# Study for the review of Commission Regulation 2019/1783 (Ecodesign of small, medium and large power transformers)

## Phase 2 report – Study Update (Draft)

September 2024

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# Document Control

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# 1 Task 1: Definition

## 1.1 General context and scope

The aim of Task 1 is to classify and define the products covered by the review of Commission Regulation (EU) 2019/1783 which amended the original Regulation for power transformers Regulation No 548/2014. The classification and definitions shall be in line with European Union (EU) product harmonisation legislation as well as from a technical, functional, economic, and environmental viewpoint. This classification and definition will be used as the basis for the review study.

The general scope of Regulation (EU) 2019/1783 has been defined by the European Commission to cover power transformers with a minimum power rating of 1 kVA used in 50 Hz electricity transmission and distribution networks or industrial applications. The objective of this chapter is to determine the product groups that are within Regulation (EU) 2019/1783. In the following sections product scope, measurement, test standards and current legislation relating to Regulation (EU) 2019/1783 will be discussed in detail. The project team intends to define this basic product scope with a focus on the environmental and economic aspects of power transformers.

## 1.2 Product definition

### 1.2.1 Product categories found in PRODCOM

In the EU import, export and production statistics are presented annual according to the PRODCOM database. NACE codes are first used to statistical classify economic activities in the EU. Using the Eurostat database it was determined that transformers fit within is a specific NACE code, the relevant code is:

NACE 27.11 “Manufacture of electric motors, generators and transformers” Power transformers also fit within the NACE category “Repair of electrical equipment” (NACE 33.14). However, this only looks at the repair of the current stock of transformers rather than the production values and import or export values to and from EU-27 Member States. Furthermore, this category also encompasses all other electrical equipment, thus, concerns were raised since there is no way of isolating the data for transformers.

PRODCOM codes are made up of 8-digits, the first 4-digits correspond to the NACE code as mentioned above, the first 6-digits are the uses to identify the statistical classification of Products by Activity (CPA), with the final 2-digits specifying the product type. The PRODCOM codes covered that are relevant to this study are classified by the following six PRODCOM codes:

- **27.11.41.20** - Liquid dielectric transformers having a power handling capacity <= 650 kVA.
- **27.11.41.50** - Liquid dielectric transformers having a power handling capacity > 650 kVA
- **27.11.41. 80** - Liquid dielectric transformers having a power handling capacity > 10,000 kVA
- **27.11.42.60** - Other transformers, having a power handling capacity > 1 kVA but <= 16 kVA.

- **27.11.43.30** - Transformers n.e.c., having a power handling capacity > 16 kVA but <= 500 kVA
- **27.11.43.80** - Transformers, n.e.c., having a power handling capacity > 500 kVA

The six codes were obtained from PRODCOM as they most closely align with the products in scope of this study. However, there are some concerns when using this PRODCOM data, where the codes and their scope are not completely clear:

- The scope of all the PRODCOM codes is very broad and is only broken down by whether it is a dry or liquid type transformers. Therefore, transformers that the regulation doesn't apply to could be included in these values.

### 1.2.2 Product categories defined under Ecodesign regulation

Small, medium, and large power transformers have been regulated since 2014 within the Ecodesign Regulation (EU) 548/2014. This regulation introduced the following definitions for: power transformers, small power transformers, medium power transformers, large power transformers, liquid-immersed transformer, dry-type transformers, medium power pole mounted transformers, and Voltage Regulation Distribution Transformer.

The commission undertook a review study on the previous Regulation (EU) 548/2014 and the subsequent amendments that came from this review study were published in Regulation (EU) 2019/1783. While most definitions from (EU) No 548/2014 were retained in (EU) No 2019/1783, the definitions for medium power transformers, large power transformers and medium power pole-mounted transformers were updated in the 2019 review. The definitions provided in 2019/1783 remained largely the same as the ones provided in the original Regulation (EU) 548/2014. The scope and definitions for the amended regulation are as follows:

- The Regulation sets out the Ecodesign requirements for placing on the market or putting into service power transformers with a minimum power rating of 1 kVA used in 50 Hz electricity transmission and distribution networks or for industrial applications.
- **'Power transformer'** means a static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of alternating voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.
- **'Small power transformer'** means a power transformer with a highest voltage for equipment not exceeding 1,1 kV.
- '**Liquid-immersed transformer'** means a power transformer in which the magnetic circuit and windings are immersed in liquid.
- **'Dry-type transformer'** means a power transformer in which the magnetic circuit and windings are not immersed in an insulating liquid.
- **'Voltage Regulation Distribution Transformer'** means a medium power transformer equipped with additional components, inside or outside of the transformer tank, to automatically control the input or output voltage of the transformer for on-load voltage regulation purposes.

The 2019 review study Regulation (EU) 2019/1783[1] amended the definitions for medium and large power transformers, and medium power pole mounted transformers. The revised definitions for these products are provided below:

- **'Medium power transformer'** means a power transformer with all windings having rated power lower than or equal to 3 150 kVA, and highest voltage for equipment greater than 1,1 kV and lower than or equal to 36 kV.
- '**Large power transformer'** means a power transformer with at least one winding having either rated power greater than 3 150 kVA or highest voltage for equipment greater than 36 kV.
- **'Medium power pole-mounted transformer'** means a power transformer with a rated power of up to 400 kVA suitable for outdoor service and specifically designed to be mounted on the support structures of overhead power lines.

## 1.2.3 IEC 60076 standards and upcoming updates

This section will provide an overview of the existing IEC 60076 standards and its upcoming updates. The IEC 60076 series of standards provides the definitions, measurement and testing methods that allow the harmonic quantification of a power transformers performance. Section 2.1.2.1 of the Phase 1 report summarises the full list of IEC 60076 series of standards in detail.

CENELEC is the European Committee for Electrotechnical standardization, who are responsible European standardization in the area of electrical engineering. CENELEC has fully harmonised the IEC 60076 series of standards into EN standards. The Regulation's harmonised standards are referred to as the EN 60076-X series. CENELEC also developed the EU's own series of standards which are based upon the IEC standards, these are known as EN 50708 series of standards. This series of standards has many similarities with the international standard but is more tailored to the EU's requirements. As previously mentioned in the Phase 1 report, the CENELEC adopts elements of the IEC standards within its own series of standards called EN 50708-X series. At the time of writing this report the 'EN 50708-1- Common requirements' standard is also undergoing a review with CENELEC TC 14 publishing the draft version prEN 50708-1-1: 2023 in August 2023[2].

### 1.2.3.1 Revision of IEC 60076-1: 2011

The 'IEC 60076-1 Power transformers – General' standard is currently being revised since the previous version dates back to 2011. The revision may have significant implications on this review study of Regulation (EU) 2019/1783. Therefore, the Commission will continue to work closely with CENELEC thus, ensuring that when the standard is published the Regulation continues to align closely with it. The updated version of IEC 60076-1 is due to be published at the beginning of 2025[3], with the initial proposal having been shared with the study team. This timeframe will mean that the updated standard is due to be published after the findings of this review are published. There are specific updates which have been highlighted by the study team which should be discussed, since these updates could impact the Regulation. Firstly, IEC 60076-1:2011 did not define medium or large power

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[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1783

[2] https://global.ihs.com/doc_detail.cfm?document_name=PREN%2050708%2D1%2D1&item_s_key=00794906 Extracted {04/04/2024}

[3] https://www.iec.ch/dyn/www/f?p=103:23:708247011980236::::FSP_ORG_ID,FSP_LANG_ID:1224,25

transformers within its list of definitions. One of the significant updates to IEC 60076-1 is the addition of definitions for medium and large power transformers.

These definitions are currently still being drafted by the IEC TC 14. However, it looks likely the new standard's definition for medium and large power transformers are set to classify transformers in a different range of voltages than what is provided by EN 50708 and the Regulation. Medium power transformers are to be defined by having a highest rated power of the highest rated winding > 3,150 kVA. While large transformers are to be defined as products where the highest rated power of the highest rated winding is > 31.5 MVA.

Furthermore, the new standard has defined small power transformers. Previously, this definition was not included in either the IEC standard or the Regulation. The draft IEC standard defines small transformers as transformers with a highest rated power of the highest rated winding ≤ 3,150 kVA.

### *Updates to IEC 60076-1 definitions*

As per feedback received from CENELEC the new draft version of IEC 60076-1:2023 is due to contain a new definition for power transformers. The standard currently defines a power transformer as *"a static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power"*[4].

This definition meant that static pieces of equipment which transform a system of alternative voltage into another system of voltage and current at the same frequency could not be considered within the scope of TC14. Therefore, it was seen as preventing the development of innovative technologies. For example, technologies which can transform a system of alternative voltage into another system of voltage and current. Additionally, the current definition does not define the limits and applications of other technologies providing the transformation of a system of alternating voltage and current into another system of voltage and current. Thus, excluding more types of transformers from fitting within the scope of the standard, such as electronic power transformers.

The revised definition for power transformer now addresses these shortfalls. It ensures that the new IEC standard takes a technology neutral approach which would define transformers as a device that transmits electrical power by changing alternating voltage and alternating current to another level. As a result of this update the definition adopted by EN 50708 will therefore, be updated. Overall, it is likely that if this update is published by TC14 then the Regulation will adopt it. However, since the standard is due to be published after the results of this study the Regulation will maintain its current definition of power transformers.

The updates made to the IEC 60076-1 standard will directly impact the definitions in EN 50708-1 because the standard currently utilises the definition for power transformers from IEC 60076-1. Therefore, if the new definition is upheld by the draft IEC 60076-1:2023 the EN standard also adopt the technology neutral approach. However, it should be noted that the EN standard shall retain its own definitions for medium and large power transformers.

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[4] https://www.iec.ch/homepage

***Updates to transformer size categorisation within IEC 60076-1***

Table 1.1 provide a comparison of the definitions for small, medium, and large power transformers in the IEC, EN standards and the Regulation. Demonstrating the distinctions between the definitions provided by the IEC and EN standards, in particular the thresholds for both medium and large transformers. As mentioned, the Regulation adopts the definitions from the EN standard, therefore, it closely aligns with the sizes provided here. Table 1.1 demonstrates that the IEC standard determines small transformers as those with a rated power of ≤ 3,150 kVA. Meanwhile the EN standard does not provide a definition of small transformers. Whereas the Regulation defines small power transformers those transformers >1 kVA & <1.1 kV. Meanwhile, medium power transformers as defined by the Regulation and standard align with the small power transformers definition of small power transformers. Similarly, in the IEC standard the definition of medium power transformers describes them as having the same rated power as the large power transformer classified in the EN standard.

Table 1.1 Summary of definitions for transformer provided in the current and revised draft 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<br>> 1,1 and ≤ 36 kV | ≤ 3,150 kVA<br>> 1.1 kV and ≤ 36 kV |
| Large power transformers | Standard does not define this | > 31,5 MVA | > 3,150 kVA<br>> 36 kV | > 3,150 kVA<br>> 36 kV |

It should be noted that there will not be any changes made to the definitions of medium and large power transformers in the draft version of prEN 50708-1:2023. Therefore, this has not been included in Table 1.1. As a result, the regulation shall maintain its current definitions. Likewise, EN 50708-1 does not adopt the new definition for small transformers and therefore, thus, this will also not be included. Therefore, the Regulation will continue to align its definitions with the EN 50708 standard.

## 1.2.4 Distinguishing small and medium transformer sizes

Small and medium transformers are separately defined within Regulation (EU) 2019/1783 because they are used in different applications. Medium power transformers are defined as having a rated power < 3,150 kVA and a highest voltage of > 1.1 kV and < 36 kV. Whereas a small power transformers are those with a highest voltage < 1.1 kV. Since the scope of the Regulation only includes transformers which are > 1 kVA, transformers that are > 1 kVA and < 1.1 kV are defined as small power transformers within the Ecodesign regulation. However, small power transformers within this power range are not required to meet the energy efficiency requirements of the Regulation. They do however, fit within the scope of TC 14 as seen in Table 1.2, which provides the testing methodology for power transformers. Table 1.2 also provides the scope of TC 96 which covers the safety aspects of transformers in the IEC 61558 series of standards.

Table 1.2 Comparison of the transformers within scope of IEC TC 14, TC 96 and the Regulation.

| Technical group/ Regulation | Scope |
|---|---|
| TC 14 | > 1 kVA and > 1000 V |
| TC 96 | < 1000 V |
| Regulation (EU) 2019/ 1783 | > 1 kVA |

The standard IEC 60076-20:2017 provides the test methodology for medium and large power transformers energy efficiency in the Regulation. However, small power transformers do not fit within the scope of TC 14 therefore, as a result they do not have a testing methodology. Table 1.2 displays that the scope of TC 96 applies to small power transformers. However, this standard only considers the safety aspects of power transformers, power supplies, reactors and similar products that do not exceed a supply voltage of 1000 V[5]. Therefore, no testing methodology is provided in either TC 14 or TC 96 for small power transformers.

To summarise the different rated power ranges that are defined by the Regulation, Table 1.3 provides a summary of the definitions for small and medium power transformers.

Table 1.3 Summary of the definitions of small and medium power transformers provided by Regulation (EU) 2019/1783

| Transformer definition in the Regulation | Highest voltage (Um) | Rated power (Sr) |
|---|---|---|
| Small power transformers | Um ≤ 1.1 kV | > 1 kVA and < 5 kVA |
| Medium power transformers | 1.1 kV < Um ≤ 36 kV | 5 kVA ≤ Sr < 40 MVA |

As discussed in Section 1.2.3 there are due to be updates made to the definitions of small, medium and large power transformers. Nevertheless, despite the additions to the definitions of IEC 60076-1 standard. It is expected that the definition for small and medium transformers in the regulation will remain the same. This aligns with the draft EU standard prEN 50708-1, as shown in Table 1.1 **Error! Reference source not found.** which will maintain the current definitions for small and medium transformers. However, aligning the definition of medium power transformers with the TC14 scope may facilitate any confusion that is caused by small power transformers defined by the Regulation.

Despite the changes to the definitions of small and medium power transformers in the draft IEC 60076 standard, there will be no change to the scope of TC 14. Table 1.1 demonstrates that the scope of the draft IEC 60076 standard will remain the same and continue to not include small power transformers as defined by the Regulation within it. TC96 covers transformers that are < 1000 V, however, this standard only covers the safety aspects of these transformers. Thus, no testing methodology exists for transformers that are > 1 kVA and > 1 kV.

### 1.2.5 Categorisations under dry and liquid types

This section will hyperlink to the Phase 1 section which covers the items: *d) the possibility to adopt a technology-neutral approach to the minimum requirements set*

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[5] https://www.iec.ch/dyn/www/f?p=103:7:::::FSP_ORG_ID:1292

*out for liquid-immersed, dry-type and, possibly, electronic transformers; & p) functional categorisation of power transformers (including conventional transformers, overload transformers and fire performant transformers and any others that the contractor may suggest).*

## 1.3 Measurement and test standards

### 1.3.1 Relevant test standards

This section will hyperlink to the Phase 1 section which covers the item: *j)an analysis of the standards, and their relevance for regulatory purposes*.

### 1.3.2 PEI test methodology

This section will hyperlink to the Phase 1 section which covers the item: *c) the possibility of utilising the PEI calculation for losses alongside the losses in absolute values for medium power transformers*.

## 1.4 Existing legislation and agreements

This section identifies existing legislation that may affect power transformers. This is considered at the European and Member State level as well as Third Countries (e.g. UK and USA).

### 1.4.1 Existing EU regulations

#### 1.4.1.1 Commission Regulation (EU) No 2019/1783 for small, medium, and large power transformers

The first Ecodesign requirements for power transformers were enforced by Commission Regulation (EU) No 548/2014 taking effect from June 2014. This Regulation developed the first mandatory levels of efficiency for power transformers in the EU from 1st July 2015. The tier 1 requirements set out in (EU) No 548/2014 covered all medium and large power transformers > 1.1 kV. In 2019 a review was conducted on (EU) No 548/2014 with the scope of this to consider if the industry was ready to move onto the more stringent tier 2 efficiency requirements. It also made certain amendments to the previous regulation, such as updating definitions. The review study determined that the industry should continue to have to meet tier 1 requirements until 2021, at which point the performance requirements should be uplifted. Following the study Regulation No (EU) 2019/1783 was published on 1st October 2019.

