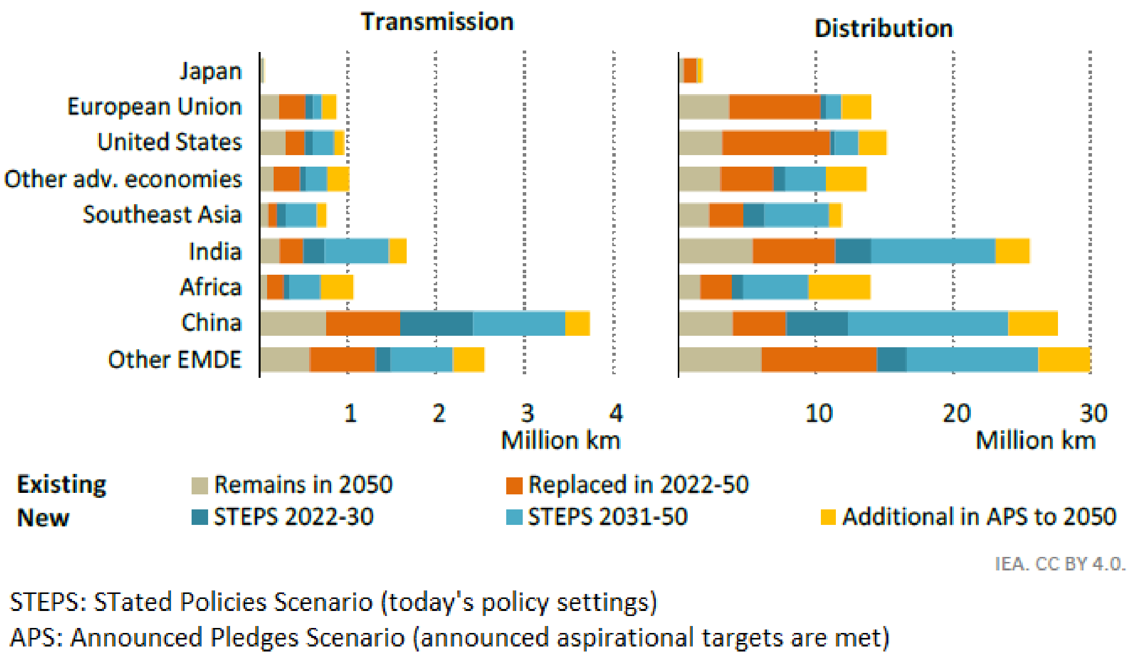
As of 2021, the total length of electricity transmission connections in the EU amounts to about 500,000 km, comparable to the network in the United States. In China the transmission cable infrastructure is significantly larger, and has reached a total length of about 1.5 million kilometres, with more than half a million km of new lines installed in the last 10 years. Significant grid expansions have also been achieved in India (180,000 km of new lines in the last decade) and Brazil (92,000 km of new lines).

Advanced economies have experienced a more limited expansion (about +9%) of their existing transmission infrastructure. This can be explained by an already mature network and ongoing rural-urban migration trends, which have limited the need for new connections in rural areas. In the specific case of the European Union, the total transmission length has increased by 12%, while in the United States the growth has been more limited (+3%).

The distribution infrastructure exhibits similar trends: most of the grid expansion in recent years has been carried out in Emerging Market and Development Economies (EMDPs), whose grids have grown on average by 40% in the last decade. The distribution grid expansion in advanced economies has been significantly smaller (about +8% in the EU) since electricity access is already close to 100%.

In terms of future trends, projections on the grid capacity over the period 2022-2050 are provided in (IEA, 2022) and summarized in ***Figure 4***.

Figure 4: Grid development by type, region and scenario, 2022-2050



Source: (IEA, 2022)

According to the Stated Policies Scenarios (blue and light blue in the figure), 1.3 million km of new transmission lines and 45 million km of new distribution lines will be built by 2030 for the networks of the considered countries. The expansion will continue in the subsequent twenty years, with additional 1.8 million km of new transmission lines and 45 million km of distribution lines. The substantial increase in network capacity will be driven by two main factors: the growing electricity demand (expected to be more than doubled by 2050) and the rapid penetration of additional renewable generation.

It is important to emphasize that advanced economies, whose network infrastructure is already well developed and older, will focus more on replacing aging assets rather than building new lines. In the case of the European Union, over 7 million km of lines (including about 300,000 km of transmission lines) will have to be renewed by 2050. This substantial investment effort is reflected in the projection in **Table 1** of the potential demand for High-Voltage (HV) and Extra High-Voltage (EHV) cables over the next ten years, estimated by Europacable on the basis of the ENTSO-E's TYNDP and the different National Development Plans. The total projected demand over the time period 2024-2035 (TYNDP24) amounts to almost 100,000 km of new cables, with a +11% increase with respect to the same estimate over the 2022-2032 period (TYNDP22).

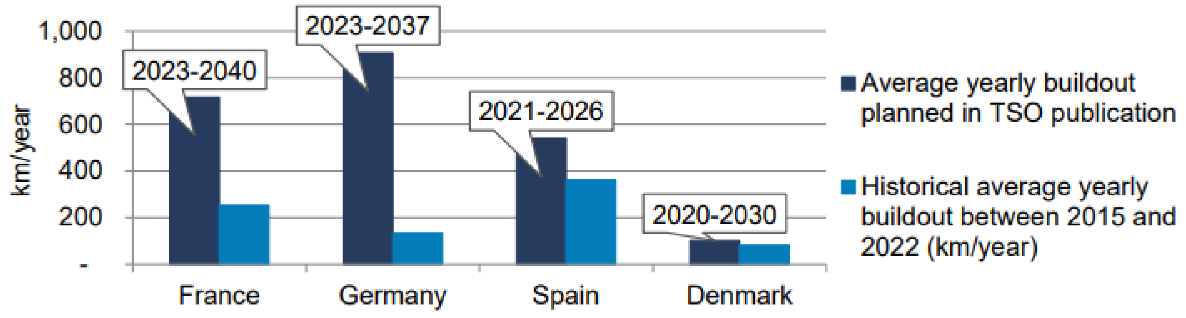
Table 1: *Projected 10-year EU demand of HV and EHV cables*

Cables (km)	HV & EHV AC land	HV & EHV DC land	HV & EHV AC subsea	HV & EHV DC subsea	Total
ENTSO-E's TYNDP 2022	804	9,670	2,478	38,752	51,764
ENTSO-E's TYNDP 2022 & European National Development Plans	4,116	14,054	11,295	58,292	87,757
ENTSO-E's TYNDP 2024 & European National Development Plans	4,299	16,692	13,260	63,103	97,354

Source: Europacable elaboration of TYNDP 2022, TYNDP 2024 and European National Development Plans.

It is worth pointing out that the considerable network expansion planned in the upcoming years is not uniformly distributed among all countries, with some nations called to step up more significantly their investments. In this regard, the study presented in (Compass Lexecon, 2024) and summarized in ***Figure 5***, shows significant differences between the European countries they have analysed. For example, while Denmark will only need to slightly increase their yearly average buildout, Germany will be called to achieve s a yearly growth in the next 15 year that is about 5 times higher than in recent years.

Figure 5: Average growth in TSO network size - Past and planned yearly buildout (km/year)



Source: Compaxx Lexecon elaboration of TSOs and ENTSO-E data

2.1.3 Technology costs

An assessment of the costs of distribution and transmission lines must take into account the considerable impact that the length of the line and the voltage levels have on the overall cost of the asset. One of the most updated summaries in this regard is provided by the analysis in (PwC, 2003), which has supported the publication of the unit investment cost indicators for assets with conventional conductors in (ACER, 2023), partially reported in ***Figure 6***.

Figure 6: Unit Investment Cost Indicators for Energy Infrastructure Categories

Asset category	Subcategory	Average UIC	Median UIC	Q1	Q3	N. of assets
Overhead line (million EUR/km)	110-150 kV 2 circuits	0,325	0,26	0,224	0,393	3
	220 kV 1 circuit	0,412	0,362	0,303	0,543	7
	220 kV 2 circuits	0,53	0,503	0,442	0,673	21
	330 kV 2 circuits	0,574	0,530	0,522	0,573	5
	380-400 kV 1 circuit	0,465	0,397	0,298	0,606	18
	380-400 kV 2 circuits	1,261	1,05	0,533	1,635	45
Underground cable (million EUR/km)	110 - 150 kV 1 circuit	0,831	0,551	0,425	0,643	14
	110 - 150 kV 2 circuits	2,232	1,68	0,847	3,065	4
	220 - 225 kV 1 circuit	1,778	1,91	1,234	2,108	16
	220 - 225 kV 2 circuits	4,402	4,387	4,232	4,556	4
	300 - 500 kV 1 circuit	1,309	1,131	1,046	1,394	4
Submarine cable (million EUR/km)	AC	2,007	2,468	1,203	2,527	9
	DC	1,108	1,086	0,903	1,258	6
Offshore transmission cable (million EUR/km)		3,289	3,003	2,761	4,339	7