Regulation (EU) 2019/1783 sets the requirements for power transformers with a minimum power rating of 1 kVA used in 50 Hz electricity transmissions and distribution networks or for industrial applications[6]. While this covers a wide range of transformers there are a significant number of types of transformers which are not within the scope of Regulation (EU) 2019/1783. The list of excluded products is provided in Article 1 of the Regulation, labelled a) to p).

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[6] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1783

Previously the Regulation adopted the harmonised standards from EN 50588 and EN 50629. EN 50588 covered medium power transformers with an Um (rated power) < 36 kV, while EN 50629 related to large power transformers with an Um > 36 kV[7]. The EN 50708-X series supersedes these two standards and now acts as the additional requirements for Regulation 2019/1783. The Regulation adopts the test methods for calculating the energy efficiency of medium and large power transformers using the test methods developed and presented within IEC 60076-20. Both the IEC standard and the EN standard are discussed in more detail in Section 2.1.2.1 of the Phase 1 report.

The energy efficiency requirements set for medium and large power transformers are dependent on the type of power transformer. The measurements that are used to determine energy performance are the minimum peak efficiency index (PEI) or the maximum allowed load and no-load losses. The efficiency metric used is dependent on the type and size of the transformer. Table 1.4 displays the different efficiency measurements used for the distinct types of medium power transformers that are covered by the Regulation.

Table 1.4 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 |

As displayed in Table 1.4 the energy efficiency for large power transformers is determined by its PEI, this applies for both dry and liquid large power transformers across all the rated power ranges. As per the definition of small transformers (see Section 1.2.2) small transformers are excluded from the energy efficiency requirements of the Regulation. Furthermore, there is no testing standard that provides a testing methodology for small power transformers. The IEC 60076 standard only applies to medium and large power transformers. However, small power transformers are still within the scope of the Regulation and must provide information and technical documents when sold in the EU market.

The Regulation sets out the PEI and maximum load or no-load losses within the tables published in Annex 1 of the Regulation[8,9]. The tables shown below (Table 1.4, Table 1.5, Table 1.6, Table 1.7, Table 1.8, Table 1.9, Table 1.10, Table 1.11 and, Table 1.12) present the performance requirements for medium, large power transformers and liquid immersed medium pole mounted power transformers.

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[7] Phase 1 Report - Phase-1-Technical-Analysis-Transformers-Review_Draft.pdf (eco-transformers-review.eu)

[8] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1783

[9] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2014.152.01.0001.01.ENG

### *Minimum energy efficiency requirements for three-medium power transformers with rated power ≤ 3150 kVA*

Table 1.5 Maximum load and no-load losses for three-phase liquid immersed medium power transformers with one winding < 24 kV and the other < 1.1 kV

| | Tier 1 (from 1 July 2015) | | Tier 2 (from 1 July 2021) | |
|---|---|---|---|---|
| **Rated Power (kVA)** | **Maximum load losses (W)** | **Maximum no-load losses (W)** | **Maximum load losses (W)** | **Maximum no-load losses (W)** |
| ≤ 25 | 900 | 70 | 600 | 63 |
| 50 | 1100 | 90 | 750 | 81 |
| 100 | 1750 | 145 | 1250 | 130 |
| 160 | 2350 | 210 | 1750 | 189 |
| 250 | 3250 | 300 | 2350 | 270 |
| 315 | 3900 | 360 | 2800 | 324 |
| 400 | 4600 | 430 | 3250 | 387 |
| 500 | 5500 | 510 | 3900 | 459 |
| 630 | 6500 | 600 | 4600 | 540 |
| 800 | 8400 | 650 | 6000 | 585 |
| 1000 | 10500 | 770 | 7600 | 693 |
| 1250 | 11000 | 950 | 9500 | 855 |
| 1600 | 14000 | 1200 | 12000 | 1080 |
| 2000 | 18000 | 1450 | 15000 | 1305 |
| 2500 | 22000 | 1750 | 18500 | 1575 |
| 3150 | 27500 | 2200 | 23000 | 1980 |

Table 1.6 Maximum load and no-load losses for three-phase dry-type medium power transformers with one winding < 24 kV and the other < 1.1 kV

| | Tier 1 (from 1 July 2015) | | Tier 2 (from 1 July 2021) | |
|---|---|---|---|---|
| **Rated Power (kVA)** | **Maximum load losses(W)** | **Maximum no-load losses (W)** | **Maximum load losses (W)** | **Maximum no-load losses (W)** |
| ≤ 50 | 1700 | 200 | 1500 | 180 |
| 100 | 2050 | 280 | 1800 | 252 |
| 160 | 2900 | 400 | 2600 | 360 |
| 250 | 3800 | 520 | 2600 | 360 |
| 400 | 5500 | 750 | 4500 | 675 |
| 630 | 7600 | 1100 | 7100 | 990 |
| 800 | 8000 | 1300 | 8000 | 1170 |
| 1000 | 9000 | 1550 | 9000 | 1395 |
| 1250 | 11000 | 1800 | 11000 | 1620 |
| 1600 | 13000 | 2200 | 13000 | 1980 |
| 2000 | 16000 | 2600 | 16000 | 2340 |
| 2500 | 19000 | 3100 | 19000 | 2790 |
| 3150 | 22000 | 3800 | 22000 | 3420 |

### *Minimum energy efficiency requirements for power transformers with rated power > 3150 kVA*

Table 1.7 Minimum PEI values for liquid immersed large power transformers

| Rated power (kVA) | Tier 1 (from 1 July 2015) | Tier 2 (from 1 July 2021) |
|---|---|---|
| | Minimum Peak Efficiency Index (%) | |
| 3 150 < $S_r$ ≤ 4 000 | 99,465 | 99,532 |
| 5 000 | 99,483 | 99,548 |
| 6 300 | 99,510 | 99,571 |
| 8 000 | 99,535 | 99,593 |
| 10 000 | 99,560 | 99,615 |
| 12 500 | 99,588 | 99,640 |
| 16 000 | 99,615 | 99,663 |
| 20 000 | 99,639 | 99,684 |
| 25 000 | 99,657 | 99,700 |
| 31 500 | 99,671 | 99,712 |
| 40 000 | 99,684 | 99,724 |

Table 1.8 Minimum PEI values for dry-type power transformers

| Rated power (kVA) | Tier 1 (from 1 July 2015) | Tier 2 (from 1 July 2021) |
|---|---|---|
| | Minimum Peak Efficiency Index (%) | |
| 3 150 < $S_r$ ≤ 4 000 | 99,348 | 99,382 |
| 5 000 | 99,354 | 99,387 |
| 6 300 | 99,356 | 99,389 |
| 8 000 | 99,357 | 99,390 |
| ≥ 10 000 | 99,357 | 99,390 |

### *Minimum energy efficiency requirements for medium pole-mounted transformers*

Table 1.9 Maximum load and no-load losses for medium power liquid immersed pole-mounted transformers

| Rated Power (kVA) | Maximum load losses (in W) | Maximum no-load losses (in W) |
|---|---|---|
| 25 | $B_k$ (725) | $A_0$ (70) |
| 50 | $B_k$ (875) | $A_0$ (90) |
| 100 | $B_k$ (1475) | $A_0$ (145) |
| 160 | $C_k$ + 32% (3102) | $C_0$ - 10% (270) |
| 200 | $B_k$ (2333) | $B_0$ (310) |
| 250 | $B_k$ (2750) | $B_0$ (360) |
| 315 | $B_k$ (3250) | $B_0$ (440) |

### *Minimum energy efficiency requirements for large power transformers*

Table 1.10 Minimum PEI for liquid immersed large power transformers

| Rated power (MVA) | Tier 1 (from 1 July 2015) | Tier 2 (from 1 July 2021) |
|---|---|---|
| | Minimum Peak Efficiency Index (%) | |
| ≤ 0,025 | 97,742 | 98,251 |
| 0,05 | 98,584 | 98,891 |
| 0,1 | 98,867 | 99,093 |
| 0,16 | 99,012 | 99,191 |
| 0,25 | 99,112 | 99,283 |
| 0,315 | 99,154 | 99,320 |
| 0,4 | 99,209 | 99,369 |
| 0,5 | 99,247 | 99,398 |
| 0,63 | 99,295 | 99,437 |
| 0,8 | 99,343 | 99,473 |
| 1 | 99,360 | 99,484 |
| 1,25 | 99,418 | 99,487 |
| 1,6 | 99,424 | 99,494 |
| 2 | 99,426 | 99,502 |
| 2,5 | 99,441 | 99,514 |
| 3,15 | 99,444 | 99,518 |
| 4 | 99,465 | 99,532 |
| 5 | 99,483 | 99,548 |
| 6,3 | 99,510 | 99,571 |
| 8 | 99,535 | 99,593 |
| 10 | 99,560 | 99,615 |
| 12,5 | 99,588 | 99,640 |
| 16 | 99,615 | 99,663 |
| 20 | 99,639 | 99,684 |
| 25 | 99,657 | 99,700 |
| 31,5 | 99,671 | 99,712 |
| 40 | 99,684 | 99,724 |
| 50 | 99,696 | 99,734 |
| 63 | 99,709 | 99,745 |
| 80 | 99,723 | 99,758 |
| 100 | 99,737 | 99,770 |
| 125 | 99,737 | 99,780 |
| 160 | 99,737 | 99,790 |
| ≥ 200 | 99,737 | 99,797 |

Table 1.11 Minimum PEI requirements for dry-type large power transformers with Um < 36 kV

| Rated Power (MVA) | Tier 1 (from 1 July 2015) | Tier 2 (from 1 July 2021) |
|---|---|---|
| | Minimum Peak Efficiency Index (%) | |
| 3,15 < Sr ≤ 4 | 99,348 | 99,382 |
| 5 | 99,354 | 99,387 |
| 6,3 | 99,356 | 99,389 |
| 8 | 99,357 | 99,390 |
| ≥ 10 | 99,357 | 99,390 |

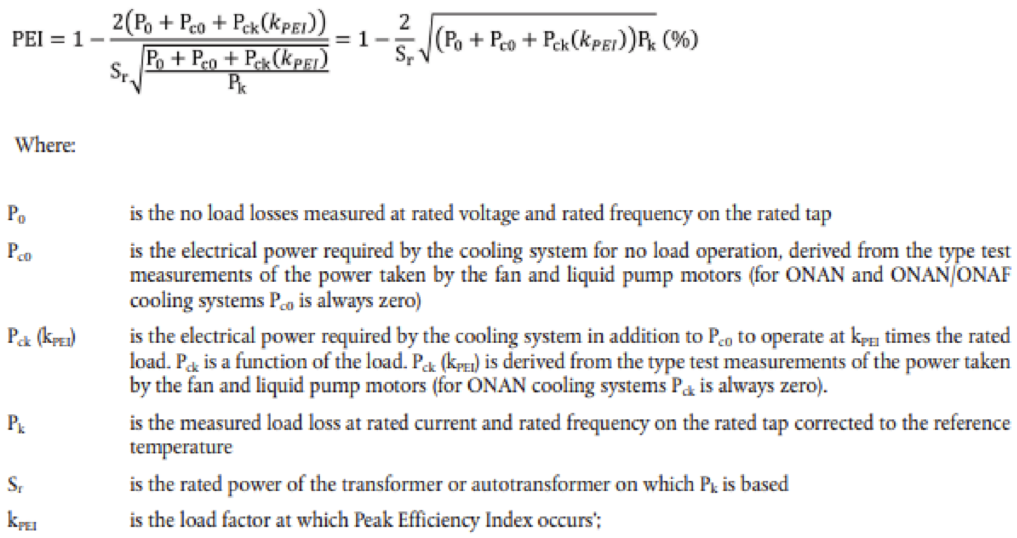
Table 1.12 Minimum PEI for dry-type large power transformers with Um > 36 kV

| Rated power (MVA) | Tier 1 (from 1 July 2015) | Tier 2 (from 1 July 2021) |
|---|---|---|
| | Minimum Peak Efficiency Index (%) | |
| ≤ 0,05 | 96,174 | 96,590 |
| 0,1 | 97,514 | 97,790 |
| 0,16 | 97,792 | 98,016 |
| 0,25 | 98,155 | 98,345 |
| 0,4 | 98,334 | 98,570 |
| 0,63 | 98,494 | 98,619 |
| 0,8 | 98,677 | 98,745 |
| 1 | 98,775 | 98,837 |
| 1,25 | 98,832 | 98,892 |
| 1,6 | 98,903 | 98,960 |
| 2 | 98,942 | 98,996 |
| 2,5 | 98,933 | 99,045 |
| 3,15 | 99,048 | 99,097 |
| 4 | 99,158 | 99,225 |
| 5 | 99,200 | 99,265 |
| 6,3 | 99,242 | 99,303 |
| 8 | 99,298 | 99,356 |
| 10 | 99,330 | 99,385 |
| 12,5 | 99,370 | 99,422 |
| 16 | 99,416 | 99,464 |
| 20 | 99,468 | 99,513 |
| 25 | 99,521 | 99,564 |
| 31,5 | 99,551 | 99,592 |
| 40 | 99,567 | 99,607 |
| 50 | 99,585 | 99,623 |
| ≥ 63 | 99,590 | 99,626 |

### *PEI calculation method*

The Regulation specifies a PEI calculation, this is displayed in Figure 1.1. This calculation brings together load and no-load losses in the same calculation for larger transformers. For medium power transformers only load and no-load losses requirements are specified within the regulation and no PEI requirement is defined.

Figure 1.1 Extract of the PEI calculation from Commission Regulation (EU) 2019/1783[10]



$$\mathrm{PEI} = 1 - \frac{2\left(\mathrm{P}_0 + \mathrm{P}_{c0} + \mathrm{P}_{ck}(k_{PEI})\right)}{\mathrm{S}_r\sqrt{\frac{\mathrm{P}_0 + \mathrm{P}_{c0} + \mathrm{P}_{ck}(k_{PEI})}{\mathrm{P}_k}}} = 1 - \frac{2}{\mathrm{S}_r}\sqrt{\left(\mathrm{P}_0 + \mathrm{P}_{c0} + \mathrm{P}_{ck}(k_{PEI})\right)\mathrm{P}_k}\ (\%)$$

Where:

| | |
|---|---|
| $P_0$ | is the no load losses measured at rated voltage and rated frequency on the rated tap |
| $P_{c0}$ | is the electrical power required by the cooling system for no load operation, derived from the type test measurements of the power taken by the fan and liquid pump motors (for ONAN and ONAN/ONAF cooling systems $P_{c0}$ is always zero) |
| $P_{ck}$ ($k_{PEI}$) | is the electrical power required by the cooling system in addition to $P_{c0}$ to operate at $k_{PEI}$ times the rated load. $P_{ck}$ is a function of the load. $P_{ck}$ ($k_{PEI}$) is derived from the type test measurements of the power taken by the fan and liquid pump motors (for ONAN cooling systems $P_{ck}$ is always zero). |
| $P_k$ | is the measured load loss at rated current and rated frequency on the rated tap corrected to the reference temperature |
| $S_r$ | is the rated power of the transformer or autotransformer on which $P_k$ is based |
| $k_{PEI}$ | is the load factor at which Peak Efficiency Index occurs'; |

### *Information requirements*

On top of the performance requirements for medium and large power transformers the Regulation also requires manufacturers to provide product and technical information. As mentioned, since small power transformers which are > 1kVA and < 1.1 kV are within the scope of the Regulation these are also required to provide this product information. The information requirement entered into force from the 1st July 2015.

The product information included in the scope of the Regulation must be presented in the any form of product documentation, which is free to access on the manufacturer's website. The product information that is reported shall include the following:

a) Information on rated power, load loss and no-load loss and the electrical power of any cooling system required at no load.

b) For liquid filled pole mounted medium power transformers and large transformers, the value for PEI and the power at which is occurs.

c) For dual voltage transformers, the maximum rated power at the lower voltage.

d) Information on the weight of the all the main components of the power transformer.

e) For medium power pole mounted transformers, a visible display 'For pole-mounted operation only'.

In addition, the information under a, c and d shall be included on the rating plate of the power transformer.

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[10] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1783

The technical document that is within the scope of the Regulation includes:

a) Manufacturers name and address
b) Model identifier

### 1.4.2 Third country legislation

*This section will hyperlink to the Phase 1 section which covers the third country legislation.*

### 1.4.3 EU regulation comparison with third countries

This section will hyperlink to the Phase 1 section which covers the item: *l) Ecodesign (or similar) requirements for power transformers in other jurisdictions, in particular the US and Japan and in comparison to current Ecodesign requirements for Tier 2*.

# 2 Task 2: Economic and market analysis

The aim of Task 2 is to research, identify and present a suite of key market data relating to the transformers product group. This includes sales and trade volumes within the EU-27 as well as installed base or “stock” estimates, and annual sales growth rate and replacement rate forecasts. The Task 2 report will also present insight on the latest market trends as well as a set of price data.

## 2.1 Generic economic data

The first sub-task details the following key economic data for the transformers product group, presented in physical units for the year 2022:

- EU import (quantity and value)
- EU export (quantity and value)
- EU production sold (quantity and value)
- Apparent consumption (i.e. EU production quantity + EU import quantity – EU export quantity)

The data presented below are derived from official EU statistics, namely the PRODCOM category covering the product group. 2022 was chosen as the reference year because it represents the latest full year for which EU-27 has reported data into PRODCOM. In 2022, all 27 EU countries have individually reported values to PRODCOM on their imports, exports and production of the six different types of transformers. For this study, the data has been considered for the EU-27 as a whole, and hence not considering the trade made between EU member states.

Table 2.1 presents the available PRODCOM EU-27 data for six different product codes of transformers:

Table 2.1 PRODCOM data for the EU 27 in the year 2022[11]

| **PRODCOM product code and description** | **27.11.41.20**<br>**Liquid dielectric transformers having a power handling capacity <= 650 kVA** | **27.11.41.50**<br>**Liquid dielectric transformers having a power handling capacity > 650 kVA but <= 10 000 kVA** | **27.11.41.80**<br>**Liquid dielectric transformers having a power handling capacity > 10,000 kVA** | **27.11.42.60**<br>**Other transformers, having a power handling capacity > 1 kVA but <= 16 kVA** | **27.11.43.30**<br>**Transformers n.e.c., having a power handling capacity > 16 kVA but <= 500 kVA** | **27.11.43.80**<br>**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 |

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[11] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

| PRODCOM product code and description | 27.11.41.20<br>Liquid dielectric transformers having a power handling capacity <= 650 kVA | 27.11.41.50<br>Liquid dielectric transformers having a power handling capacity > 650 kVA but <= 10 000 kVA | 27.11.41.80<br>Liquid dielectric transformers having a power handling capacity > 10,000 kVA | 27.11.42.60<br>Other transformers, having a power handling capacity > 1 kVA but <= 16 kVA | 27.11.43.30<br>Transformers n.e.c., having a power handling capacity > 16 kVA but <= 500 kVA | 27.11.43.80<br>Transformers, n.e.c., having a power handling capacity > 500 kVA |
|---|---|---|---|---|---|---|
| Sold Production Value (in 1000 €) | 871,153,223 | 862,178,402 | 2,636,363,521 | 318,000,000 | 560,000,000 | 928,477,610 |
| Sold Production (quantity) | 101,968 | 333,727 | 4,187 | 1,957,635 | 1,500,000 | 71,707 |

We have extracted these six codes from PRODCOM as they are the most likely to overlap with the scope of the study. However, there are some concerns when using the PRODCOM data, where the codes and their scope are not completely clear:

- The scope of all the PRODCOM codes is very broad and only breaks them down by dry or liquid type transformers. Therefore, transformers that the regulation doesn't apply to could be included in these values.

Table 2.2 below showcases the value per unit in 2022 for import, export and sold production for each type of transformer, and was calculated by dividing the value by the quantity:

Table 2.2 Transformer value per unit for import, export and sold production in 2022[12]

| PRODCOM product code and description | Import Value per Unit (€) | Export Value per Unit (€) | Sold Production Value per Unit (€) |
|---|---|---|---|
| **27.11.41.20**<br>**Liquid dielectric transformers having a power handling capacity <= 650 kVA** | 119,632,348.24 | 256,118.74 | 8,543,398.15 |
| **27.11.41.50**<br>**Liquid dielectric transformers having a power handling capacity > 650 kVA but <= 10 000 kVA** | 2,788,743.70 | 1,054,880.07 | 2,583,484.11 |
| **27.11.41.80**<br>**Liquid dielectric transformers having a power handling capacity > 10,000 kVA** | 4,970,282.60 | 9,711,652.49 | 629,654,530.93 |
| **27.11.42.60**<br>**Other transformers, having a power handling capacity > 1 kVA but <= 16 kVA** | 11,864.97 | 35,266.17 | 162,826.57 |
| **27.11.43.30**<br>**Transformers n.e.c., having a power handling capacity > 16 kVA but <= 500 kVA** | 111,536.76 | 266,438.28 | 379,332.17 |
| **27.11.43.80** |  |  |  |

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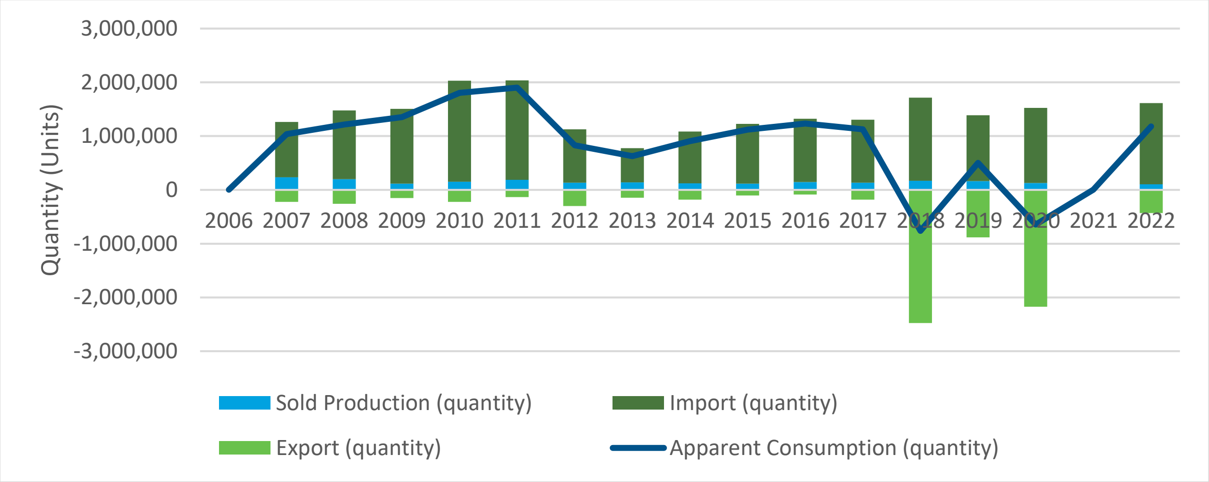
[12] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

|  |  |  |  |
|---|---|---|---|
| **Transformers, n.e.c., having a power handling capacity > 500 kVA** | 212,172.85 | 11,589,013.79 | 12,948,214.40 |

These numbers do not seem realistic, and this is most likely due to inconsistencies within the PRODCOM data. The research team have queried Eurostat about these issues in the data, but they have not commented as of yet.

To analyse the trade from previous years, Figures 2.1 – 2.6 were collated using production, import and export data from PRODCOM for each type of transformer product code. Value of the EU apparent consumption was calculated using the formula: *EU production sold* + *EU import* – *EU export.* Certain years were omitted due to extreme outliers being present in the data. It is noted that negative apparent consumption is not valid, and this is due to inconsistencies between the statistics for quantity and value of imports and exports.

Figure 2.1 EU-27 trade progression for liquid dielectric transformers having a power handling capacity of <= 650 kVA[13,14]



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[13] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

[14] 2006 and 2021 omitted due to inconsistency.

Figure 2.2 EU-27 trade progression for liquid dielectric transformers having a power handling capacity > 650 kVA but <= 10,000 kVA[15,16]

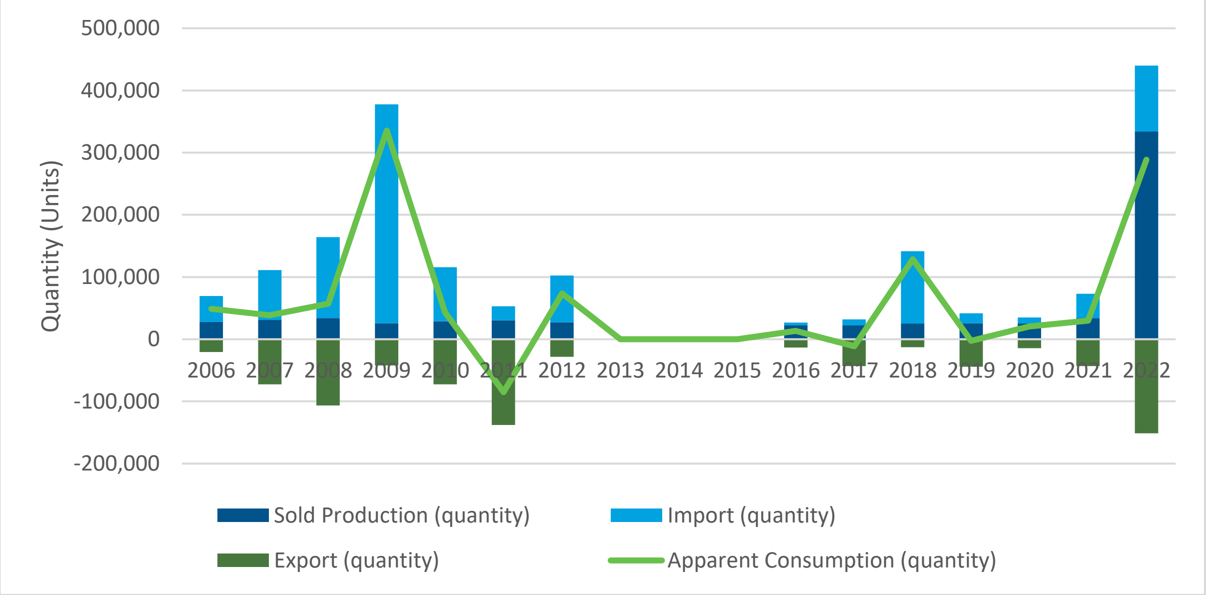
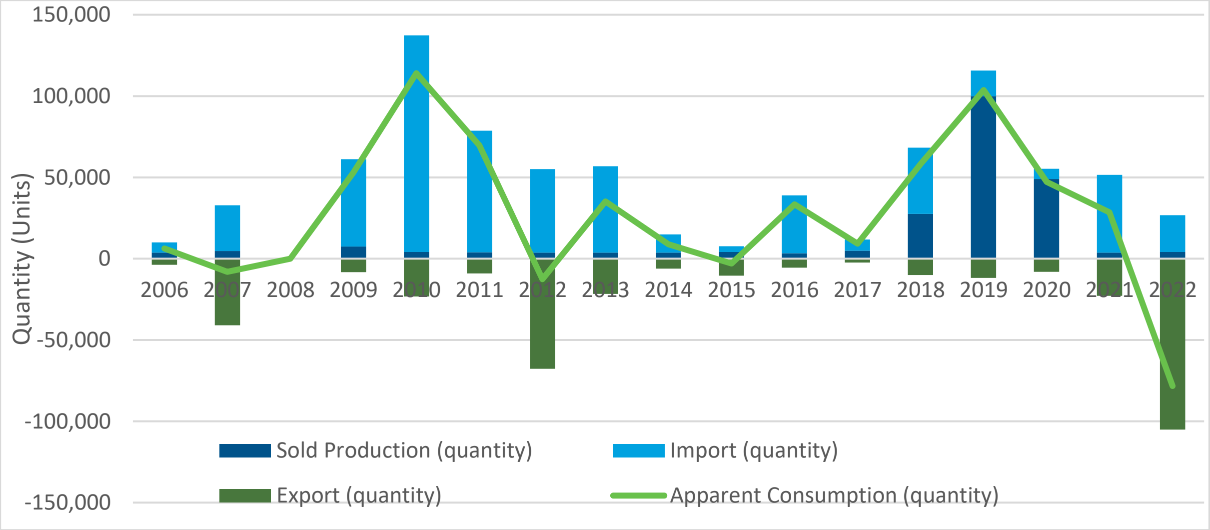


Figure 2.3 EU-27 trade progression for liquid dielectric transformers having a power handling capacity > 10,000 kVA[17,18]



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[15] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

[16] 2013, 2014 and 2015 omitted due to inconsistency.

[17] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

[18] 2008 omitted due to inconsistency.

Figure 2.4 U-27 trade progression for other transformers, having a power handling capacity > 1 kVA but <= 16 kVA[19]

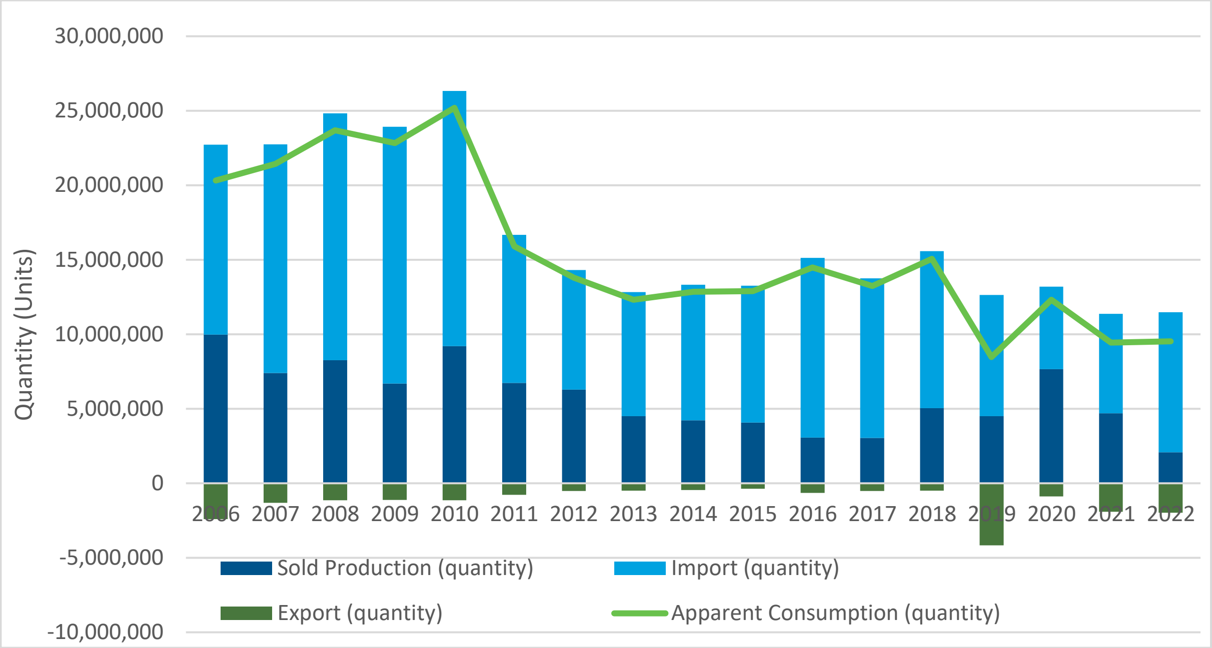
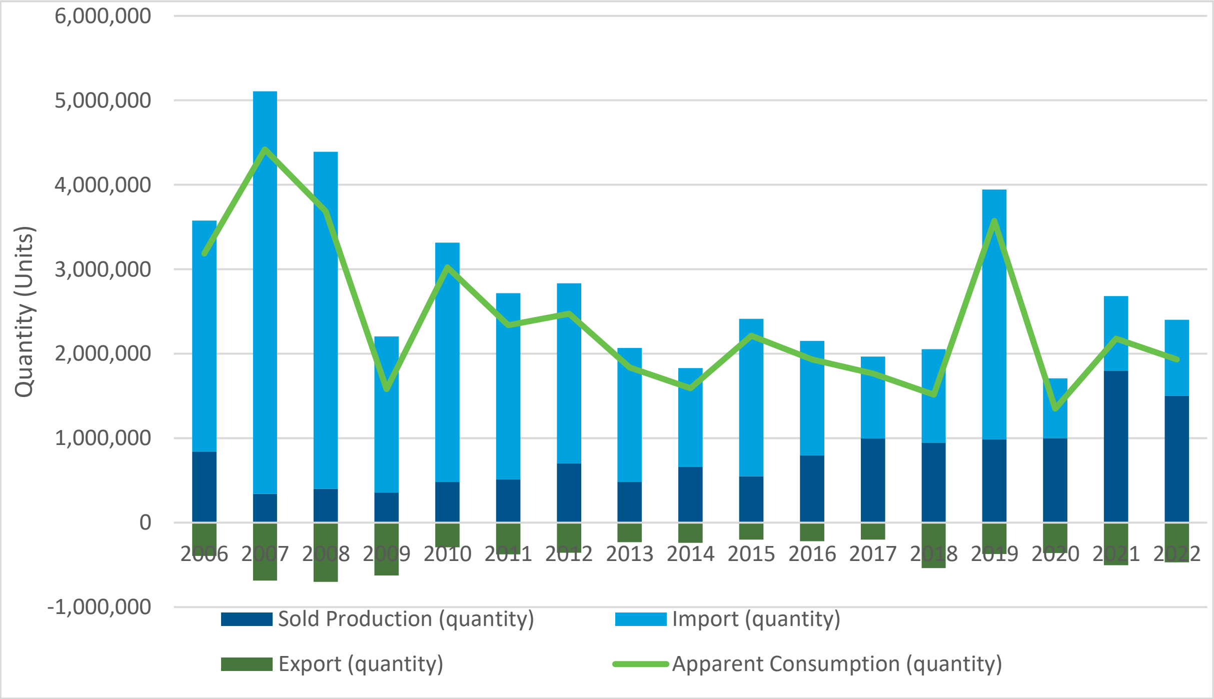