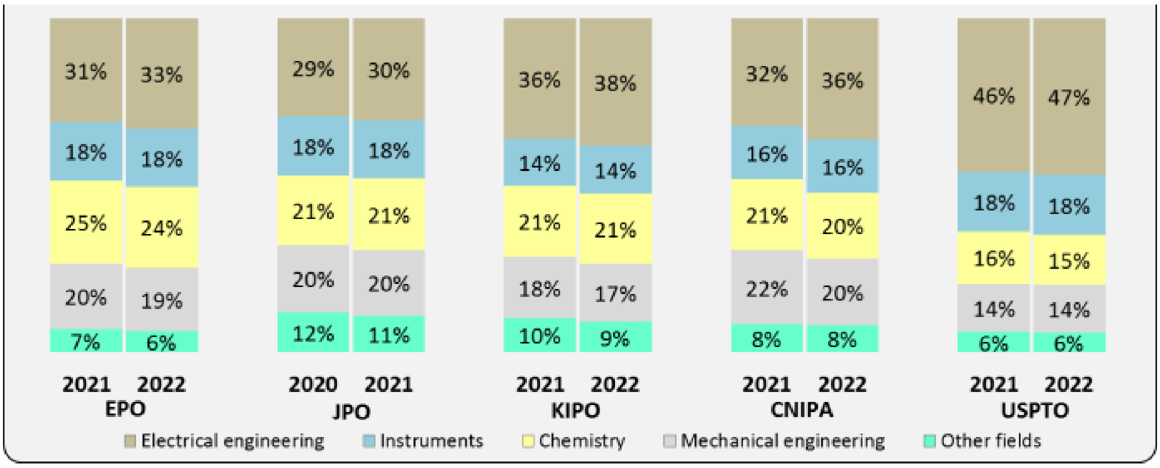
Source: (ACER, 2023)

As expected, overhead lines generally represent the cheapest solution, with a median price of the assets developed in the last ten years that range between 0.26 M€/km (2 circuits 110-150kV lines) to 1.05M€/km (2 circuits, 380-400kV). On the other hand, the unit cost of underground cables is significantly higher, with a cost increase of about 3-5 times. It is also interesting to notice that, in terms of submarine cables, the median cost per length is lower in the DC case (1.086 M€/km) than in the AC case (2.486 M€/km). The increased cost in the case of 2 circuits configurations (for the same voltage level) is due to the different number of wires used (6 sets of conductors vs 3 sets in the 1-circuit case). The differences in the quantile (Q1 and Q3) values in ***Figure 6*** also highlight the significant variability of the unitary costs, as these can fluctuate on the basis of the specific characteristics of the different network projects.

2.1.4 Patenting trends

An analysis of the patenting trends must consider that the main available resources on this topic apply the International Patent Classification (IPC). Such classification envisages 5 main technological sectors and includes lines and cables within the "electrical engineering" category, more specifically in its "electrical machinery, apparatus, energy" field. Within this framework, it can be seen from ***Figure 7*** that the share of electrical engineering patent applications in Europe (EPO) tends to be slightly higher than Japan (JPO) but lower than the other considered regions, i.e., South Korea (KIPO), China (CNIPA) and the United States (USPTO).

Figure 7: Patent applications filed by sector of technology and region



Source: (fiveIPoffices, 2022)

A closer look at the data regarding the electrical engineering sector and in particular at the field of "Electrical machinery, apparatus, energy", as summarized in ***Figure 8***, shows that the share of patent application in this field in Europe amount to 7% of the total, a percentage that is quite similar to the other regions (from 6% of the US to 9% of Japan). However, it is important to underline that the European applications exhibit by far the largest increase (+18%) with respect to 2021 of the patent applications compared to all the other considered regions.

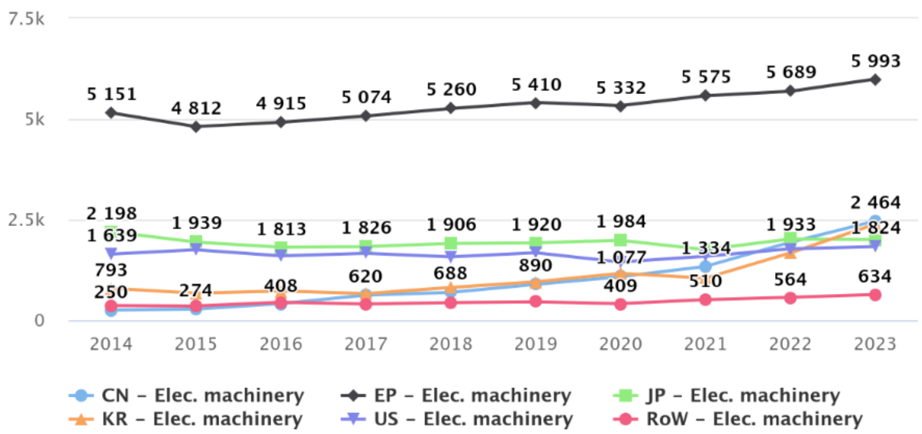
Figure 8: Distribution of applications filed by field of technology - 2022

Field of technology	EPO		JPO		KIPO		CNIPA		USPTO	
	Share	Change	Share	Change	Share	Change	Share	Change	Share	Change
1. Electrical machinery, apparatus, energy	7%	+18%	9%	0%	8%	+6%	7%	+11%	6%	+7%
2. Audio-visual technology			4%	7%	4%	+4%			4%	-3%
3. Telecommunications										
4. Digital communication	9%	+11%			5%	+10%	5%	+16%	10%	-3%
5. Basic communication processes										
6. Computer technology	8%	+2%	6%	3%	7%	+5%	15%	+17%	15%	+2%
7. IT methods for management			3%	+14%	7%	+5%	3%	+20%	4%	-2%
8. Semiconductors			4%	7%	6%	+9%			5%	0%

Source: (fiveIPoffices, 2022)

In terms of historical trends, summarized in ***Figure 9***, it can be seen that the patent application to the European Patent Office by European countries (black trace – EP members in the figure) have been steadily increasing in the last decade, achieving an overall increase of +16% with respect to 2014.

Figure 9: European patent applications in the "Electrical machinery, apparatus, energy" field



Source: (European Patent Office, 2024)

2.1.5 Public funding and impact of EU-supported research

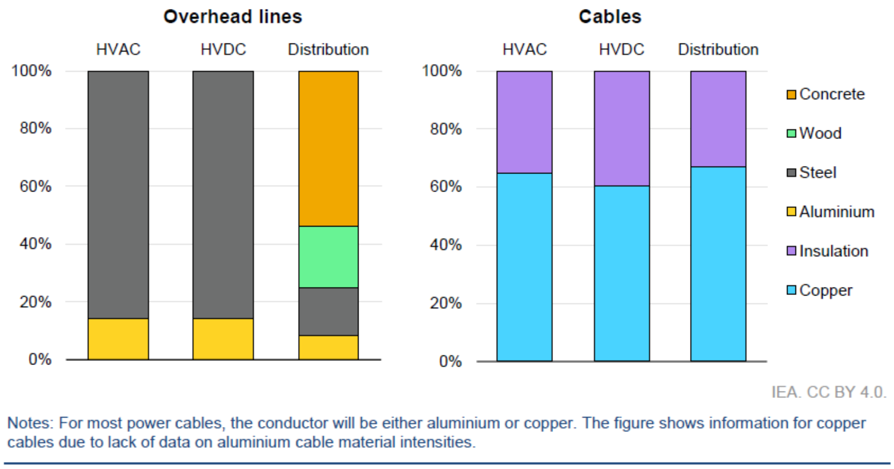
In terms of research, a substantial effort has focused on HVDC assets and applications, as detailed in last year's CETO report (De Paola, Andreadou, & Kotsakis, 2023). Given the mature status of AC technologies for wires and cables, ongoing research projects are investigating novel types of superconducting cables (SCARLET project – 19.6 M€ budget and SUBRACABLE – 3.5 M€ budget), considering alternative insulation materials and manufacturing solutions (NEWGEN project – 7.6 M€ budget) or analysing novel switchgear solutions (MISSION project – 10.4 M€ budget).

In terms of future research planning, the research activities in this field are funded at the European level by the cluster "Climate, Energy and Mobility" of the Horizon Europe programme. In its 2023-2025 Work Programme (European Commission , 2024), 5 different projects are specifically addressing research questions related to electrical wires and cables, for a total budget of 61.6M€, of which 27.6 M€ are EU contributions. Moreover, other envisioned research activities are expected to tackle related scientific and technological themes, such as new tools for network planning and design, for a total budget of 46 M€ (with 20M€ EU contributions).

2.2 Value chain analysis

For an assessment of the value chain for electric wires and cables, it is useful to consider their typical material composition, summarized in ***Figure 10***. In the case of overhead lines, aluminium is usually preferred to copper as conducting material, since its lower conductibility (-39% with respect to copper) is counterbalanced by a substantial weight reduction (-70%). In general, an aluminium wire will require a larger cross-section (+50%) to pass the same amount of electricity than copper, but its weight will be halved (IRENA, 2021). The material requirements of the supporting structures include wood, steel and concrete for the pylons of the distribution grid and steel for the supporting towers of the transmission network.

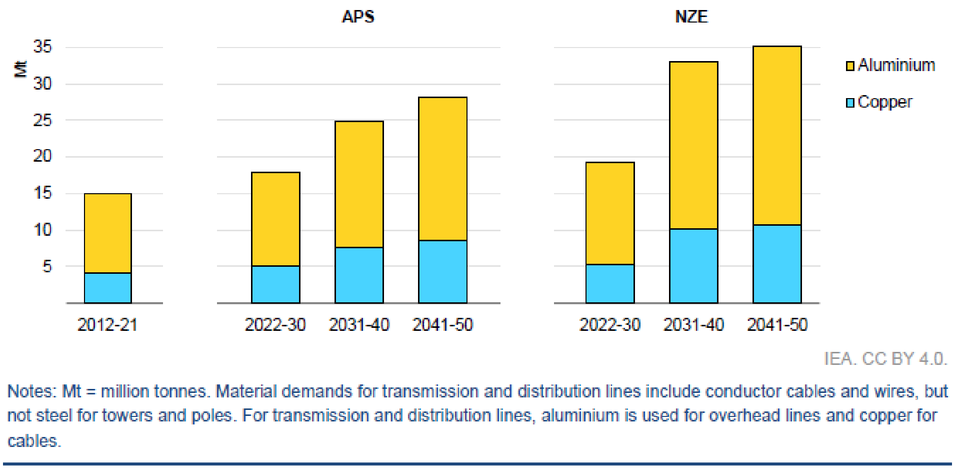
Figure 10: *Typical material composition of overhead lines and cables and their supporting structures by weight*



Source: (IEA, 2023b)

Consistently with the grid development scenarios presented in Section 1.b, the substantial expansion of distribution and transmission networks expected in the next 30 years will lead to a rapidly growing demand for copper and aluminium. According to the estimate provided in (IEA, 2023b) and shown in ***Figure 11***, in the Announced Pledges Scenario (APS), which assumes that the announced decarbonisation ambitions and targets are met, the grid needs for copper and aluminium will almost double in the decade 2041-2050 compared to 2012-2021. In the shorter term, the demand increase will be more limited, with average yearly copper demand going from 5Mt/year in 2012-2021 to 5.5 MT/year in 2022-2030 and aluminium demand rising from 12 Mt/year (2012-2021) to 13 Mt/year (2022-2030). In the NZE scenario, which envisages net zero emissions from the energy sector in 2050, the materials demand is even more significant, reaching 12 Mt/year for copper and almost 27 Mt/year for aluminium in 2041-2050.

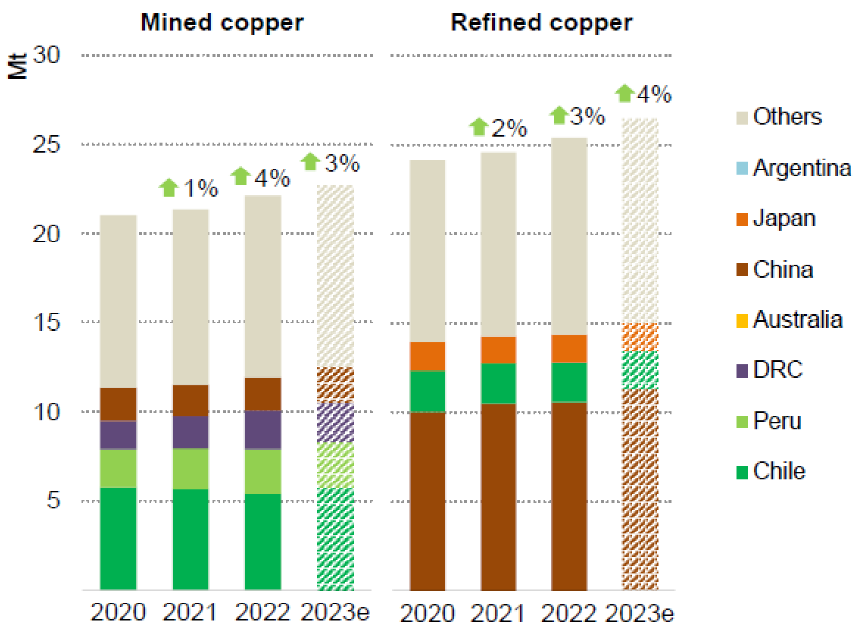
Figure 11: Average annual material needs for transmission and distribution lines in the Announced Pledges Scenario (APS) and Net Zero Scenario (NZE)



Source: (IEA, 2023b)

In this context of growing demand for copper and aluminium, there are some uncertainties and risks associated to their procurement (IEA, 2023c). In the case of aluminium, the Russian invasion of Ukraine has led to price spikes, reaching the record level of 3210$/t in March 2022. After some months, prices dropped to 2000-2500$/t in late 2022 and 2023. However, some criticalities remain, with European smelters that have reduced their production as a result of increasing energy prices, leading to the lowest inventory levels in the London Metal Exchange since 1990. In the short term, the supply situation for copper appears less problematic, with production picking up in 2022 after several flat years (see ***Figure 12***) and prices dropping. However, there are uncertainties and risks over the medium-long term, as the production in Chile and Peru might be reduced or disrupted, while the lack of large-scale projects in the pipeline might slow down the production after 2024. In this scenario, a copper demand increase, for example due to an acceleration of the energy transition and a recovery of the Chinese economy, could have a significant impact on prices.

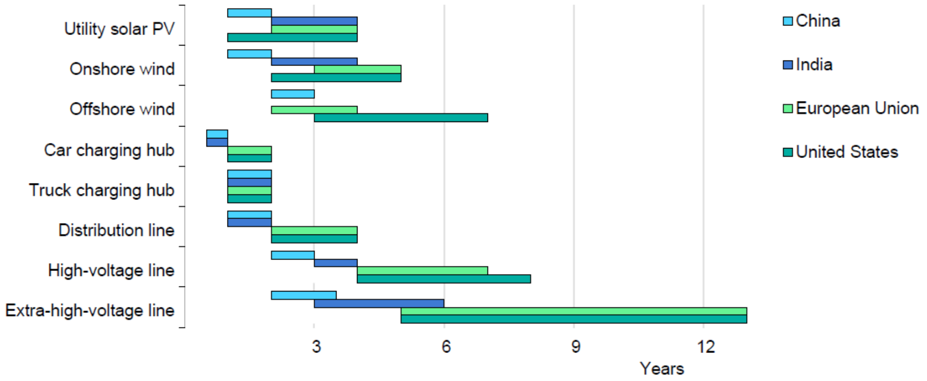
Figure 12: Production trends for copper, to be compared with the projected requirements for cables rising from a current value of 5 Mt/y to 8-12 MT/y in the 2041-2050 period.



Source: IEA Analysis based on S&S Global and Wood Mackenzie

A potential risk for the supply chain that could be exacerbated by increasing costs and difficult procurement of materials is an increased deployment time for new grid projects. One of the most recent analyses in such sense is presented in (IEA, 2023b) and shown in ***Figure 13***. The time ranges of typical recently commissioned project indicate significant variability with respect to voltage levels and geographical region. In the case of the EU, distribution lines are generally deployed in 2-4 years, with significantly higher times for high-voltage lines (4-7 years) and extra-high-voltage lines (5-13 years). If the deployment times were to increase even further, this could negatively impact the fulfilment of the massive requirements for network expansion and replacement discussed in Section 2.1.2. A slower grid expansion could also represent a bottleneck for a large-scale roll-out of new renewable generators (e.g., solar PV and wind) which typically exhibit shorter deployment times.

Figure 13: Typical deployment time for electricity grids, solar PV, wind and EV charging stations



Notes: Ranges reflect typical projects commissioned in the last three years. Distribution line = 1-36 kV overhead line. Transmission is split between high-voltage line = 36-220 kV overhead line; and extra-high-voltage line = 220-765 kV overhead line. To date, India has not developed offshore wind projects.

Source: (IEA, 2023b)

2.3 EU Market position and global competitiveness

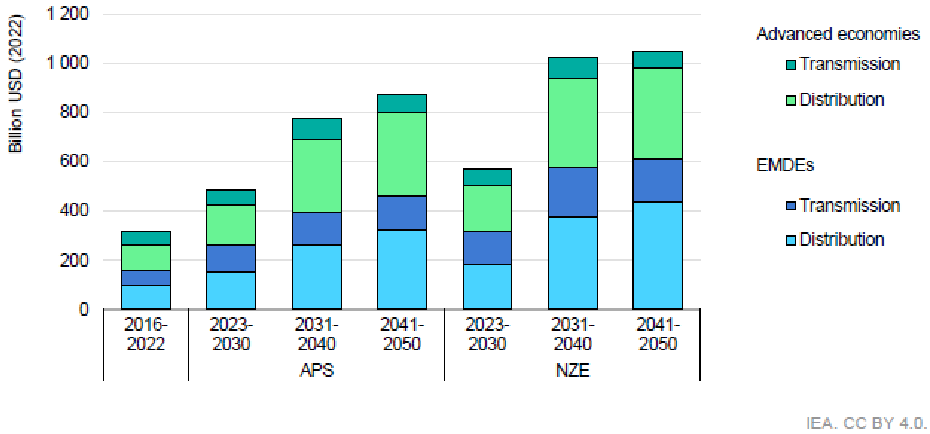
2.3.1 Global and EU market leaders

EU companies are currently leaders in wire and cable manufacturing. Some of the main European manufacturers include Prysmian group (Italy), NKT (Denmark) and Nexans (France), with the addition of Tele-Fonika (Poland) and Hellenic Cables (Greece) which also provide products for low-voltage levels. Outside Europe, the most important companies are General Cable and Southwire (USA), Finolex cables (India), Sumitomo and Hitachi Cable (Japan), and TBEA, NBO and ZTT (China).

2.3.2 Market value

Recent analyses provided in (IEA, 2023b) and summarised in ***Figure 14*** indicate an average yearly worldwide investment in grid infrastructure that amounts to about 350 bn$, approximatively equally split between advanced economies and Emerging Market and Developing Economies (EMDEs), with distribution networks taking up about two thirds of the total investments. The investments are expected to increase significantly in the next 20-30 years, reaching in the 2041-2050 decade a yearly average of 850 bn$ and 1000 bn$ for the Announced Pledges Scenario and the Net Zero Emissions case, respectively.