Figure 2.5 EU-27 trade progression for transformers n.e.c., having a power handling capacity > 16 kVA but <= 500 kVA[20]



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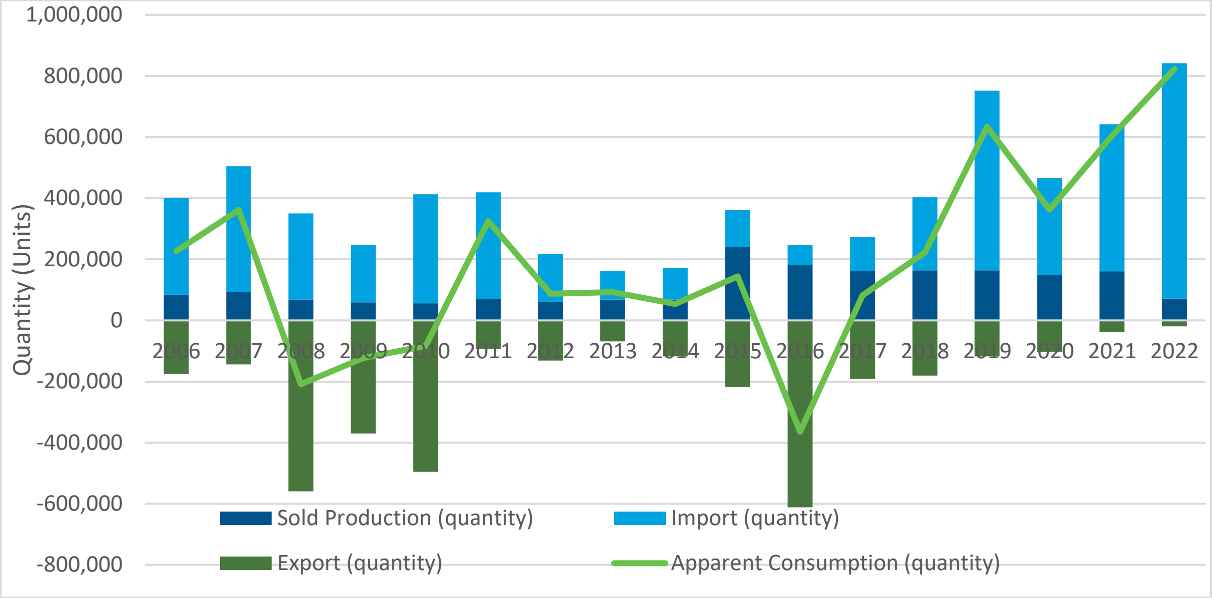
[19] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

[20] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

Figure 2.6 EU-27 trade progression for transformers, n.e.c., having a power handling capacity > 500 kVA[21]



The market data from PRODCOM shows that the low voltage transformer, having a power handling capacity > 1 kVA but <= 16 kVA (Figure 2.4), has by far the largest market segment, with an apparent consumption of over 9.5 million units in 2022. This is over 7.6 million units larger than the next largest category, transformers n.e.c., having a power handling capacity > 16 kVA but <= 500 kVA (Figure 2.5). However, it has decreased significantly from its peak apparent consumption level of over 25 million units in 2010.

To avoid any negative apparent consumption values, these values were omitted, and average values were calculated over every three-year period except for 2021-2022 (due to the total amount of years not being a multiple of 3).

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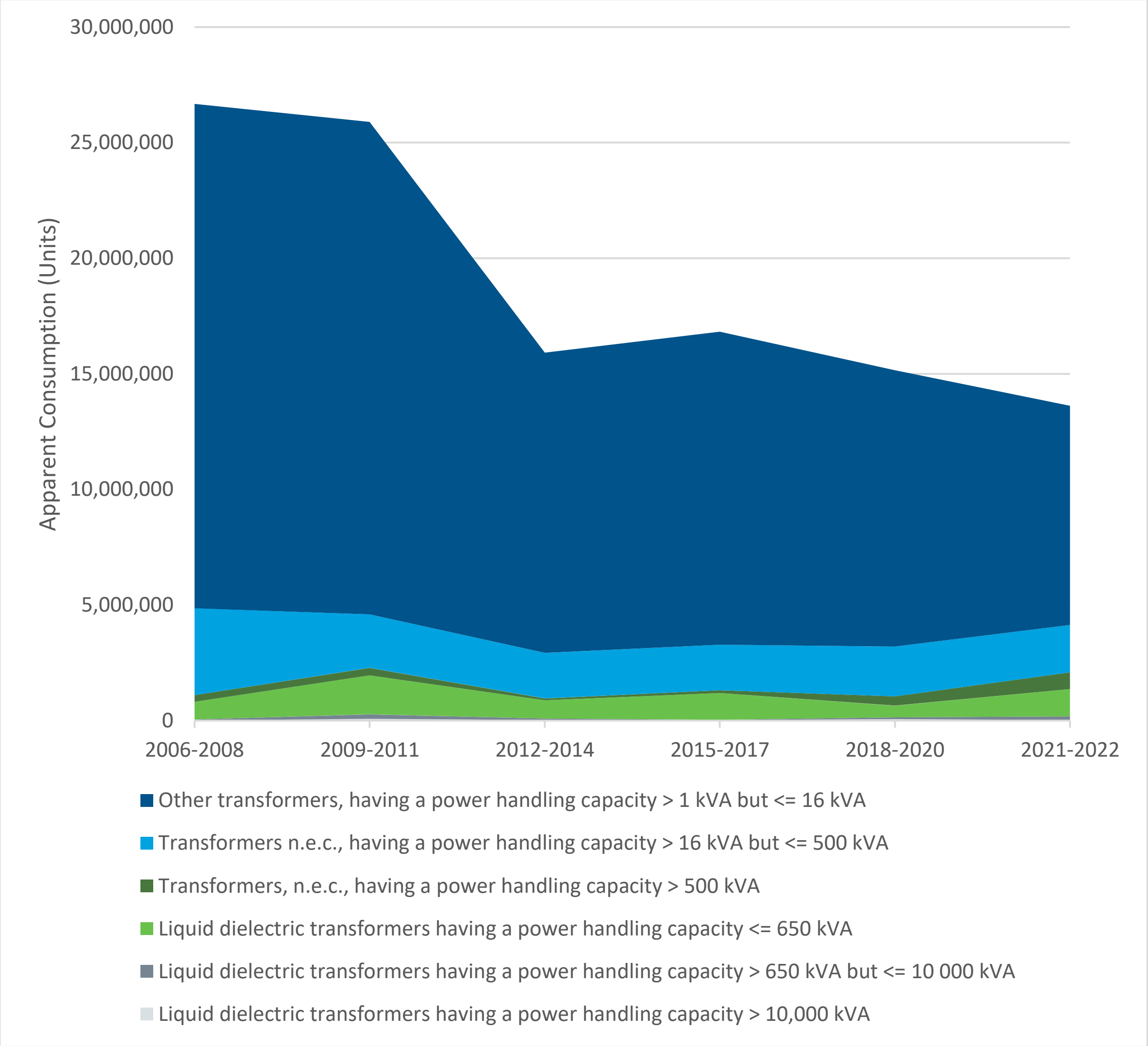
[21] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

Figure 2.7 Apparent consumption for each transformer type, averaged over three- and two-year periods[22]



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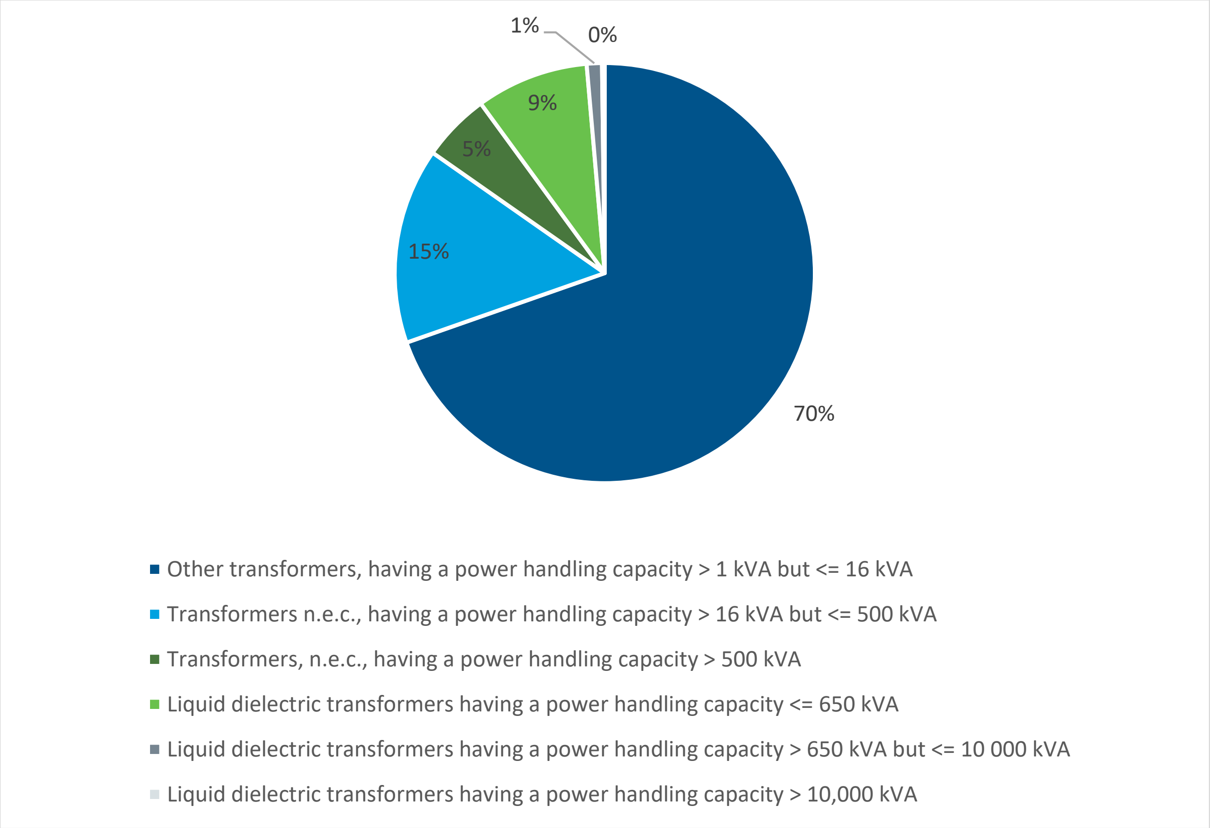
[22] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

Figure 2.8 Apparent consumption market share from 2021-2022[23]



As shown in the above figures, small transformers dominate the market share, with the large transformer market share being very small.

## 2.2 Market and stock data

The second sub-task details the following market and stock data for the transformers product group, presented in physical units for the EU-27:

- Installed base (stock)
- Annual sales growth rate
- Average technical and economic product life
- Replacement and retrofit rates

### 2.2.1 Stakeholder engagement

The study team approached manufacturers and suppliers to participate in this study. Six quantitative questionnaires were submitted by stakeholders.

### 2.2.2 Installed base stock

Data from the Ecodesign Impact Accounting (EIA) annual report 2021 was used to determine the sales and stock of various types of transformers from 1990 – 2050[24].

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[23] Database - Prodcom - statistics by product - Eurostat (europa.eu) [extracted on 25/01/2024]

[24] https://op.europa.eu/en/publication-detail/-/publication/392bc471-76ae-11ed-9887-01aa75ed71a1/language-en

The stock in a given year consists of products sold in that year and of products sold in previous years that have not yet reached their end-of-life, and is calculated via the following formula:

$$Stock_0 = \sum_{t=0}^{-Life} Sales_t$$

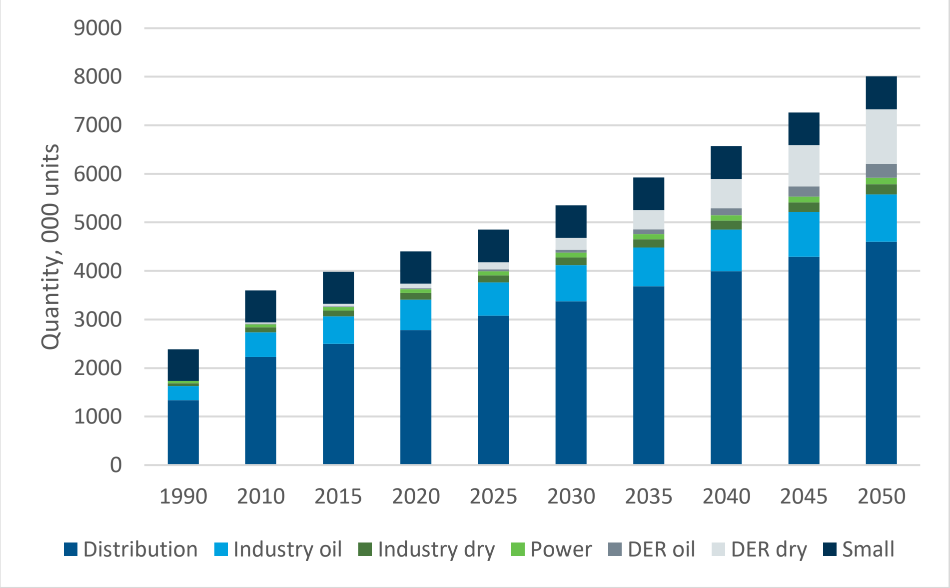
The EIA report categorises the transformer types as follows, which are the representative power ranges considered (i.e. the figures are sums of transfers which average out to the power rating of each transformer type):

Table 2.3 EIA transformer categories[25]

| Transformer Type | Power rating | P0 (No-load losses) | Pk (Load losses) |
|---|---|---|---|
| Distribution | 400 kVA | 750 W | 4600 W |
| Industry oil | 1 MVA | 17000 W | 10500 W |
| Industry dry | 1.25 MVA | 2800 W | 13100 W |
| Power | 100 MVA | 40.5 kW | 326 kW |
| DER oil | 2 MVA | 3.1 kW | 21 kW |
| DER dry | 2 MVA | 4 kW | 18 kW |
| Small | 16 kVA | 110 W | 750 W |

Figure 2.9 below presents the stock data according to the transformer definitions used by this EIA report:

Figure 2.9 EU-27 transformer installed stock[26]



It can be seen above that 400 kVA range distribution transformers are expected to dominate the market share in terms of stock, with the DER dry and DER oil transformers increasing the most.