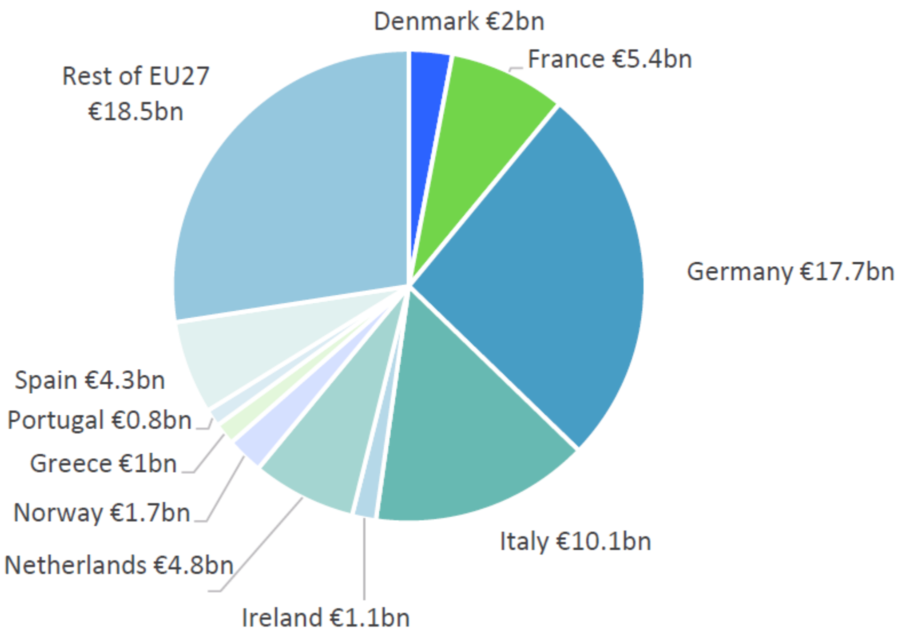
Figure 14: Average annual transmission and distribution investment in Emerging Markets and Developing Economies (EMDEs) and advanced economies, 2016-2050



Note: EMDEs = emerging market and developing economies.
Source: IEA (2022), World Energy Outlook 2022.

At the EU level, it is interesting to point out the differences in expected investments between each country, mostly driven by population density, increases in peak demand and speed of the energy transition. As indicated in (Eurelectric, 2024) and shown in *Figure 15*, more than half of the EU-wide distribution grid investments will be carried out in only three countries (Germany, Italy and France), with Germany accounting for about 25% of the EU total investments.

Figure 15: Annual distribution grid investments for 2025-2050 by country (bn€)



Source: (Eurelectric, 2024)

3 Power transformers

Transformers have an essential role in the grid, as shown in Figure 1 above.. Here we address the technology development and trends, value chain analysis and EU market position and competitiveness. Before going into the details, it is useful to consider the relevant regulatory and standardisation developments.

First of all, the regulation for transformers is the 2019/ 1783 Regulation[1], amending the original Ecodesign 548/2014 Regulation. This covers power transformers with minimum power rating of 1 kVA and used in a network of 50 Hz (ICF, 2024).

The revision of the Ecodesign Regulation for transformers indicated that it should not add requirements that could potentially lead to a reduction of Europe's production capacity. In addition, it stated that the current efficiency requirements should be maintained (The European Association of the Electricity Transmission and Distribution Equipment and Services Industry, 2024).

It should also be noticed here that the Ecodesign Regulation has been under review for energy efficiency issues, technological updates and issues regarding market changes. Among others, Article 7 already mentions the points to be reviewed, such as the appropriateness of setting performance requirements for specific types of transformers, the assessment of techno-economic aspects for power transformers (ICF, 2023).

The transformers regulation covers several types of transformers. It also offers specifications for different voltage levels and power ratings, while giving also guidelines for materials, insulation and construction methods (ICF, 2023).

Regarding standardisation, the IEC 60076 standards define the measurement, testing and the harmonic quantification of power transformer performance. This is a family of standards defining the characteristics and features according to their categorization (ICF, 2024).

The use of this family of standards is also supported by Eurelectric (Eurelectric, 2023, January), as it sets the requirements within the EU. In general, the standards used worldwide can be listed as follows (list is not exhaustive), (ICF, 2023):

- IEC 60076-X series (International Electrotechnical Commission)
- IEEE C57.12 series (Institute of Electrical and Electronics Engineers)
- EN 50708-2-1 Power transformers. Additional European requirements - Medium power transformer. General requirements
- EN 50708-3-1 Power transformers. Additional European requirements - Large power transformers. General requirements
- National Electrical Manufacturers Association (NEMA) TP-1

The first two are the most used worldwide, with the IEEE standards being mainly used in the US, Canada and Chile. The IEC 60076 and IEEE C57.12 families of standards have many similarities especially for the design and testing of the transformers. On the other hand they have also differences, such as for load loss reference temperature, waveform correction and loss tolerances. Practically, the EU aligns to the IEC 60076 with the EN 50708 standard[2] [(ICF, 2023)].

3.1 Technology development and trends

3.1.1 Technology readiness level

Here we consider the technology readiness level for transformers, covering the categories used on the current grid, as well as other technological aspects, such as efficiency requirements; the role of materials for the proper functioning of transformers including repair issues and the smart dimension.

According to Figure 2, shown earlier in this report, the technology readiness level for the power transformers is at level 9 (TRL9): actual system proven in operational environment.

<u>Categorisation of transformers (current grid):</u>

[1] Regulation - 2019/1783 - EN - EUR-Lex (europa.eu)
[2] Power transformers - CEN-CENELEC (cencenelec.eu)

The (ICF, 2024) study states that transformers can be categorised among:

- Small transformers: transformers with highest voltage for equipment not over 1.1 kV.
- Medium transformers: transformers with power lower than or equal to 3150 kVA and voltage higher than 1.1 kV and lower than 36 kV.
- Large power transformers: transformers with highest voltage for equipment greater than 36 kV and at least one winding with power greater than 3150 kVA.
- Liquid-immersed transformers: a transformer where the magnetic circuit and windings are immersed in water.
- Dry-type transformers: a transformer where the windings and the magnetic circuit are immersed into an insulating liquid.
- Medium power pole mounted transformers: a power transformer with power of up to 400 kVA, specifically designed for the overhead power lines.
- Voltage Regulation Distribution Transformer: a medium power transformer which has additional components to control the output and input voltage of the transformer.

Another categorization can be made according to the application for transformers (ICF, 2023):

- Overload Transformers: made for applications where it is likely to have an overload.
- Ultrahigh Voltage Transformers: manufactured for very high voltage applications, for example exceeding 800 kV.
- Fire Performant Transformers: made with increased safety characteristics for fire events.
- Transformers for Renewable Energy Applications: transformers designed for renewable energy applications, as the name implies.
- Transformers for Rectifier Applications: transformers designed to provide a DC power supply.
- Generators Excitation Transformers: mainly made for large rotating machines.
- Bank of Single-Phase Transformers: transformers of single phase, as the name implies.
- Auxiliaries' Transformers for Nuclear Safety Applications: transformers for nuclear applications, as the name implies.
- Fault Current Limiting Transformers: transformers to limit fault currents in electrical systems.
- Step-up Power Transformers for Electricity Production/Generation: transformers to enhance efficiency of electricity transmission.
- Transformers for Railway Feeding Systems: transformers to be used in railway power supply systems.
- Earthing or Grounding Transformers: for earthing applications.
- Transformers Specifically Designed for Explosion-Proof and Underground Mining Applications: to be used in dangerous environments.
- Transformers Specifically Designed for Deep-Water (Submerged) Applications: used in underwater transformers.
- Medium Voltage (MV) to Medium Voltage (MV) Interface Transformers up to 5 MVA: to be used for medium voltage interface applications.

Table 2 shows the categorization of large, medium and small transformers (ICF, 2024). All these transformers are covered by the Ecodesign Regulation EU 548/ 2014.

Table 2: *The transformer categorization according to the IEC 60076-1 standard, EN 50708-1:2020 standard and Regulation (EU) 2019/1783*

Transformer type	Definition from IEC 60076-1 :2011	Definition from the draft IEC 60076-1 :2023	EN 50708-1: 2020	Regulation (EU) 2019/ 1783
Small power transformers	Standard does not define this	≤ 3,150 kVA	Standards do not define this	> 1 kVA & < 1.1 kV
Medium power transformers	Standard does not define this	> 3,150 but ≤ 31,5 MVA	≤ 3,150 kVA > 1,1 and ≤ 36 kV	≤ 3,150 kVA > 1.1 kV and ≤ 36 kV
Large power transformers	Standard does not define this	> 31,5 MVA	> 3,150 kVA > 36 kV	> 3,150 kVA > 36 kV

Source: (ICF, 2024)

Energy Efficiency Requirements issues:

There are specific energy efficiency requirements for medium and large power transformers, depending on their type. Energy performance is determined by the minimum peak efficiency index (PEI) or the maximum allowed load and no-load losses, depending on the transformers category. Table 3 summarises the situation. Small transformers are excluded from the energy efficiency requirements; however, they should be accompanied by documentation on their performance.

Table 3: Summary of the efficiency metric requirements for medium power transformers in Regulation (EU) 2019/1783

Type of power transformer	Rated power (Sr)	Regulation efficiency metric
Medium power transformer (dry and liquid)	≤ 3,150 kVA	Maximum load or no-load losses
Large power transformers	> 3,150 kVA	PEI (%)
Liquid immersed medium pole mounted transformer	25 kVA – 315 kVA	Maximum load or no-load losses

Source: (ICF, 2024)

In general, nowadays, transformers are 99% efficient (Eurelectric, 2023, January). Reduced losses are associated with a more sustainable transformer (Banovic, 2024).

Energy efficiency in transformers is also addressed in the 2019/1783 Ecodesign Regulation, where the categorization of tier 1 and tier 2 transformers is introduced. The Ecodesign Tier 1 was set in 2015 and defines energy efficiency requirements for transformers with power ratings between 1 kVA and 2500 kVA. Ecodesign Tier 2 was set in 2021 and defines stricter requirements for energy efficiency for transformers with power ratings between 1 kVA and 5000 kVA.

Several concerns have been raised about these requirements, in particular about the introduction of stricter requirements for losses. It is claimed that these would necessitate higher material usage, especially for copper and steel. For example, if a transformers has losses in the range of 10%, this would mean around a 15 – 44% increase in material needs and a 25 – 51% increase in cost. This would have an impact on the supply chain and consequently a negative impact on transformer manufacturing, when demand is increasing (The European Association of the Electricity Transmission and Distribution Equipment and Services Industry, 2024). More information about transformer materials can be found in the in section 3.2 below.

Role of materials for transformers proper functioning repair and lifetime of transformers:

Materials and components have a key role for a transformer's proper functioning. Table 4 shows the parts that can encounter defects during its operation and, specifically for large transformers, it shows the likelihood of a certain failure mode for specific components. Concerning the possibility of repairing defective transformers, major repairs are associated only with HV transformers. (Eurelectric, 2023, January).

Table 4: *Encountered defects for components within a liquid immersed distribution transformer and likelihood of failure for large transformers*

	Liquid immersed distribution transformer	**Large transformers**
Component	**Percentage of encountered defects**	**Likelihood of failure**
Insulation	10%	-
Windings	10% (Often linked to insulation)	50%
Cooling systems	10% (Waterproofing and/or clogging)	-
Tap changer	40%	20-25%
Bushings	20%	20-25%
Relays	-	-
Core	5%	-
Oil quality	5% (Entry of humidity/water through sealings or poor handling during maintenance operations)	

Source: (ICF, 2024)

Transformers typically has a lifespan of 30-40 years, a lifetime period that can be extended with maintenance and service. It is also important for the transformer components to operate within their nominal capacity, as a non-correct usage can lead to their failure and thus become problematic for the whole transformer. Ageing of transformer components can lead to safety compromise, due to higher risk of short circuits and electrical faults. A way to prevent malfunctioning is to place sensors to transformers, which would transmit data about the condition under which the transformer works (IEA, 2023b).

Transformers can accommodate increased loading for short periods. They have an extra-built-in capacity; however, when this extra capacity is used, it is expected to have an increased transformer failure. Therefore, loading patterns will probably play an important role in the life of transformer assets (NREL, Feb 2024).

Digitisation and the Smart Dimension of Transformers:

Renewable energy sources can be better integrated when combined with smart technologies applied at transformers level. Another issue is the tendency to equip transformers with smart devices, such as intelligent electronic devices in order to achieve grid monitoring and increase visibility of the low-voltage grid (McKinsey, 2024, February).

Digital technologies, including artificial intelligence (AI) may be used for congestion management and also to forecast the energy load for the day-ahead. Such tools, including the Internet-of-Things (IoT) can also be used in order to predict the behaviour and manage assets like transformers; the tools can be used to monitor transformers, thus anticipating failures and optimizing investment and maintenance actions (EDSO, 2024, June).

In addition, old transformers may exhibit issues for incorporating energy produced by renewable energy sources, such as reverse power flows. Older designs used "flag and pennant" tap changers, which have limitations for high level of reverse power flows. New transformers are equipped with vacuum tap changers and such issues are not encountered (Eurelectric, 2023, January).

Another important factor has to do with the increasing market share of electric vehicles. To accommodate this, studies have shown that one of the first of the grid components that needs to be upgraded is the transformer in order to ensure they are voltage-regulated (IEA, 2023a).

3.1.2 Installed capacity and production

In this subsection, we give information about the transformers capacity and about the installed transformers. We also give information about the rules for transformers replacement or insertion in the grid in specific countries.

<u>Capacity and installed transformers</u>:

In the EU and Norway[3]it is estimated that there are around 4.5 million transformers installed. It is foreseen that this number will double by 2050 (Lexecon, 2024, June), reaching up to 9 million, with annual additions of 172,000 transformers per year until 2050 (Eurelectric, 2024).

Also globally annual additions and replacements of transformers are expected to rise significantly. For the decade 2011-2021, there was a rate of 2.4 TW / year for transformer replacements and additions. Assuming the development follows the IEA net zero emissions targets (IEA, 2023a), this number is foreseen to rise to 4.9 TW / year for the period up to 2030, and to rise to around 6.5 TW / year until 2040, before then decreasing to 4.8 TW / year around 2050. This implies huge growth in the power transformer industry. It is also noteworthy that the major share will be for developing economies (IEA, 2023a).

<u>Rules in specific countries for transformers insertion or replacement in the grid</u>:

Each country can have different rules for transformers replacement or insertion of new transformers in the grid. In the following we list some important aspects applied in specific countries (ACER, 2020, December):

- Spain: qualitative modernisation and replacement criteria are followed, when an insertion of a new power transformer in the grid takes place or when an existing one is substituted, which has entered in service 2 years ago or more.
- Croatia: modernisation/ replacement criteria are implemented when a modification takes place in the system, like the insertion of a new Distribution System Operator / Transmission System Operator (DSO/TSO) transformer.
- Portugal: a new transformer is installed or an old one is replaced in a substation directly connected to the transmission grid, when it exceeds more than 10% of the total power transformer capacity installed.
- Estonia: the TSO needs to assess compliance with the already set requirements with respect to transformer factory acceptance test reports.
- UK: when a transformer is replaced, its effect on fault level contribution and reactive capability are addressed.

For more detailed information not only for transformers, but also for other grid components, the reader is directed to the relevant source (ACER, 2020, December).

3.1.3 Technology costs

The principal cost for transformers are the materials, which account for 60 – 75% of the overall cost of a large transformer. Copper accounts for 25% of the materials cost, while the grain-oriented electrical steel (GOES) takes up to 20 – 25% of the total materials cost. More information about the materials for transformers can be found in Section 3.2 on value chain analysis (IEA, 2023a).

It is also important to note that transportation of large power transformers has an impact on the total cost. The weight of such systems can reach around 100 – 400 tonnes. Usually the various parts are transported separately, resulting in 20% of the transformer cost. Shipping a large transformer internationally can take up to 6 months, in total (IEA, 2023a).

[3] The information available is for the EU and Norway combined.

The following, shows the prices of transformers, as reported in 2024 (ICF, 2024). The types of transformers are linked to the categories of transformers mentioned in Section 3.1.

Table 5: *Price per unit for each type of transformer*

Product Type **Transformers**	**Range of purchase price (€/ unit)**
MV/LV Distribution oil-immersed	12,008
Small transformers including Separation/ Isolation	1,821
Industry oil-immersed	19,930
Industry dry-type	26,512
Power Transformer	1,400,719
DER oil-immersed	40,625
DER dry-type	51,285

Source: (ICF, 2024)

Together with the transformers prices, it may be interesting to check also the prices for basic transformer materials and in general the cost of transformers' production *(ICF, 2024). Table 6* shows these material prices.

Table 6: *Prices of the main materials used in a distribution transformer, as extracted from (ICF, 2024).*

Material	**Cost per kg**
Aluminium	€6.00
Copper	€12.00
Magnetic sheet (quality M070 = 0.70 W/kg at 1.7 T)	€5.50
Oil	€2.00
Tank + Cover	€4.50

Source: (ICF, 2024)

3.1.4 Patenting trends

Data from the World Intellectual Property Organisation[4], clearly show that transformers are a category for patents; in particular, they are under the H01F category, including magnets, inductances, transformers and selection of materials for their magnetic properties. However, the data referring to number of patents and trends from EPO and IP5 is only available in dis-aggregated form for the "electrical machinery" category. The reader is redirected to the cables section above with details on this general category. For the time being, the data for transformers is aggregated together with the rest of the "electrical machinery".

[4] International Patent Classification (IPC) (wipo.int)

3.1.5 Public funding and impact of EU-supported research

There are many European funded projects dealing directly or indirectly with transformers, according to CORDIS[5], the European Commission website for research and innovation. in the framework of Horizon Europe and Horizon 2020 programmes, there are 267 projects that deal with power transformers in the energy and industrial technologies fields. A detailed analysis is beyond the scope of this report.

3.2 Value chain analysis

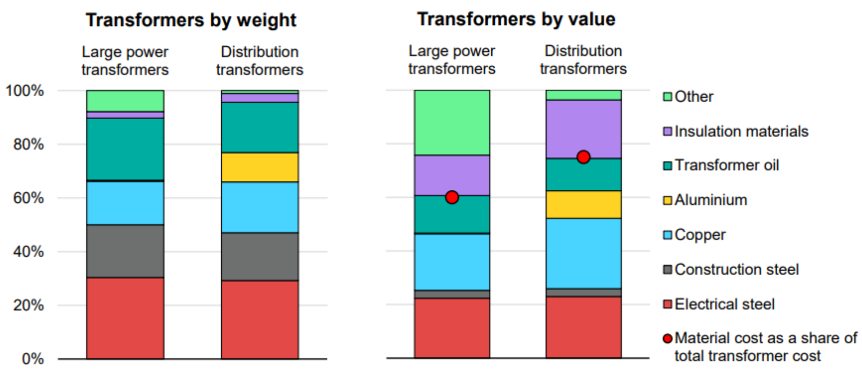
This section gives information about transformer materials and relevant upstream and downstream issues to this regard. In particular we address grain-oriented electrical steel, (GOES); shortage in transformers; lead times; other materials of transformers, including recycling of materials and concerns raised.

Materials of transformers and issues regarding GOES:

Figure 16 shows the material composition of transformers. Typically 50% of the material required for the transformers is steel and out of this steel, 60% is the processed material known as “grain-oriented electrical steel” (GOES). Other materials include aluminium and copper, transformer oil for insulation, insulation material, paper, pressboard, plastic, porcelain and rubber. Transformer oil is used in all types of transformers in order to cool down the windings and core, and it serves as insulation. It also prevents other components, such as the copper coils from getting damaged. Transformers use both mineral oil and bio-based oils (Grand view research).

GOES has specific magnetic properties and high magnetic permeability. The remainder of the steel is construction steel. GOES is a key material for transformers. For instance, the quality level together with the use of high permeability varieties, can result in smaller transformers, necessitating less oil for insulation, thus also reducing electrical losses. For this reason, there is the tendency to have higher quality GOES to satisfy stricter values for efficiency standards (IEA, 2023b). GOES can also be replaced by amorphous steel. This way, higher transformer efficiency can be obtained; however, the disadvantage is that it results in larger and heavier transformers with a more sophisticated manufacturing procedure (IEA, 2023a). In overall, GOES accounts for more than the 20% of the total cost of the transformer. Its cost is 2.5 times larger than that of construction steel.