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[25] https://op.europa.eu/en/publication-detail/-/publication/392bc471-76ae-11ed-9887-01aa75ed71a1/language-en [extracted on 04/04/2024]

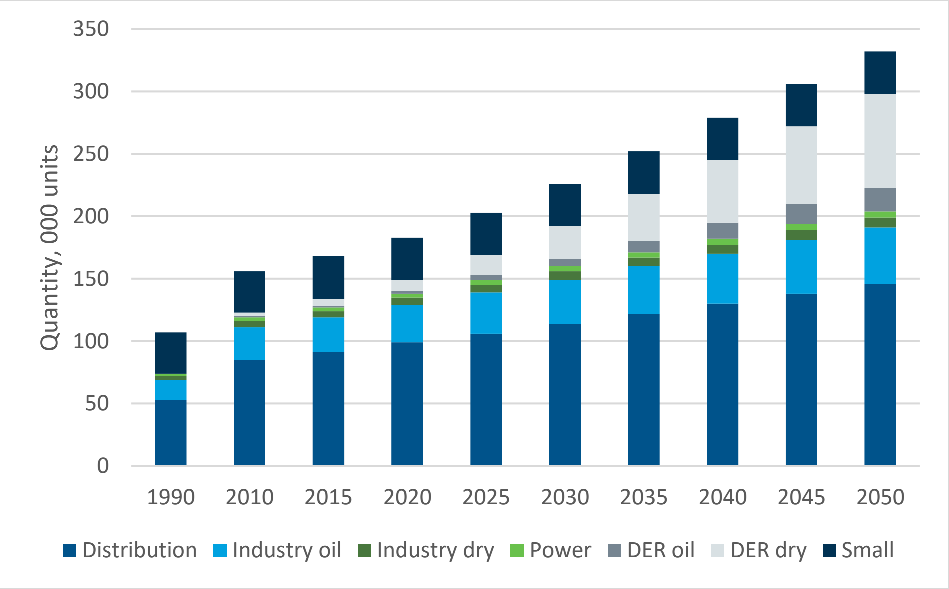
[26] https://op.europa.eu/en/publication-detail/-/publication/392bc471-76ae-11ed-9887-01aa75ed71a1/language-en [extracted on 04/04/2024]

### 2.2.3 Annual sales growth rate

The Europe distribution transformer market is expected to continue to grow. This is due to high energy and power consumption across industrial and residential sectors, growing demand for distribution transformers, the growth of renewable energy generation, smart grid infrastructure development, and research and development investments in these.

The EIA 2021 report's projections for transformer sales within the EU-27 until 2050 are shown below in Figure 2.10.

Figure 2.10 EU-27 transformer sales[27]



From this, the sales growth rate for each transformer type was determined for the given time intervals:

Table 2.4 EU-27 transformer sales growth rate[28]

| Year | 1990 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|
| Distribution | - | 60% | 7% | 9% | 7% | 8% | 7% | 7% | 6% | 6% |
| Industry oil | - | 63% | 8% | 7% | 10% | 6% | 9% | 5% | 8% | 5% |
| Industry dry | - | 67% | 0% | 20% | 0% | 17% | 0% | 0% | 14% | 0% |
| Power | - | 50% | 0% | 0% | 33% | 0% | 0% | 25% | 0% | 0% |
| DER oil | - | 0% | 0% | 100% | 100% | 50% | 50% | 44% | 23% | 19% |
| DER dry | - | 0% | 100% | 50% | 78% | 63% | 46% | 32% | 24% | 21% |
| Small | - | 0% | 3% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

Out of these transformer types, sales for the DER oil and DER dry (both 2 MVA) are expected to grow the most by 2050.

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[27] https://op.europa.eu/en/publication-detail/-/publication/392bc471-76ae-11ed-9887-01aa75ed71a1/language-en [extracted on 04/04/2024]

[28] https://op.europa.eu/en/publication-detail/-/publication/392bc471-76ae-11ed-9887-01aa75ed71a1/language-en [extracted on 04/04/2024]

### 2.2.4 Product lifetime

From the 2011 preparatory study it was determined that MV/LV distribution transformers have an average economic lifetime of 30 to 40 years. Industry and DER transformers have a technical lifetime of 25 to 30 years. For power transformers the average economic lifetime is higher about 30 years. For smaller transformers, a lifetime of 10 years was assumed.

Estimates for the technical and economic lifetime for each transformer type are shown below, taken from the 2011 preparatory study. Stakeholders have stated that these estimations are still accurate, and that, in some cases, the technical lifetime is longer than the economic lifetime:

Table 2.5 Economic and technical lifetime for each transformer type

| Transformer Type | Economic lifetime | Technical lifetime |
|---|---|---|
| MV/LV Distribution oil-immersed (400kVA) (24/0,4kV) | 40 years | 60 years |
| Small transformers including Separation/ Isolation (16kVA) (24/0,4kV) | 10 years | |
| Industry oil-immersed (1MV) (24/0,4kV) | 25 years | |
| Industry dry-type (1.25MVA) (24/0,4kV) | 30 years | |
| Power Transformer (100MVA, primary voltage 132kV, secondary voltage 33kV)(132/33kV) | 30 years | 80 years |
| DER oil-immersed (2MVA) (24/0,4kV) | 25 years | |
| DER dry-type (2MVA) (24/0,4kV) | 25 years | |
| Other (from 63 to 400kV / 30 to 600MVA) | 40 years | 80 years |

## 2.3 Market channels

### 2.3.1 Main manufacturers

The major manufacturers in the EU-27 market for transformers are ABB, Siemens, Areva, Schneider Electric, Cotradis, Efacec, Pauwels, SGB/Smit, Transfix, GE, Hitachi and Vijai.

## 2.4 Market Trends

### 2.4.1 Trends regarding transformer power ratings

#### 2.4.1.1 Data on European transformer types and ratings

During the inquiry phase, manufacturers and operators provided technical and economic information. Feedback from 2 stakeholders indicated that the load on a 400 kVA transformer may grow or exceed 400 kVA. Therefore, the existing transformer may be replaced by a larger rated unit, i.e. a 400 kVA unit is replaced by a 630 kVA or 1 MVA unit.

Despite this demand trend, most existing transformers are installed in packaged substations of minimal dimensions. It can be difficult to install larger packaged substations, as the physical sites and existing footprints would constrain the replacement installation size to fit current substation format. 5 stakeholders submitted data for 400 kVA distribution transforms, indicating that this will remain to be the most common power rating for a distribution transformer.

Furthermore, the lifecycle of transformers is 20-40 years. The previous preparatory study in 2011 referenced 400 kVA distribution transformer as base case 1. The market landscape has not changed drastically since then, and thus the assumptions made are still relevant and representative of the technological spectrum of transformers in European markets[29].

#### 2.4.1.2 Flat distribution transformer sales

According to the 2021 EIA report, as illustrated in Figure 2.10 and Table 2.4, the year-on-year growth of 400 kVA distribution transformer sales is linear (6-7%). DER transformers are growing more rapidly, demonstrating higher adoption rates in the renewable energy space. While distribution transformers maintain steady sales growth, DER transformers are leading towards a greener and more sustainable energy future, and thus no rapid infrastructure updates are required to meet the electricity demand for distribution transformers[30].

### 2.4.2 Trends regarding average load factors

The 2011 preparatory study included the following table, summarising the main user parameters for different types of transformers:

Table 2.6 Summary of the main user parameters for different types of transformers[31]

| Typical transformer | Load factors (a) | Load form factors (kf) | Power factor (Pf) | Load factors eq. flat($a_c$) | Avail-ability factor (Af) | B/A TCO ratio ($a_e^2$) | Aver-age Life-time |
|---|---|---|---|---|---|---|---|
| MV/LV distribution oil | 0.15 | 1.073 | 0.9 | 0.18 | 1 | 0.0324 | 40 |
| Industry oil | 0.3 | 1.096 | 0.9 | 0.37 | 1 | 0.1369 | 25 |
| Industry dry | 0.3 | 1.096 | 0.9 | 0.37 | 1 | 0.1369 | 30 |
| Power | 0.2 | 1.08 | 0.9 | 0.24 | 1 | 0.0576 | 30 |
| DER (liquid-immersed and dry-type) | 0.25 | 1.5 | 0.9 | 0.42 | 1 | 0.1764 | 25 |

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[29] 2023 stakeholder feedback

[30] https://op.europa.eu/en/publication-detail/-/publication/392bc471-76ae-11ed-9887-01aa75ed71a1/language-en [extracted on 04/04/2024]

[31] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

| Typical transformer | Load factors (a) | Load form factors (kf) | Power factor (Pf) | Load factors eq. flat($a_c$) | Avail-ability factor (Af) | B/A TCO ratio ($a_e^2$) | Aver-age Life-time |
|---|---|---|---|---|---|---|---|
| Separation/isolation | 0.4 | 1.096 | 0.9 | 0.49 | 0.2 | 0.2401 | 10 |

Due to the long lifetime of these transformers, it is assumed that these parameters are still valid.

A 2022 study corroborates this, showing that medium sized distribution transformer loadings have average load factors around 15%, root mean square (RMS) equivalent average of around 30%, and peak loads close to 80% of nameplate capacity.[32]

### 2.4.3 Impact of renewable energy integration

This section will hyperlink to the Phase 1 section which covers the item *q) a techno-economic analysis on the relevance and feasibility of requirements (in particular for low-to-medium and medium-to-high voltage transformers) related to design features aimed to increase the efficiency and lifetime of transformers when working with reversed power flows (due, for instance, to electricity from renewable energy sources injected in the grid at lower voltage levels).*

### 2.4.4 Market trends on amorphous steel supply chain

The global capacity of amorphous steel of 140,000 tons per year. Compared to the 2.5 million of grain-oriented electrical steel produced in 2009, amorphous metal constitutes less than 6% of the global supply for electrical steel.[33]

Amorphous core materials can decrease the no-load magnetic losses by over 50%. However, they are not yet manufactured within the EU.

One stakeholder has provided data on where amorphous steel material is being manufactured globally, with none being manufactured in the EU-27:

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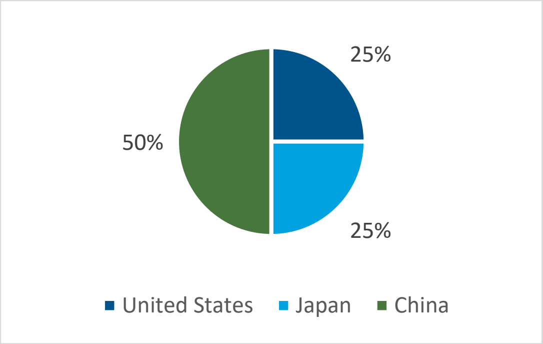
[32] https://www.cargill.com/doc/1432242849725/sustainable-peak-load-transformer-article.pdf [2022, extracted 04/04/2024]

[33] https://www.researchgate.net/profile/Bruno-Santos-77/publication/281638260_Energy-efficient_distribution_transformers_in_Europe_impact_of_Ecodesign_regulation/links/575595c908ae155a87b9962c/Energy-efficient-distribution-transformers-in-Europe-impact-of-Ecodesign-regulation.pdf [2022, extracted 04/04/2024]

Figure 2.11 Amorphous steel countries of manufacture[34]



The stakeholder also provided data on where most of the amorphous core transformers are manufactured for MV/LV Distribution oil-immersed (400kVa) (24/0,4kV) and small transformers including separation/isolation (16kVA) (24/0,4kV) types:

Figure 2.12 MV/LV Distribution oil-immersed (400 kVA) (24/0,4kV) country of manufacture:[35]

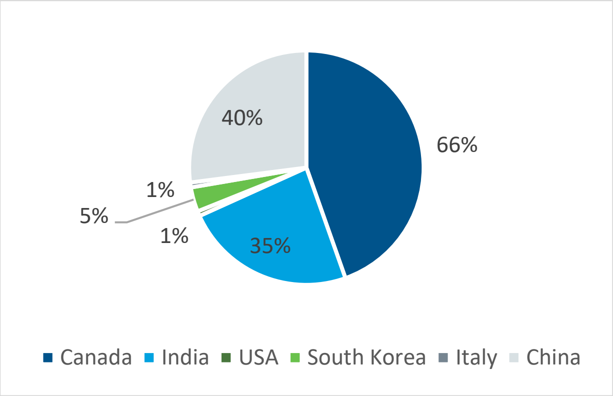
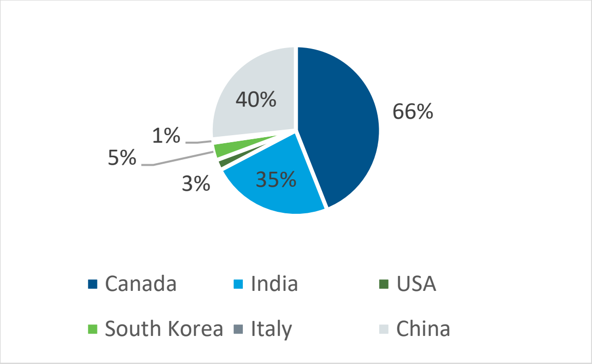


Figure 2.13 Small transformers including separation/isolation (16 kVA) (24/0,4kV) country of manufacture:[36]



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[34] 2024 stakeholder quantitative questionnaire feedback

[35] 2024 stakeholder quantitative questionnaire feedback

[36] 2024 stakeholder quantitative questionnaire feedback

## 2.5 User expenditure base data

### 2.5.1 Transformer prices

This data is presented in Table 2.7 according to the seven transformer categories and was determined by adjusting the prices determined in the 2011 preparatory study for the average EU-27 inflation. Inflation values were obtained from PRODCOM[37]. This is considered to be more accurate than calculating the transformer price from the PRODCOM quantity and value statistics.

Table 2.7 Price per unit for each type of transformer[38]

| Product Type | Range of purchase price (€/ unit) |
|---|---|
| Transformers | |
| 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 |

### 2.5.2 Transformer production costs

One stakeholder provided the following cost data for the main materials used in 630 kVA and 400 kVA distribution transformer for tier 2 aluminium and copper types:

Table 2.8 Prices of the main materials used in a distribution transformer[39]

| Material | Cost per kg |
|---|---|
| Aluminium | €6.00 |
| Copper | €12.00 |
| Magnetic sheet (quality M070 = 0.70 W/kg at 1.7 T) | €5.50 |

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[37] Consumer prices - inflation - Statistics Explained (europa.eu) [Extracted 05/04/2024]

[38] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

[39] 2024 stakeholder feedback

| | |
|---|---|
| Oil | €2.00 |
| Tank + Cover | €4.50 |

Information regarding those transformers' material content and dimensions (note that these dimensions are for the entire transformer, i.e. the external dimensions). The production costs for these transformer types are calculated to be the following:

Table 2.9 Transformer production costs, material content and dimensions[40]

| Transformer type | 630 kVA, Al | 630 kVA, Cu | 400 kVA, Al | 400 kVA, Cu |
|---|---|---|---|---|
| Aluminium mass (kg) | 426 | - | 308 | - |
| Copper mass (kg) | - | 631 | - | 496 |
| Magnetic Sheet mass (kg) | 1106 | 633 | 782 | 499 |
| Oil mass (kg) | 366 | 262 | 288 | 206 |
| Tank + cover mass (kg) | 298 | 264 | 192 | 173 |
| Length (mm) | 1265 | 1285 | 1195 | 1025 |
| Width (mm) | 865 | 865 | 700 | 865 |
| Height (mm) | 1700 | 1700 | 1590 | 1590 |
| Total Cost of Raw Materials | €10,712 | €12,766 | €7,589 | €9,887 |

### 2.5.3 Electricity prices

This section will hyperlink to the Phase 1 section which covers the item *n) impact of rising electricity prices on current and potentially stricter Ecodesign requirements.*

The EU average price in the first half of 2023 for electricity by household consumers was €0.2890 per kWh, which is the weighted average using the most recent (2022) data for electricity by household consumers.[41]

For future projections, it is chosen to not extrapolate based on previous years due to vast variation taking place in the last couple of years, and rather apply inflation to this price.

### 2.5.4 Repair and maintenance costs

One stakeholder has stated that the average repair costs for transformers over the product lifetime is 30 – 40% of the cost of a new transformer.

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[40] 2024 stakeholder feedback

41 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_household_consumers [Extracted 05/04/2024]

[41] https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2021-09/MEErP_revision_draft_report_Task_1-2_24-06-2021.pdf [Extracted 05/04/2024]

### 2.5.5 Interest and inflation rate

For future inflation forecasting, an inflation value of 2% will be applied. This is in line with the medium-term target inflation rate set by the European Central Bank.[42]

A 3% discount rate is the latest recommendation by the European Commission.[43] As the discount rate is *interest minus inflation*, a 5% interest rate is used.

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[42] The ECB's monetary policy strategy statement (europa.eu)

[43] European Commission, BETTER REGULATION TOOLBOX, November 2021.