Figure 16: Composition of transformers in terms of their material by weight and by value



Source: (IEA, 2023b)

The production of transformers is highly dependent on GOES (IEA, 2023b). In 2020, GOES accounted for 3.8 Mt manufacturing capacity. Only some countries were involved in its manufacture, in the EU namely: Germany, France, Poland and Czechia. China has the highest consumption (1.33 Mt) at worldwide level, followed by the European Union at 0.23 Mt and the United States at 0.15 Mt.

Another issue for the transformers’ materials has been raised by (Eurelectric, 2022), stating that lack in high quality steel (GOES), results in manufacturers using lower quality steel or amorphous steel. This raises cost and weight up to 15-20% (Eurelectric, 2023, January).

As a result, a higher quantity of material is needed, leading to heavier transformers and higher losses. In addition, this type of steel is produced through fossil fired generation resulting in high carbon dioxide emissions. On the other hand, GOES is linked to higher efficiency requirements, as indicated by the Ecodesign regulation.

[5] Search | CORDIS | European Commission (europa.eu)

Subsequently, steel like amorphous steel could result in having higher carbon dioxide emissions, with respect to the emissions if GOES would have been used for transformers. Eurelectric has communicated the issue to the European Commission, in order to work towards its solution (Euractiv, 2024).

According to (The European Association of the Electricity Transmission and Distribution Equipment and Services Industry, 2024), it is claimed that amorphous core transformers can cause issues to Europe's manufacturing and the supply chain; in particular, it may cause dependency on third countries. This material can also result in transformers of big dimensions with greater weight. It is also noteworthy that in the USA, it has been decided to maintain 75% of the market with GOES, due to the disadvantages resulting from amorphous steel (The European Association of the Electricity Transmission and Distribution Equipment and Services Industry, 2024).

In addition, amorphous steel would not be aligned with EU policies on Critical Raw Materials, due to its manufacturing only outside the EU, for example in India, China, Japan and the US according to (Eurelectric, 2023, January).

<u>Supply shortages</u> :

There have been recent disruptions to the supply of transformers due to materials shortage and the demand increase. A shortage of GOES led to an increase in transformers' prices by 70% from 2020 to 2022. (IEA, 2023b).

Materials and labour shortages also contributed to delays in the production of transformers, which in turn - alongside the accelerated grid expansion- give rise to a market shortage (T&D World, 2022), (Kann, 2024). As a consequence, the transformer shortage is creating an effect on prices to consumers.

<u>Lead times</u>:

Another important factor is the increase in transformer lead times in recent years, reaching up to 4 years for large power transformers. This contributes also the supply constraints, as mentioned by several manufacturers, (Mackenzie, 2024), (Lexecon, 2024, June). It is forecasted that the lead times will continue to increase in the next years and then stabilise around 2027 (Banovic, 2024).

<u>Other materials – demand, recycling and concerns</u>:

For copper, it is foreseen that the amount of material used for grids and transformers accounts to 20% of the overall production during 2022 – 2030, whereas for aluminium the share reaches 25% (IEA, 2023a). Although these values do not exclusively refer to the needs of transformers, but to the needs of the grid including transformers, they do give an indication about the demand of such materials, which influences also the transformer market (IEA, 2023b), (IEA, 2023a).

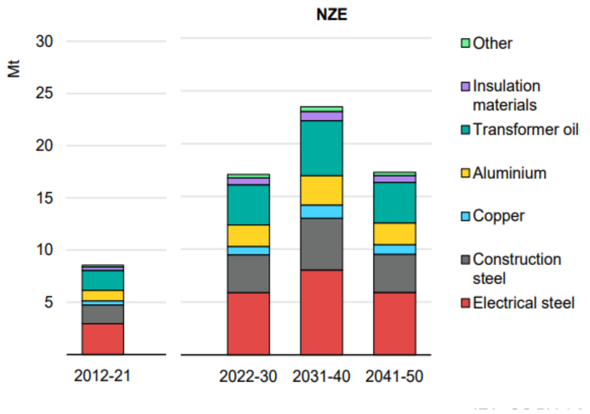
In overall, to construct the transformers, the demand for materials including copper, aluminium, steel, oil and insulation material is foreseen to get increased from 9 Mt/ year in 2012 – 2021 to 17 Mt/ year in 2022 – 2030 and even greater than 23 Mt/ year for 2031 – 2040, whereas a decrease is expected afterwards, for the years 2041 – 2050 to 17 Mt/ year. Regarding oil, to avoid accidental fires, bio-based transformer oils have been developed, which are not toxic and non-combustible (IEA, 2023a).

Around 75% of a transformer's materials can be recycled, especially the steel, oil and copper, whereas other parts, like plastic joints, buffers and silica connectors cannot be recycled at present. When transformers reach the end of their service life (maximum 50 years approximately), they are often recycled. At this stage, most parts of the transformer can be recycled, whereas other parts can be disposed .

Figure *17* shows the average needs for materials per year for the transformers between 2015 – 2050, in line with a net zero emissions pathway.

Around 75% of a transformer's materials can be recycled, especially the steel, oil and copper, whereas other parts, like plastic joints, buffers and silica connectors cannot be recycled at present. When transformers reach the end of their service life (maximum 50 years approximately), they are often recycled. At this stage, most parts of the transformer can be recycled, whereas other parts can be disposed (Alfen Integrated Management System, 2020).

Figure 17: Average needs for materials per year between 2015 - 2050



Source: (IEA, 2023b).

Transformers manufacturing:

In general, a high level of technical expertise and specialized labour is needed to build transformers and there is hardly any automation in the manufacturing process. Such technical expertise includes advanced electrical knowledge, which makes it hard to find such capable workers (Euractiv, 2024). Manufacturing plants, especially for extra-high-voltage transformers, are often located close to where the demand is high, thus avoiding transport over long distances (IEA, 2023b).

Manufacturing complexity also depends on the size of transformer. The manufacturing comprises of: core building, windings manufacturing, oil tank construction, assembly of the various parts and final testing. On the other hand, for large power transformers, their production is more demanding. Large transformers are also heavy and difficult to transport; they need to be designed by specialized engineers and they require a big amount of materials, which are sometimes rare. Their manufacturing is not simple, as there are high standards for safety and high quality testing. The manufacturing also entails here special drying ovens for windings and high power testing laboratories. On the other hand, large transformers are fundamental for the grid operation. Only for the USA, over 90% of the electricity consumed passes through a large power transformer (IEA, 2023b).

3.3 EU Market position and global competiveness

3.3.1 Global and EU market leaders

Transformers manufacturers:

The following manufacturers of large transformers account for more than 40% of the global market (IEA, 2023b), (IEA, 2023a).

- Hitachi Energy (Switzerland)
- Siemens Energy (Germany)
- Mitsubishi Electric and Toshiba (Japan)
- General Electric and Westinghouse (United States)
- Hyundai Heavy Industries (Korea)
- Chint and China XD electric (China)
- Compton Greaves (India)

For the medium- voltage and distribution transformers, numerous companies produce them worldwide (IEA, 2023a). The following lists manufacturers of power transformers independently of their size (Global Power Transformers Industry) and (Grand view research):

- ETEL Transformers Pty Ltd
- ABB

- Altro Transformers
- Southern Electronic Services
- Schneider Electric
- Tyree Industries
- Wilson Transformer Company
- Alstom SA
- Hyosung Power & Industrial Systems Performance Group
- Crompton Greaves Ltd.
- GE Co.
- Hyundai Heavy Industries Co. Ltd.
- Siemens Energy
- Mitsubishi Electric Corporation
- Toshiba Corp.
- Bharat Heavy Electricals Limited

The main EU manufacturers of transformers include ABB, Siemens, Areva, Schneider Electric, Cotradis, Efacec, Pauwels, SGB/Smit, Transfix, GE, Hitachi and Vijai (ICF, 2024). It is worth mentioning that Hitachi alone intends to invest 1.5 billion euros in order to enhance the transformers industry globally (Hitachi Energy, 2024).

Transformer market and market of transformer components:

The transformer market can be defined as a "low volume business", according to (ICF, 2024). However for some "high value items", such GOES and HV bushings, a global market exists. For the other parts of the transformer, which are considered lower value parts, there are local or regional markets . The supply market for different components have different features in different locations; for example, in Europe and China there are plenty of regional suppliers. On the contrary, in North and South America and in Australia, there are few suppliers for each component categorie. India has a big number of suppliers for transformer components (ICF, 2024).

The 70% of power transformers are acquired by utility companies. These dictate requirements, which leads to certain pressure on the transformer industry (Kivrak, 2019).

3.3.2 Trade

The top countries exporting transformers are China, Korea, Mexico, Germany, Italy and Turkey, accounting for up to 75% of the total exports of transformers, whereas the USA has been main importer of transformers. Transformers are mainly needed, where there is growing electricity demand, chiefly in the Middle East and Southeast Asia (IEA, 2023a).

With respect to GOES, the 90% of exports is just from five countries, namely, Germany, Japan, Korea, China and Russia. On the other hand, the countries that import GOES the most are: Mexico, Turkey, Italy, India, and Canada, accounting for 60% of the imports worldwide.