# 3 Task 3: User behaviour

## 3.1 Systems aspects of the use phase for ErPs with direct impact

### 3.1.1 User information

Transformers are procured in a B2B market with technical and economic skilled end-users. Generally, there are the following types of users of transformers within the scope of this study:

1. Utilities that operate the electrical distribution or transmission grid, also known as Transmission Network Operators (TNO) or Distribution Network Operators (DNO).
2. Owners of large industrial plants or large sites in the tertiary sector. These include office buildings, hospitals and shopping malls etc.
3. Owners of small industrial transformers, with the transformers being a part of a particular system or equipment in some cases

### 3.1.2 Procurement practices

Procurement of transformers is based on the Total Cost of Ownership, with the transformer losses being taken into account by utilities. Capitalisation is not used to minimise transformer losses, but rather is used to minimise the investment required to obtain the greatest energy savings for the least cost. This results in the selection of transformers whose losses are economically optimal, but not minimal.

Essentially, the process of capitalisation involves the calculation of the value today of the savings from losses over the transformer’s lifetime. The cost of the electricity saved is predicted over the 30-50 year lifetime of the analysis, and the product of kWh and electricity cost then discounted at an appropriate interest rate to a Present Value today. This calculation has great uncertainty, and the capitalisation factors involve judgement and sophisticated financial approaches when determining then.

The first step is drafting the technical specifications, guarantees and schedules identifying the requirements and minimum standards that need to be met by the manufacturers. This sets out the contractual conditions that form the basis of a contract between transformer manufacturers and the end-users. It is proposed that the total ownership cost is defined as follows:

$$TCO = IC + A \cdot (P_0 + P_{CO}) + B \cdot (P_k + P_{cs} - P_{c0})$$

Where,

| | |
|---|---|
| IC | is the initial cost of the transformer. This cost may include installation costs such as foundation and erection costs (requires a more sophisticated evaluation); |
| $P_0$ | is the no-load loss (kW) measured at rated voltage and rated frequency, on the rated tap summed; |
| $P_{c0}$ | is the cooling power (kW) needed for no-load operation; |
| $P_k$ | is the load loss (kW) due to load, measured at rated current and rated frequency on the rated tap at a reference temperature; |

$P_{cs}$ is the total cooling power needed for operation at rated power (including three winding operation if any).

### 3.1.2.1 Calculation of factor A

A is the cost of capitalization of no-load losses in Currency/kW.

The no-load losses and their associated cooling losses are present as soon as the transformer is energised, therefore the capitalization cost is the valorisation cost of energy multiplied by the operating time over the full life expectancy of the transformer as shown:

$$A = \sum_{j=1}^{n} \frac{O_{0j} * C_j}{(a + i_j)^j}$$

Where,

| | |
|---|---|
| $O_{0j}$ | is the operating time of the transformer at year j in hours; |
| $C_j$ | is the valorisation of the energy at year j in Currency/Wh if losses are expressed in W; |
| $i_j$ | is the real discount rate at year j in per unit; |
| n | is the life expectancy of the transformer in years. |

Discount rates can be expressed in either real (excluding inflation) or nominal (including inflation) terms, with both leading to identical answers providing the associated cash flows are also expressed in similar terms. However, the use of real discount rates simplifies the calculations as it assumes that all costs rise identically at the rate of inflation. If a particular cost rises in excess or below inflation e.g. marginal cost of electricity, then this excess above inflation can be more easily dealt with through a modification of the cash flow used. Accordingly all discount rates used in this analysis are real.

For simplification, if the discount rate is considered constant and the cost of energy (in real terms) equal to that at mid-transformer life, then assuming that the transformer is always energized then at year n Formula B.2 can be simplified to the form shown below:

$$A = 8760. C_{n/2} \cdot \frac{\frac{1}{1+i}\left(1 - \left(\frac{1}{1+i}\right)^n\right)}{1 - \frac{1}{1+i}} = 8760. C_{n/2} \cdot \frac{1 - \left(\frac{1}{1+i}\right)^n}{i}$$

Where,

| | |
|---|---|
| $C_{n/2}$ | is the valorisation of the energy at mid life of the transformer in Currency/kWh if losses are expressed in kW; |
| i | is the discount rate fixed over the whole life of transformer (n years); |
| n | is the ‘Useful Economic Life’ of the transformer in years, which in the past has been close to the transformers physical life expectancy (30–50 years). |

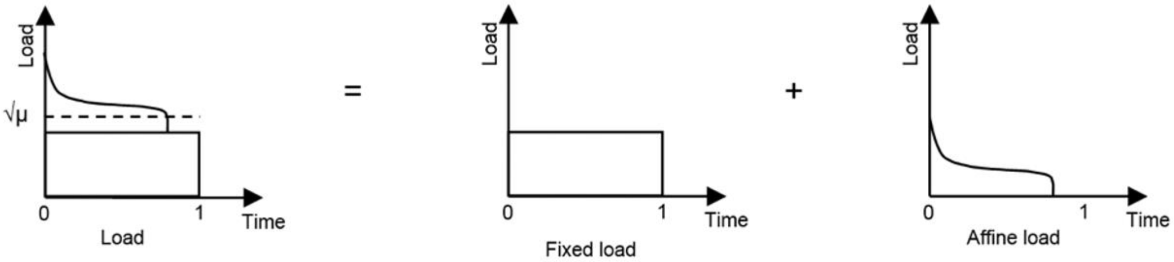
The use of $C_{n/2}$ is an approximation and overvalues the losses somewhat, but in the context of other uncertainties is acceptable.

#### 3.1.2.2 Calculation of factor B

B is the capitalization cost of the losses due to load. It is highly dependent on the load profile.

The load of a transformer can usually be split between fix load, which is constant and present all year round and affine load which depends on ambient conditions and may be present only part time. Figure 3.1 illustrates this load split:

Figure 3.1 Load profile illustration



For the sake of calculation it is useful to define the average loss load factor (μ) as the square of the r.m.s. value of the instantaneous load factors by:

$$\mu = \frac{1}{T}\int_0^T (k(t))^2 dt$$

Where,

| | |
|---|---|
| T | is equivalent to one year if k(t) is defined per hours T is 8760 h; if k(t) is defined per minutes T is 525 600 min; |
| k(t) | is the load factor as a function of time. |

The load losses capitalization cost comes as the sum of the loads factors multiplied by the cost of energy and corrected by the increase of load and the increase of transformer installed base. In the following formula below the losses are split into two parts, with each one weighted by its time base utilisation:

$$B = \sum_{j=1}^{n} \frac{\mu \cdot C_j \cdot (O_{aj} \cdot T_{aj} + O_{fj} \cdot T_{fj})}{(1 + i_j)^j} (\frac{1 + C_{\mu j}}{1 + C_{aj}})^{2j}$$

Where,

| | |
|---|---|
| μ | is the average load loss factor as defined above; |
| $C_j$ | is the valorisation of the energy at year j in Currency/Wh if losses are expressed in W; |
| $i_j$ | is the discount rate at year j in per unit; |
| $O_{aj}$ | is the operating time of the transformer at affine load during year j in hours; |
| $O_{fj}$ | is the operating time of the transformer at fixed load during year j in hours usually 8760 h if the transformer is operated all year round; |
| $T_{aj}$ | is the share of affine load in the total load loss factor at year j; |

| | |
|---|---|
| $T_{fj}$ | is the share of fixed load in the total load loss factor at year j; Taj + Tfj = 1; |
| n | is the life expectancy of the transformer in years; |
| $C_{\mu j}$ | is the rate of load loss factor increase at year j; |
| $C_{aj}$ | is the rate of installed power increase at year j. |

Usually $C_{\mu j}$ and $C_{aj}$ are taken equal to zero which corresponds to a situation where the investment is assessed on the basis that the average loading of transformer as invariant. If this is not the case special care shall be taken to avoid overloading of transformer from a certain year, as if $C_{\mu j}$ is greater than $C_{aj}$ the final factor is greater than one.

If the transformer is energized all year around and if the cost of energy is considered constant and equal to the energy valorisation at mid life of the transformer, and if usage of transformer is assumed as invariant during its all life, and if discount rate is considered constant then the formula can be simplified as in the formula below:

$$B = \mu \cdot C_{n/2} \cdot (O_a \cdot T_a + 8760.T_f) \cdot \frac{\frac{(1+C_\mu)^2}{(1+i)\cdot(1+C_a)^2} \cdot \left[1 - \left(\frac{(1+C_\mu)^2}{(1+i)\cdot(1+C_a)^2}\right)^n\right]}{1 - \frac{(1+C_\mu)^2}{(1+i)\cdot(1+C_a)^2}}$$

Where,

| | |
|---|---|
| μ | is the average load loss factor as defined above; |
| $C_{n/2}$ | is the valorisation of the energy at mid life of the transformer in €/Wh if losses are expressed in W; |
| i | is the discount rate in per unit; |
| $O_a$ | is the operating time of the transformer at affine load in hours; |
| $O_f$ | is the operating time of the transformer at fixed load in hours usually 8760 h if the transformer is operated all year round; |
| $T_a$ | is the share of affine load in the total load loss factor; |
| $T_f$ | is the share of fixed load in the total load loss factor; $T_a + T_f = 1$; |
| n | is the life expectancy of the transformer in years; |
| $C_\mu$ | is the rate of load loss factor increase; |
| $C_a$ | is the rate of installed power increase |

The B factor (Currency/kW of Load Loss) represents the value today of the total load losses saved over the lifetime of the transformer. Unlike no-load losses, the load losses are highly dependent on how heavily the transformer is loaded and over how long a period, with the load losses increasing dramatically with transformer loading (proportional to the square of the load). So a transformer with 400 identical customers will not have twice the load losses of a transformer with 200 customers, but will actually have four times the losses.

Following the same logic as for no-load losses, a purchaser would be willing to spend anything up to B Currency/kW on extra costs in improving the transformer, because as long as this extra investment is less than B, there is a positive gain to be made. However there are declining returns with increasing investment so that at some stage the benefits from the extra investment cost more than the losses saved, at which stage no further investment is economic. At this point the value of the load losses saved is balanced by the extra transformer investment cost per kW, and this value is B Currency/kW.

In practical terms this means that for transformers with heavy loads (e.g. Industrial /commercial loads, urban areas), load losses will be predominant and will give a strong return on investment; whereas on transformers with low loads (rural transformers) a very poor return on load losses would be made, and no-load losses are predominant.

It is noted that the power required by the cooling system may be treated as load losses and capitalised at the same cost.

#### 3.1.2.3 Use of A and B for tender evaluation

In a transformer tender the user should give the values of A and B which will be applied during the evaluation stage to assess the total cost of ownership (TCO).

The TCO is as defined previously and represents not only the initial purchasing cost but also the cost of the losses. The transformer manufacturer will therefore optimise the TCO in such way that the value of a reduction of losses is greater than the associated cost increase of the transformer.

The most economical transformer will be the one offering the lowest total cost of ownership as calculated by the TCO formula.

#### 3.1.2.4 Determination of factors A and B

The definition of the components of the above formulae is complex and requires very specialised skill.

Utility policies, energy mix, government political decisions, incentive for environmental concerns and prospective scenarios, discount rates and investment time horizon, as well as budget constraints can greatly affect the value used for determining the A and B factors. The variety of parameters and the fact that some of the values are necessarily subjective, or subject to considerable uncertainty can explain the diversity of capitalization costs actually used by utilities.

For industrial or private customers not subject to such considerations, determining values for the formulae components should be simpler, as many of the assumptions needed for the definition of the capitalization costs will have already been made during the establishment of the project business plan.

Therefore the inputs are defined as follows:

- n is the useful economic life of the transformer. The sensitivity of the capitalization value to n decreases as n increases;
- $C_{n/2}$ should be derived from forecasted commodity prices. The higher the cost of the energy, the greater the savings from a lower loss level will, thus justifying a higher initial cost of the transformer;
- i is the discount rate set by the company as appropriate for the investment proposed. By default the weighted average costs of capital should be used unless an alternative specific rate has been calculated for the investment. The lower the discount rate, the higher will be the present value of the losses. A low discount rate justifies high spending on reducing losses;
- Determining load and operating time can be simplified as for most of the industry the base load is predominant and therefore Ta can be considered as negligible. The formula can then be simplified as below:

$$B = \mu \cdot C_{n/2} \cdot 8760 \cdot \frac{1 - (\frac{1}{1+i})^n}{i}$$

where µ can be well approximated by the following formula:

$$\mu = (\frac{S}{S_r})^2$$

Where,

Sr is the rated power of the transformer;
S is the average forecast load.

If the process is not continuous, the yearly 8 760 h can be adjusted to reflect the actual use of the transformer. For example, a two shift industry would typically have a ratio of 2/3, resulting in 5 840 h.

Attention shall be paid to getting a good value for the average forecast load (S). This is because the loss utilization factor is predominant in determining the balance between load and no-load losses. Achieving a correct balance between load and no-load losses is critical to achieving a good efficiency in service. Specifying a low load factor will lead to a transformer having relatively higher load loss and lower no-load loss which would be inefficient if used at high loads. Conversely specifying a high load factor will lead to a transformer having relatively higher no-load losses and lower load losses which would be inefficient if used at low loads.

Then the capitalisation factors are calculated as follows:

- No-load losses capitalization cost A is determined according to the formulas in Section 3.1.2.1.
- Load losses capitalization cost B is determined according to the formulas in Section 3.1.2.2.

## 3.1.3 Use phase behaviour

### 3.1.3.1 Transformer load profile

The transformer load profile is the key input for estimating the distribution of the transformer energy use in real life. A load profile is a graph of the variation in the electrical load versus time. It is a crucial metric to take into account for the power transmission in an electricity distribution network to be efficient and reliable.

The sizing and modelling of transformers is dependent on the load profile. For residential areas, distribution transformers are often sized by the installed total power of the load, multiplied by a simultaneity. The correct sizing of a transformer is a non-expensive tool for increasing the energy efficiency of the whole system, hence the importance of the load profile.

Rather than average loads, transformers need to be sized to cope with expected peak loads. Typically, a transformer has a cyclic rating allowing for the variation in the load profile, allowing the transformer to be overloaded at peak times as long as there is a sufficient cooling down period at the lower point in the load profile.

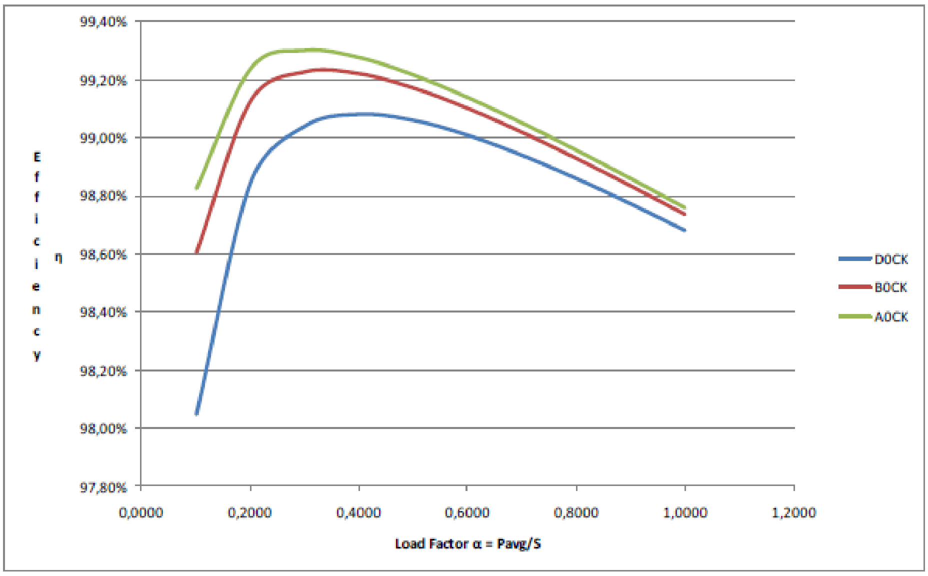
For example, distribution transformers serving mainly residential loads regularly carry average loads that are only 15 – 20% of the transformer’s rated capacity, but also must be designed to support peak loads in the morning and evening. The average transformer load tends to be fairly low due to the wide gap between peak and non-peak loads, as well as the relatively limited amount of time that the transformer is peak-loaded. In this case, total losses may be mainly attributed to core losses.

Larger distribution transformers, which are often used in transforming power for commercial or industrial customers, tend to be loaded at higher average levels over the course of the year. For example, transformers that serve businesses operating from 9:00 am to 5:00 pm typically experience a consistent and relatively higher load throughout the day compared to residential distribution transformers.

The characteristics of the load profile that the transformer is expected to be subjected to therefore highly influences the factory specification of transformers. The main characteristics are the average load form factor and the load factor, which can be calculated based on a given load profile.

Figures 3.1 and 3.2 below show the transformer efficiency for different classes of oil immersed transformers:

Figure 3.2 Efficiency curves for D0Ck, B0Ck, and A0Ck 400 kVA oil immersed transformers[44]



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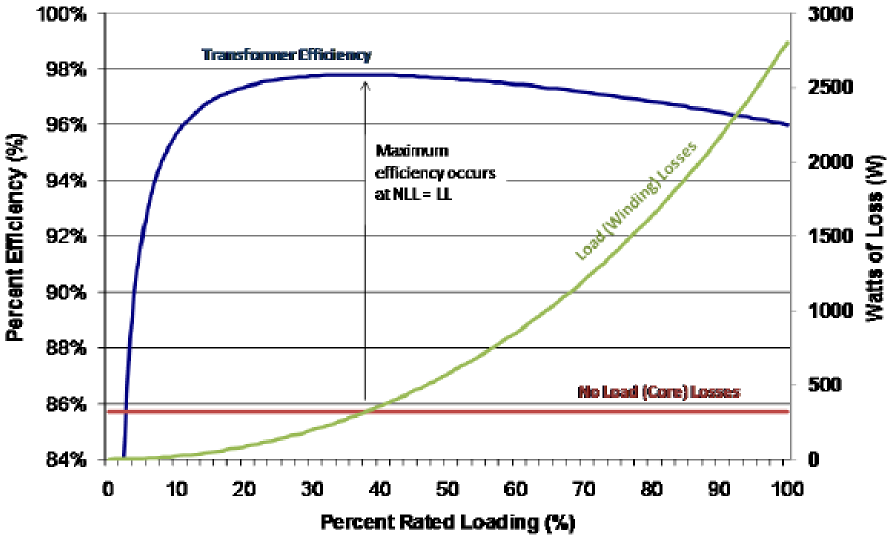
[44] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

Figure 3.3 Efficiency curve for 75 kVA oil immersed transformer[45]



These efficiency curves showcase that the load will affect the efficiency and also adversely affect the total life costs of the transformer. If the load factor (a = PAvg/S) is lower than 15%, then the overall energy-efficiency is also low. Usually, the highest efficiency (Pout/Pin) is achieved with load factors between 0.3 and 0.4. Peak load losses are more expensive, thus distribution transformers are often designed to operate on the left side compared to the top in Figure 3.1. This leaves some safety margin in case the energy consumption increases over the transformer lifetime. When transformers are sold in discrete capacity values (250, 400, 630 kVA), the end-users will often choose a transformer on the higher rated side to be safe. Therefore, a logic equivalent load factor (a=PAvg/S) to operate a transformer is approximately 0.15 – 0.3.

### 3.1.3.2 No-load losses and load losses

Two types of losses characterise the energy used by distribution transformers. No-load losses (Po) arise primarily from the switching of the magnetic field in the transformer core material. These are roughly constant and exist whenever the transformer is connected. Load losses (Pk), also known as resistance or $I^2R$ losses, vary with the load on the transformer. They are proportional to the load squared at any point.

### 3.1.3.3 Transformer power factor

The power factor is the real power used by the load divided by the apparent power required by the load conditions. It is a number between 0 and 1. The real power is the time average of the instantaneous product of the voltage and current. The apparent power is the product of the root mean square (RMS) voltage and the RMS current.

For the same amount of useful power transferred in an electric power system, load with a low power factor draws more current than a load with a high power factor. For example, if the load power factor was low at 0.7, the apparent power would be 1.4 times the real power used by the load. Additionally, the line current in the circuit

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[45] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

would be 1.4 times the current required at a 1.0 power factor. Therefore, since the losses in the circuit are proportional to the square of the current, the losses in the circuit would be doubled.

A high power factor is therefore generally desirable in a transmission system for transmission losses to be reduced, and for the voltage regulation at the load to be improved. Domestic loads typically have power factors of approximately 1, while industrial load will have lower power factors.

In the 2011 preparatory study, a power factor (PF) of 0.9 was used[46]. This was due to France (ERDF communication) using a power factor of 0.8 to procure and dimension transformers, and Synergrid in Belgium assuming a PF of 0.95 based on its experience[47]. It is assumed that a PF of 0.9 is still relevant for this study.

### 3.1.3.4 Availability factor

The availability factor (AF) indicates the proportion of time that a transformer is predicted to be energised. It is estimated to be 1, however for wind turbines it may be lower due to the non-constant wind and sun availability. Solar power plants transformers also have lower AF values as they are often disconnected at night to reduce the transformer no-load losses (P0), giving an AF of 0.5.

The AF interferes with the load factor (LF) and the load form factor (Kf).

For smaller industrial transformers, it is unlikely that they are under continuous operation. Some of them may be linked to the typical annual operational hours in industry or the service sector (2250 h/y), thus a range of AF values is possible. Some industry equipment is operated partially, such as welding, industrial batch processes and seasonal processes. These smaller transformers are also installed in the LV circuit and therefore can easily be switched off. This is the reason that smaller transformers try to avoid high inrush magnetisation currents.

The 2011 preparatory study proposed the following AF values, and it is assumed that they are still relevant for this study:

Table 3.1 Proposed Availability Factors (AF) for this study[48]

| Application | AF (typ.) | AF (min.) | AF (max.) |
|---|---|---|---|
| Distribution | 1 | 1 | 1 |
| Industry | 1 | 1 | 1 |
| Power | 1 | 1 | 1 |
| DER (Wind) | 1<br>(LF = 0.21, Kf = 1.6) | 0.85<br>(LF = 0.25, Kf = 1.5) | 1 |
| Small Industry | 0.25 | 0.12 | 1 |

### 3.1.3.5 Summary on loading profiles parameters

For reasons of comparison, a new equivalent load factor (ae) is introduced. This is defined as the equivalent load factor (Pavg/S) for a transformer in the assumption of

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[46] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

[47] Synergrid, Raming van de verliezen in de distributienetten, August 2003

[48] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

a flat load profile. Therefore, it is an ‘equivalent load factor’ with a ‘flat profile’ equivalent to Kf = 1 and PF = 1. It is defined by the following formula:

$$ae = a * Kf/PF$$

A summary of all of the loading profile parameters for different types of transformers is showcased previously in Table 2.6.

### 3.1.4 Transportation and installation constraints

Discussions with transmission network operators highlighted that large transformers can weigh up to 310 tonnes. This presents transportation challenges, for areas with mountainous terrain, particularly around the Mediterranean region. It is crucial to carefully address factors such as mountainous terrains, tunnels, train gauge limitations, and the load-bearing capacity of bridges. These factors pose less of a concern for Nordic EU countries.

One transmission network operator shared a unique approach to address transportation constraints. They provided an example of addressing transportation concerns by constructing a transformer on-site, doubling the overall cost. A 600-meter-long tent was required to assemble the transformer, measuring 6 meters long and 4 meters wide. They did not invoke the disproportionate cost mechanism for large power transformers, despite the potential case due to transportation limitations. This is due to a wider strategy utilising standardised transformers across their network, working with only 9 transformer models. This ensures availability of spare parts, facilitates easy replacement and repair, and helps maintain a stable supply.

## 3.2 Maintenance, repairability and end-of-life behaviour

### 3.2.1 Repair and maintenance practices

Stakeholder feedback provided insight into repair and maintenance practices. For liquid immersed transformers, they recommend that minimum maintenance is monitoring at least annually through an oil analysis to determine the overall health state of the equipment. The frequency of maintenance is adapted depending on the criticality of the equipment, as well as if field operators observe deviations such as oil leaks, gas production, malfunctions, generating alarms, and abnormal temperatures.

With regards to power transformers equipped with on-load regulators, these regulators must be checked periodically according to the number of manoeuvres carried out over a time period (e.g. 80,000 manoeuvres or 6 years).

All joints and accessories are replaced when a revision is performed. The transformers are encased in hot oil under vacuum (which is a very important phase, whether for new transformers or for repairs) on a testing platform, and dissolved gas analyses take place. The technical qualifications required to qualify as a maintenance operator includes basic electromechanical or electrotechnical training, along with internal training on transformer specificities and support of the technical management team made up of technical experts.

The volume of activity resulting from the operators/owners of transformers to repair/rehabilitate transformers makes it possible to maintain a healthy supplier base of maintenance service companies. Technical skills are thus maintained, and knowledge and experience is transferred between younger and older experts.

Recruitment into this industry can be difficult, especially in France. Therefore, public authorities must help to find solutions before the skills are lost due to retirement of the older employees.

Information on the encountered defects for components within a transformer was provided as follows:

Table 3.2 Encountered defects for components within a liquid immersed distribution transformer[49]

| Component | Percentage of encountered defects |
|---|---|
| Insulation | 10% |
| Windings | 10% (Often linked to insulation) |
| Cooling systems | 10% (Waterproofing and/or clogging) |
| Tap changer | 40% |
| Bushings | 20% |
| Relays | - |
| Core | 5% |
| Oil quality | 5% (Entry of humidity/water through sealings or poor handling during maintenance operations) |

Another stakeholder provided estimates on the likelihood of certain components within a large transformer to fail. The percentages given concern critical failure that generate large power transformer destruction or long-term unavailability.

Table 3.3 Large transformer components most likely to fail[50]

| Component | Likelihood of failure |
|---|---|
| Insulation | - |
| Windings | 50% |
| Cooling systems | - |
| Tap changer | 20-25% |
| Bushings | 20-25% |
| Relays | - |
| Core | - |

### 3.2.2 Economic product life

Stakeholders have stated that the technical lifetime is longer than the economic lifetime, due to there being a point where it is more expensive to maintain a transformer than it is to replace it. This is illustrated previously in Table 2.5.

### 3.2.3 End-of-life behaviour

This section will hyperlink to the Phase 1 section which covers the items: *i) material efficiency aspects; & m) strengthening potential of the existing MEPS and the potential of introducing material efficiency requirements (MMPS).*

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[49] 2024 stakeholder quantitative questionnaire feedback

[50] 2024 stakeholder quantitative questionnaire feedback

One stakeholder has provided information on end-of-life behaviour, which seem to be a high estimate. They state that for transformers at the end of their life, waste treatment operators recycle about 95% of the total weight of a transformer. 100% of material and parts that are replaced during a repair operation are recycled.

Another stakeholder has estimated that out of their stock of large power transformers, every year 1.5 – 2.3% of them are refurbished, 0.2 – 0.8% are recycled partially, and 0.08 – 0.15% are used for parts for reuse after reparation.

## 3.3 System considerations

### 3.3.1 Electricity usage predictions for EU-27

An annual Europe-wide electricity demand of over 5,700 TWh is predicted by 2050[51]. This is over double today's power consumption.

Two main trends are responsible for this:

(i) The uptake of heat pumps and the continuous increase in the use of electric appliances in the residential and tertiary sectors such as IT, leisure and communication appliances.

(ii) The electrification of transport, due to the update of electric vehicles.

For the shorter term, massive energy system changes are needed by 2030. By then, more than 40-50 million heat pumps and 50 – 70 million electric vehicles will contribute to over 335 TWh additional demand to Europe's electricity grid. DSO grids will need reinforcements and increased transformation capacity in substations to accommodate for the anticipated rise in demand and ensure quality of electricity supply[52]. To achieve this, investment in the grid needs to increase by 84%, from €36 billion (as of 2023) to €65 billion per year.

Recently, electricity demand in the European Union has fallen to levels last seen two decades ago, with consecutive declines of historic proportions in 2022 (-3.1%) and 2023 (-3.2%)[53]. This is predominantly due to lower consumption in the industrial sector amid the economic malaise. Our analysis shows that with a gradual recovery in the industrial sector, EU electricity demand would return to 2021 levels by 2026 at the earliest, with an average annual growth rate of approximately 2%.

Challenges of the electricity grid includes the development of 'the Duck Curve' with more extreme consumption profiles due to a greater consumption peak in the evening and more decentralised renewable during the day.

The Green Deal and REPowerEu targets will also require vast investments for the DSOs, such as cables, substations, smart solutions.

Replacing current transformers with ones with higher capacities may be necessary to cope with more electricity needed in the grid. This is constrained by the transformer dimensions and weight, and if a swap is not possible, the substation may need to be replaced or a new substation may need to be added at a different location.

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[51] https://op.europa.eu/en/publication-detail/-/publication/96c2ca82-e85e-11eb-93a8-01aa75ed71a1/language-en/format-PDF/source-219903975 Extraction [04/04/2024]

[52] https://www.eurelectric.org/connecting-the-dots

[53] https://iea.blob.core.windows.net/assets/6b2fd954-2017-408e-bf08-952fdd62118a/Electricity2024-Analysisandforecastto2026.pdf

# 4 Task 4: Technical Analysis

This document adheres to MEErP guidelines and aims to pinpoint, gather, analyse data, and present findings on various subjects pertaining to the Technologies under study. This encompasses a detailed technical product description encompassing performance data and the effects on resources/emissions.

Additionally, the report delves into the production, distribution, and end-of-life facets of the technologies. In the subsequent section, technical recommendations will be outlined, addressing product scope, barriers, and Ecodesign opportunities. This will also encompass insights into the typical design cycle for the products and suggested timing for implementing measures.

## 4.1 Technical product description

This section serves a dual purpose: firstly, it aims to enhance the capacity of policy makers and stakeholders, and secondly, it acts as an initial assessment, serving as a pilot or preview of the potential policy options considered in Task 6.

Within this section, you will find a detailed description and technical analysis of both the Best Available Technology (BAT) and Best Not Yet Available Technology (BNAT). These technologies are applicable to the products outlined in Task 1.

Specifically focusing on distribution and power transformers, as outlined in the study's scope in Task 1, this section explores various technological improvement options.

### 4.1.1 Existing products

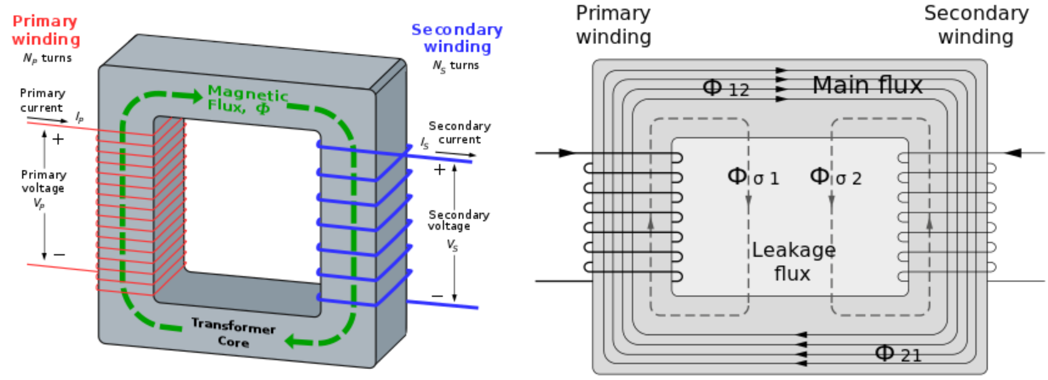
#### 4.1.1.1 Product overview

Power transformers have existed since the late 19th century. They use the principle of electromagnetic induction, discovered by Michael Faraday in 1830.

#### 4.1.1.2 Description of key components

Transformers comprise primary and secondary conductive windings, both encircling a magnetic circuit referred to as the transformer 'core.' When an alternating voltage is applied to the primary winding, it instigates a change in the magnetic field within the core. This change induces a voltage across the secondary winding, as depicted in Figure 4.1. The magnitude of the induced voltage is determined by the product of the number of turns on the winding coil and the rate of change of the magnetic flux.