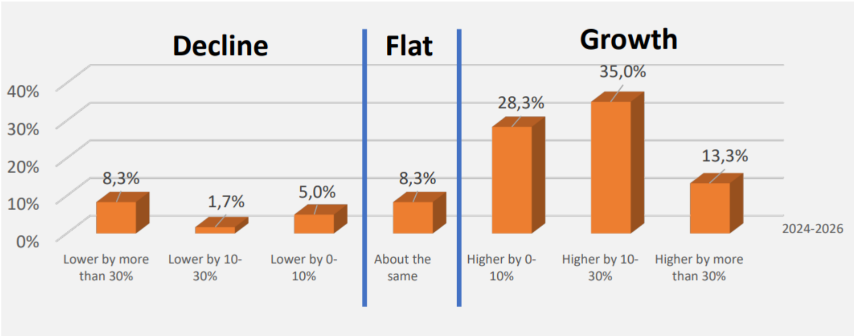
3.3.3 Market value

It is estimated that the global power transformer market was worth 22.83 billion US dollars in 2022 and it is anticipated to grow until 2030 with an annual growth rate of 7.1%, reaching up to 38.91 billion US dollars. One of the drivers for the global market growth is expected to be the developed countries. Another factor is expected to be the various governmental initiatives to install advanced power transformers together with initiatives to modernise the grid and improve efficiency.

In addition, all modern requirements for the application of environmental measures result in high level requirements for the grid and also for transformers, with the need of replacing old transformers with modern ones. This fact contributes to the increased demand of transformers (Grand view research).

It is interesting to check investments in new transformers, given by (Banovic, 2024). Figure 18 shows these new investments in MVA taking place during 2024 – 2026 in comparison to 2020 – 2023 period, where the reader can see an increase or decrease in transformers investments.

Figure 18: New MVA investments in 2024 – 2026 compared to 2020 – 2023



Source: (Banovic, 2024).

As it can be observed from the figure that, a majority of the cases (76.6%) foresee an increase in transformers investments, whereas in a minority (15%), a decrease is forecast. A decline in the investments may occur due to financial crises and political instability. The trend of increased investments on transformers is expected to continue until 2033 (Banovic, 2024).

Whereas European market for transformers accounted for the biggest share in 2019, China is expected to be an important market in the near future. This country has been the leading exporter of transformers, especially to other emerging economies, whereas the United States are the main importer of transformers, mainly from Europe and Mexico (IEA, 2023a).

The transformers market can be assessed according to the demand applications for transformers, for example residential, commercial, utilities and industrial applications. According to (Grand view research), the highest share was attributed to industrial transformers, resulting in 43.4% in 2022.

3.3.4 EU Competitiveness

The shortage of transformers and their respective materials is an issue for the European industry. According to (Euractiv, 2024), a solution could be to have partnerships with governments in order to keep the production in Europe, thus also guaranteeing a security of supply. The Net Zero Industry Act introduced in June 2024 includes a range of policy options that Member States can take advantage of in this regard.

In the following, we shed light to the European market regarding transformers. Specifically, data is shown for EU import, EU export, EU production sold and EU consumption (ICF, 2024).

Table **7** shows the above information about the main types of transformers.

Table 7: *Transformer trade data for the EU in year 2022*

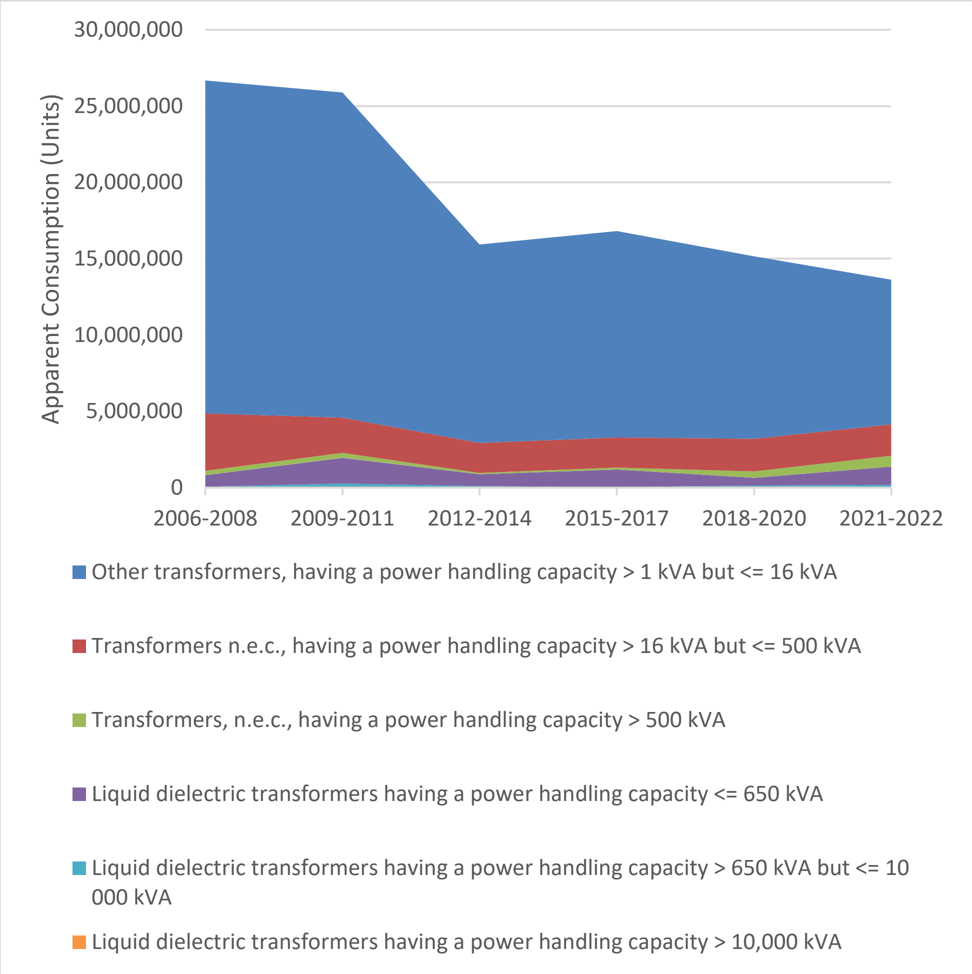
product and description	Liquid dielectric transformers having a power handling capacity <= 650 kVA	Liquid dielectric transformers having a power handling capacity > 650 kVA but <= 10 000 kVA	Liquid dielectric transformers having a power handling capacity > 10,000 kVA	Other transformers, having a power handling capacity > 1 kVA but <= 16 kVA	Transformers n.e.c., having a power handling capacity > 16 kVA but <= 500 kVA	Transformers, n.e.c., having a power handling capacity > 500 kVA
- Import (in 1000 €)	180,669,849	296,660,977	112,243,892	111,760,692	100,742,568	163,297,136
- Import (quantity)	1,510,209	106,378	22,583	9,419,383	903,223	769,642
- Export Value (in 1000 €)	110,500,381	159,813,275	1,020,510,155	69,432,875	125,479,376	220,121,728
- Export (quantity)	431,442	151,499	105,081	1,968,824	470,951	18,994
- Sold Production Value (in 1000 €)	871,153,223	862,178,402	2,636,363,521	318,000,000	560,000,000	928,477,610
Trade balance (1000 €)	-70,169,468	-136,847,702	908,266,263	-42,327,817	24,736,808	56,824,592
- Sold Production (quantity)	101,968	333,727	4,187	1,957,635	1,500,000	71,707

Source: (ICF, 2024)

Figure 19 shows the EU consumption of transformers in units (EU consumption = EU production + EU import – EU export) and Figure 20 shows the dominance of small transformers in the market and the shares of transformer types in the EU market.

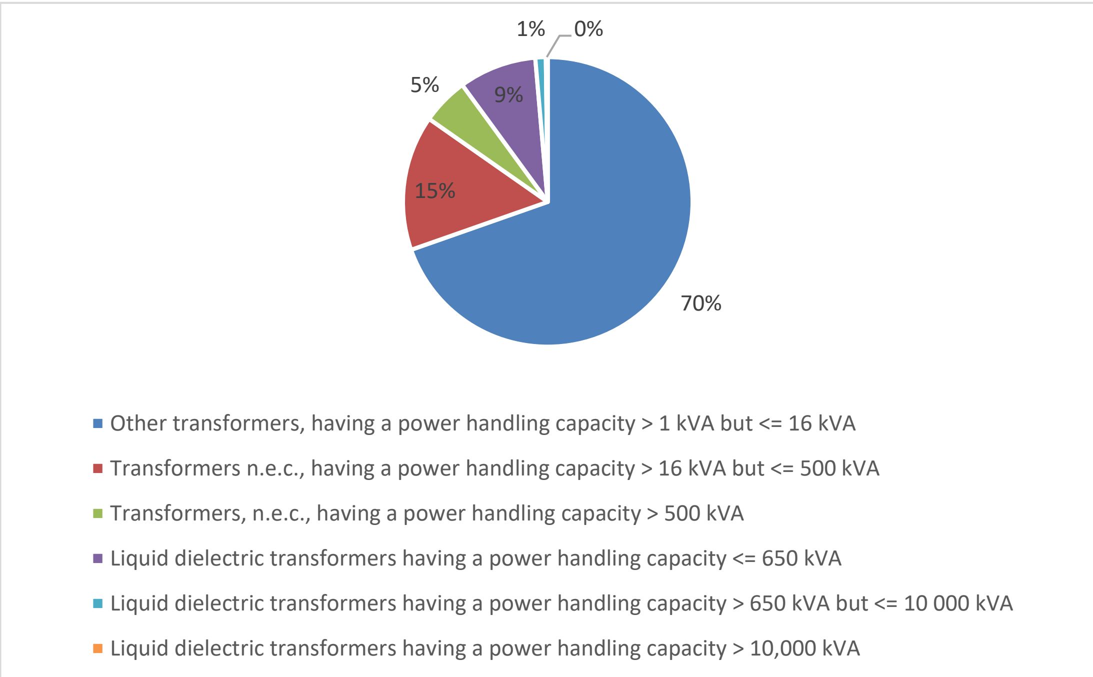
Small transformers dominate the market in terms of numbers, while those of large transformers are very small. Regarding the future transformers stock in the EU, Figure 21 and Figure 22 show the numbers with respect to different types of transformers. The future annual sales for transformers are described in Figure 22.

Figure 19: Apparent consumption for each transformer type, averaged over three- and two-year periods



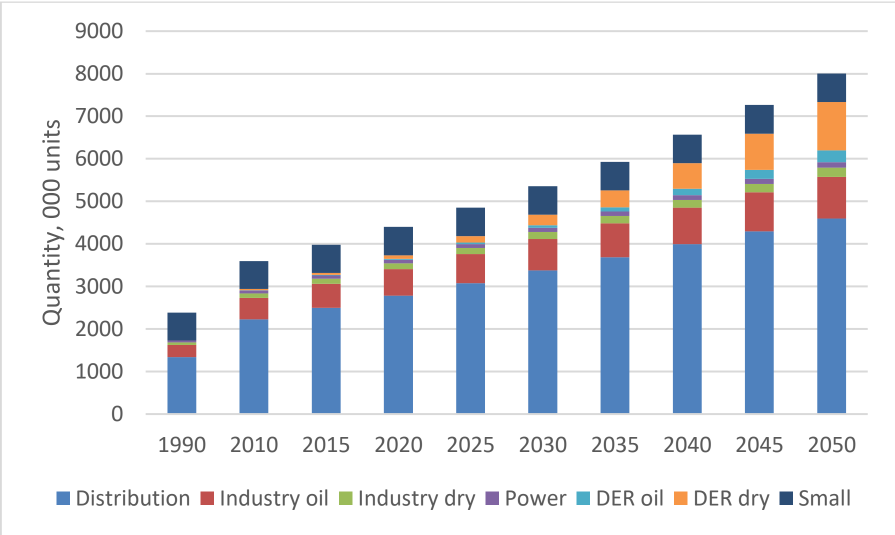
Source: (ICF, 2024)

Figure 20: EU transformer consumption market share by units from 2021-2022



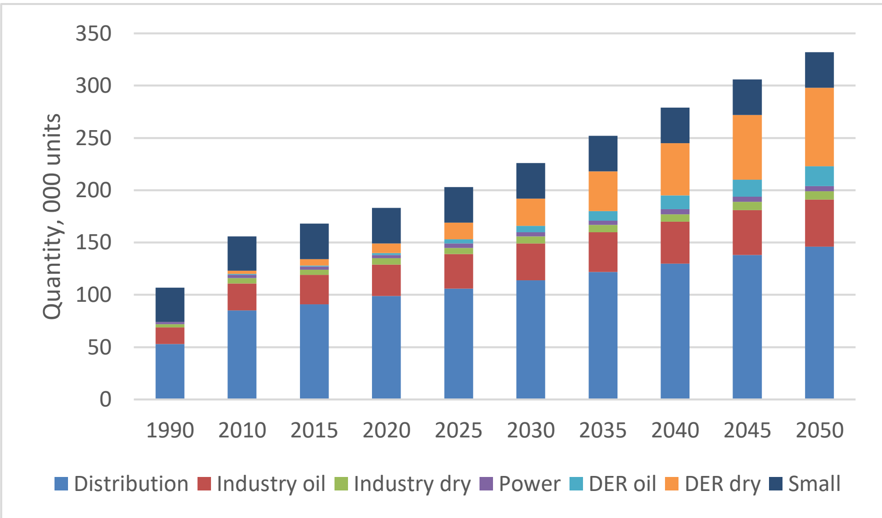
Source: (ICF, 2024)

Figure 21: EU-27 transformer installed stock



Source: (ICF, 2024)

Figure 22: EU-27 transformer annual sales (units) to 2050



Source: (ICF, 2024)

The above tables and diagrams show the situation in the EU with respect to the transformers market: imports, exports, production and consumption. It is shown the EU competitiveness at global level along with the complexity of the transformers' market together with the market of materials and components of theirs. Future policies in the field, together with policies for the environment and the materials of transformers will play a key role in the overall picture and the future of transformers' industry.

4 Conclusions

To support the energy transition, the grid is undergoing significant changes and upgrades. Given the rapid growth of the grid, it is forecasted that the average annual grid investments will be up to 520 billion dollars during 2022 – 2030, whereas the amount spent in 2021 came up to 308 billion dollars. It is also forecasted that this amount will increase further, reaching 1034 billion dollars yearly for the period 2031 – 2050. In addition, investments in the electricity grid until 2030 represent around 30% of total power sector investments, whereas this number will rise up to 45% by the year 2050.

Within the broad scope of technologies to support the smart grid, the present report has focused on grid infrastructure and in particular on grid assets that have been selected for their relevance and timely importance. The analysis in Section 2 has extended the study on High-Voltage Direct-Current (HVDC) connections presented in last year's CETO report (De Paola, Andreadou, & Kotsakis, 2023) by focusing on Alternating Current (AC) wires and cables, widely considered as one of the key enablers of the energy transition. The analysis in Section 3 has instead focused on the topic of power transformers. The main conclusions regarding the key technology development needs and trends and future development options are summarized next:

Alternating Current (AC) wires and cables

- Electricity lines and cables rely almost exclusively on well-established and mature technologies with conventional conductors. Potential alternatives, such as the use of superconductors or high-temperature low-sag conductors, are still at a laboratory or prototype stage.
- European companies are leaders in the sector of wires and cable manufacturing, both for high-voltage transmission products and for medium or low-voltage distribution assets.
- The EU network will double its transmission connections by 2050 and add around 3,000,000 km of new distribution connections. The increasing age of existing EU assets will also require substantial replacements: more than 7 million km of lines (including about 300,000 km of transmission lines) will have to be renewed by 2050.
- These substantial grid expansions will have significant material requirements, particularly in terms of copper and aluminium. The supply chains of these materials are expected to keep up in the short term but, on the medium-long term, there are potential risks of disruption due for example to high demand and the concentration of refined copper production.

Power transformers

- Power transformers are categorised as TRL9 (Technology Readiness Level 9), meaning that the actual system is proven in operational environment.
- It is estimated that there are 4.5 million transformers (within the EU plus Norway) installed, and this value is expected to double until 2050.
- Transformers are 99% efficient; as they need to support the smart grid, transformers are starting to be equipped with intelligent electronic devices and artificial intelligence (AI) techniques are being used to manage these assets.
- Manufacturing of transformers requires high level of technical expertise and specialised labour. It remains relatively labour-intensive
- Lifetime of transformers is around 30-40 years, which can reach up to 50 years, which is considered the end of their "life" and can be recycled.
- There is a shortage in transformers and increased lead times.
- The main players of EU-27 manufacturers are: ABB, Siemens, Areva, Schneider Electric, Cotradis, Efacec, Pauwels, SGB/Smit, Transfix, GE, Hitachi and Vijai.
- The global market of transformers was estimated to 22.83 billion US dollars in 2022; it is estimated to grow up to 38.91 billion US dollars until 2030.

All of the above, prove the importance of grid cables and transformers and reveal their key role in the future smart grid and consequently for the realization of the energy transition.

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List of abbreviations and definitions

Abbreviations	Definitions
AC	Alternating Current
APS	Announced Pledges Scenario
CAAGR	Compound Average Annual Growth Rate
CETO	Clean Energy Technology Observatory
DC	Direct Current
EHV	Extra High Voltage
EMDEs	Emerging Market and Developing Economies
ETS	Economic Transition Scenario
GIL	Gas-Insulated Lines
GOES	Grain Oriented Electrical Steel
HV	High Voltage
HVDC	High Voltage Direct Current
HTS	High-Temperature Superconductor
IoT	Internet of Things
IPC	International Patent Classification
NEMA	National Electrical Manufacturers Association
NZE	Net-Zero Energy
NZS	Net-Zero Scenario
PEI	Power Efficiency Index
STEPS	STated Policies Scenario
TRL	Technology Readiness Level
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
XLPE	Cross-Linked Polyethylene

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Annexes

Annex 1 Summary Table of Data Sources for the CETO Indicators

Theme	Indicator	Main data source
Technology maturity status, development and trends	Technology readiness level	(ENTSO-E, 2024) (IEA, 2023a) (NREL, Feb 2024) (ICF, 2024) (Eurelectric, 2023, January) (McKinsey, 2024, February)
	Installed capacity & energy production	(IEA, 2023a) (IEA, 2023b) (IEA, 2022) (Compass Lexecon, 2024) (Eurelectric, 2024)
	Technology costs	(PwC, 2003) (ACER, 2023) (IEA, 2023a)
	Public and private RD&I funding	
	Patenting trends	(fiveIPoffices, 2022) (European Patent Office, 2024)
	Scientific publication trends	Horizon 2020 and Horizon Europe database
	Assessment of R&I project developments	
Value chain analysis	Turnover	(IEA, 2023b) (IRENA, 2021) (IEA, 2023a) (Grand view research)
	Gross Value Added	(IEA, 2023d) (Compass Lexecon, 2024) (IEA, 2023b)
	Environmental and socio-economic sustainability	(Eurelectric, 2024) (Euractiv, 2024)
	EU companies and roles	Discussions with stakeholders
	Employment	
	Energy intensity and labour productivity	(Banovic, 2024)

		(T&D World, 2022) (Kann, 2024)
	EU industrial production	(Lexecon, 2024, June) (Euractiv, 2024) (Mackenzie, 2024) (T&D World, 2022)
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections	(IEA, 2023d) (Compass Lexecon, 2024) (IEA, 2023b) (ICF, 2024) (Grand view research)
	EU market share vs third countries share, including EU market leaders and global market leaders	(IEA, 2023d) (Compass Lexecon, 2024) (Banovic, 2024) (IEA, 2023b) (ICF, 2024) (Grand view research) (Eurelectric, 2023, January)
	EU trade (imports, exports) and trade balance	(ICF, 2024) (Euractiv, 2024)
	Resource efficiency and dependencies (in relation EU competiveness)	

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