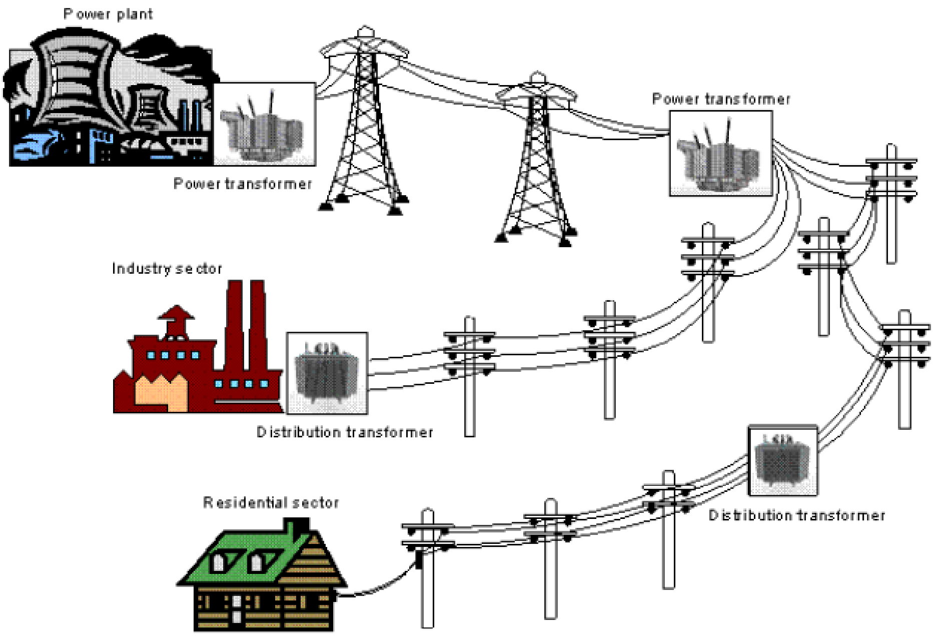
Figure 4.1 Diagrams showing the physics of a transformer[54][55]



The outcome of this process is the generation of secondary electrical voltages and currents, intricately linked to the primary voltages and currents by the ratio of the number of turns on the primary and secondary windings.

Transformers play a crucial role in the electrical grid system by stepping up the output from centralized power plants to a very high voltage for efficient long-distance transmission. Subsequently, they step down the voltage in stages to meet the requirements for end-use. Figure 4.2 visually represents their function in the electric distribution system, serving as step-up transformers when positioned near centralized power plants and as step-down transformers when voltage reduction is necessary for residential, industrial, and commercial applications.

Figure 4.2 Diagram of the electricity distribution system and the role of transformers within it[56]



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[54] https://en.wikibooks.org/wiki/A-level_Physics_%28Advancing_Physics%29/Transformers

[55] https://en.m.wikipedia.org/wiki/File:Transformer_Flux.svg

[56] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

There are many different types and sizes (Table 4.1), with huge numbers in operation across the world.

Table 4.1 A selection of transformer types[57]

| Transformer group | Voltage (kV) | Phases | Typical insulation | Common Use |
|---|---|---|---|---|
| Large power | >245<br>(High Voltage) | Single and Three | Liquid-filled | Stepping up to or down from higher voltages for transmission of electricity over long distances; substation transformers |
| Medium power | >36 & ≤230<br>(Medium Voltage) | Single and Three | Liquid-filled or dry<br>Dry-type | Stepping voltages down from a sub-transmission system to a primary distribution system. |
| Medium voltage distribution | ≤36<br>(Medium Voltage) | Single and Three | Liquid-filled or Dry-type | Stepping voltages down does within a distribution circuit from a primary to a secondary distribution voltage |
| Low voltage distribution | ≤1<br>(Low Voltage) | Single and Three | Dry-type | Stepping voltages down within a distribution circuit of a building or to supply power to equipment. |

Transformers exhibit an exceptionally lengthy lifespan in comparison to other products subject to Ecodesign regulations. Typically designed with a lifespan of 20–40 years, transformers often surpass these expectations, with actual operational durations frequently extending well beyond.

Transformers are classified by size and insulation type (dry or liquid-immersed).

- **Small power transformers:** highest voltage for equipment not exceeding 1.1 kV.
- **Medium power transformers:** highest voltage for equipment between 1.1 kV and 36 kV and rated power within a range of 5 – 40 000 kVA.

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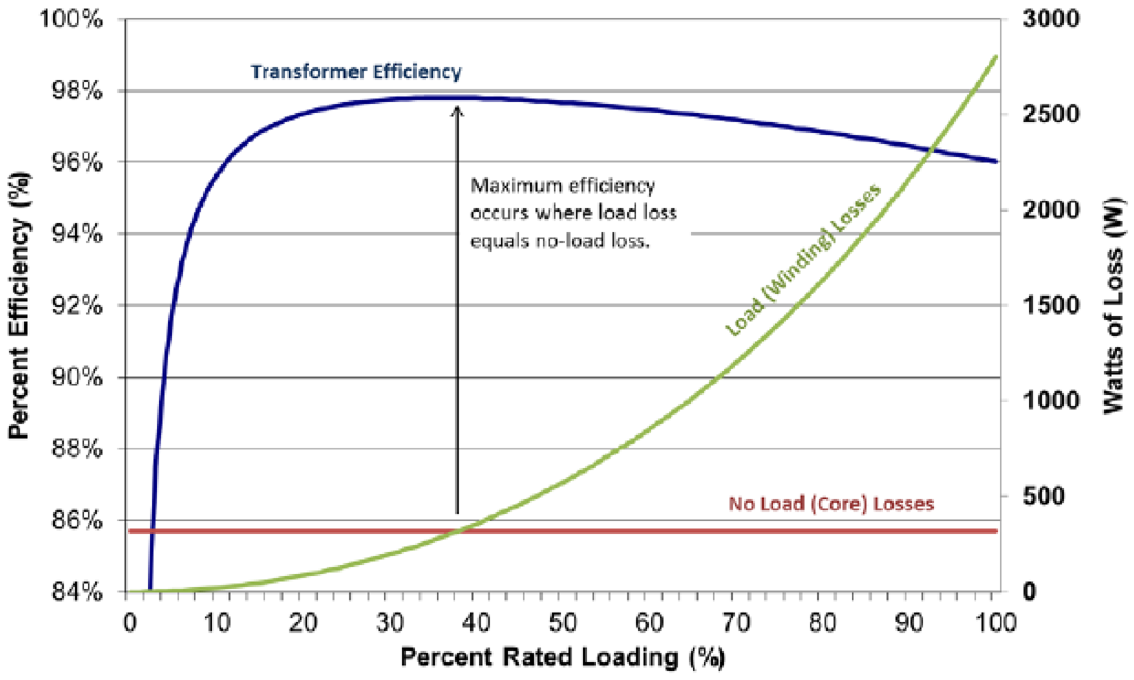
[57] https://united4efficiency.org/wp-content/uploads/2017/11/U4E-TransformersGuide-201711-Final.pdf

- **Large power transformers:** highest voltage for equipment exceeding 36 kV (and a rated power equal or higher than 5 kVA), or a rated power equal to or higher than 40 MVA (regardless of the highest voltage for equipment).

The main factors affecting transformer efficiency are core losses, winding losses and loading of transformer, expanded as follows:

- **Core losses**, also known as 'iron losses' or 'no load losses'. These losses arise within the ferromagnetic transformer core due to fluctuations in magnetic flux density. Two primary types of losses contribute to this phenomenon: hysteresis losses, resulting from the repetitive magnetization and demagnetization of the core, causing heat; and losses through induced eddy currents, which resist the main flux. Collectively, these losses are illustrated as 'leakage flux' above. Importantly, these losses remain constant irrespective of the electrical load applied to the secondary winding of the transformer.
- **Winding losses**, also known as 'copper losses' or 'load losses'. These are losses that occur in the electrically conductive primary and secondary windings. They are generated from resistive heating of the winding wires, which is proportional to the current flowing through the wires and the resistance provided by them (which relates to their resistivity of the material used, usually copper, the cross-sectional area and the length of the wire used in the winding).
- **Loading of transformer** has a direct impact on transformer efficiency. As can be seen from Figure 4.3, the maximum transformer efficiency occurs where the core loss equals the winding loss, which is generally at a small % of the maximum electrical load.

Figure 4.3 Transformer losses[58]



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[58] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

Core (no-load) losses can be minimized by constructing the core from materials with high magnetic permeability to facilitate a substantial magnetic flux while maintaining low conductivity to mitigate eddy currents. This often involves assembling thin steel laminations, creating the required magnetic path with minimal losses. The thickness of the steel sheets plays a crucial role; thinner sheets resist eddy currents more effectively, while larger sheets enhance permeability to the primary magnetic flux. The crystalline structure of the metal also influences losses, with conventional iron-silicon 'electrical steel' being more susceptible to eddy currents than 'amorphous' metal. Amorphous metal, characterized by a random atomic structure, reduces hysteresis and eddy current losses significantly. Typically composed of iron, boron, silicon, and phosphorous, amorphous metal is manufactured as thin foils with high permeability and low conductivity. Therefore, the primary strategy to minimize core losses involves careful selection of core materials, their size, and assembly.

Winding (no-load) losses can be diminished by increasing the size of the windings or employing materials with lower electrical resistance. These actions decrease the resistance of the winding, consequently reducing heat loss (proportional to the square of the current flowing through the winding multiplied by its resistance).

It's important to note that efforts to improve either core or winding losses entail trade-offs due to the inherent characteristics of electromagnetic induction within transformers (Table 4.2).

Table 4.2 Interaction between core and winding losses improvement measures

| | APPROACH | NO-LOAD (CORE) LOSSES | LOAD (WINDING) LOSSES | EFFECT ON PRICE |
|---|---|---|---|---|
| DECREASE NO-LOAD LOSSES | Use lower-loss core materials | Lower | No change | Higher |
| | Use better core construction techniques | Lower | No change | Higher |
| | Decrease flux density by increasing core cross-sectional area | Lower | Higher | Higher |
| | Decrease flux density by decreasing volts/ turn | Lower | Higher | Higher |
| | Decrease flux path length by decreasing conductor cross sectional area | Lower | Higher | Lower |
| DECREASE LOAD LOSSES | Use lower-loss conductor materials | No change/ lower | Lower | Higher |

| | APPROACH | NO-LOAD (CORE) LOSSES | LOAD (WINDING) LOSSES | EFFECT ON PRICE |
|---|---|---|---|---|
| | Decrease current density by increasing conductor cross-sectional area | Higher | Lower | Higher |
| | Decrease current path length decreasing core cross-sectional area | Higher | Lower | Lower |
| | Decrease current path length by increasing volts/turn | Higher | Lower | Lower |
| | Reduce core cross-section by increasing flux density through better core steels, reducing conductor length | Higher/ no change | Lower | Lower |

**Transformer auxiliary power**, which is the power required for transformer auxiliary equipment (cooling fans, pumps, monitoring devices) are assumed to be negligible in comparison with other factors. Transformer cooling has a direct impact on transformer lifespan, a key factor in consideration of material efficiency and upcoming proposed new Ecodesign for Sustainable Products Regulation (published Mar 2022). Nevertheless, improving cooling aspects of transformers may introduce other adverse trade-offs, particularly on increasing transformer auxiliary power, and hence their energy consumption is also considered in the energy efficiency testing.

#### 4.1.1.3 Standard improvement options and Best Available Technology

BAT is defined as:

- "Best" shall mean most effective in achieving a high level of environmental performance of the product;

- "Available" technology shall mean that developed on a scale which allows implementation for the relevant product, under economically and technically viable conditions (expected to be introduced at product level within at least 2-3 years), taking into consideration the costs and benefits, whether or not the technology is used or produced inside the Member States in question or the EU-27, as long as they are reasonably accessible to the product manufacturer.

#### 4.1.1.4 Use of Copper compared to Aluminium conductors.

In the past three decades, aluminium wound transformers have demonstrated reliability comparable to copper wound units, leading to aluminium's widespread adoption as the primary conductor material in transformers. Alongside its excellent performance, the lower and more stable cost of aluminium compared to copper has driven organizations to favour aluminium wound transformers, where copper was once preferred.

Both copper and aluminium distribution transformers adhere to the same efficiency standards set by the latest regulations. While copper boasts superior thermal and electrical conductivity, as well as tensile strength compared to aluminium, the larger cross-sectional area of aluminium coils compensates for its lower conductivity, resulting in similar energy losses between the two materials.

Regarding cost, copper's higher raw material cost makes transformers with copper windings potentially up to twice as expensive as those with aluminium windings. However, factors such as tensile strength and size differences also play a role in the overall cost considerations.

Manufacturing preferences lean toward aluminium due to its greater malleability, ease of handling, and welding compared to copper. While aluminium undergoes oxidation, aluminium's oxide forms a protective coating around the conductor.

Despite these advantages, copper windings offer several benefits, including higher mechanical strength, less susceptibility to galvanic action, and a longer fatigue life compared to aluminium. Fatigue life is defined as the number of loading (stress) cycles of a specified character that a specimen sustains before failure of a specified nature occurs. Additionally, copper's superior conductivity allows for smaller and lighter transformer designs.

When comparing the two materials' winding losses, copper is typically used in high-voltage windings, while aluminium may be utilized in low-voltage windings to reduce eddy current losses. Both copper and aluminium have specific technical parameters suitable for transformer applications, and manufacturers select the most appropriate material based on considerations such as losses and cost-effectiveness.

In summary, while aluminium wound transformers have become dominant due to their reliability and cost advantages, copper windings still offer distinct advantages in certain applications, and manufacturers make informed decisions based on technical requirements and cost.

#### 4.1.1.5 Main technical differences of amorphous core transformers compared to silicon steel

- The saturation magnetic flux density is lower in amorphous metal cores than in silicon steel transformer cores. Therefore, amorphous metal cores need a large cross-section to achieve similar levels of total core flux that occur in normal transformers. This results in an increase in the load losses (Pk), as a larger core cross-section involves more winding conductor length, and thus an increase in resistance. A design induction of 1.35T allows 110% overvoltage without saturation. 110% overvoltage is 7 VA/kg at 85°C core temperature, which is hotter than cores get during normal operation.[59]

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[59] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

- The AMT core material density is 7,200 kg/m$^3$, and the core space factor should be 84%. The cores should be supported from the coils.
- A limitation of the amorphous metal manufacturing process is that an extremely rapid cooling of molten metal is required, thus it can only be produced in very thin, long, and brittle strips that cannot easily be cut to shape. The brittleness of the material poses a risk of dielectric breakdown due to particles being present inside the active part of the transformers. The typical widths of amorphous ribbon is 142, 170 and 213.3 mm, and multiple widths can be stacked side by side.
- 'Wound core' technology is required, thus only one strip width is needed. This results in the core having a rectangular cross-section, and hence more winding conductor loss.
- The forces during short circuit testing differ between oval shaped and rectangular coils. However, the unbalanced axial forces are virtually eliminated by using a sheet or foil wound low voltage coil. It is a universal technique to use sheet wound low voltage coils, which eliminates most of the axial forces by balancing its current distribution to match the high voltage coil current distribution. This could be why no power transformers were developed based on amorphous material until the last decade. Transformers can pass the short circuit qualification tests of European Utilities with skilled engineering techniques[60].
- Amorphous Steel transformers can constructed 3-phase 3-limb as well as 3-phase 5-limb core forms.
- These transformers tend to have higher noise levels when constructed without additional sound level reducing measures. This is due to their bigger size as well as to the higher magnetostriction value of AM compared to GO. T&D Europe have stated that European manufacturers estimate that the difference in noise is around 10db (A) between amorphous transformers and the better level of losses with standard magnetic steel transformers (400 kVA).
- As long as magnetic saturation is avoided, the magnetisation requirement of these transformers is generally lower compared to silicon121 due to the higher magnetic permeability. 0.5 VA/kg (1.3 T) is typically required for AMT, whilst 0.7 VA/kg is required for silicon. Stray losses are reduced in ATM due to the higher magnetic permeability compared to silicon steel[61].
- Corner losses due to flux deviation are absent
- Compared to silicon steel, AMT are less subjective to harmonic currents. The core losses of material 2605SA1 are proportional to frequency and maximum flux density:

$$\mathrm{Pcore}\left[\frac{\mathrm{W}}{\mathrm{kg}}\right] \sim \mathrm{f}^{1.51} * \mathrm{Bmax}^{1.74}$$

Where,

f is the frequency [kHz]

Bmax is the maximum flux density [T]

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[60] B. JARRY (2009), P. LAUZEVIS P. LAGACHE M. SACOTTE, ‗AMORPHOUS SHEET CORE TRANSFORMERS UNDER EXPERIMENTATION ON THE ERDF NETWORK', CIRED conference paper, 20th International Conference on Electricity Distribution Prague, 8-11 June 2009.

[61] M.J. Heathcote (2007): ‗J&P Transformer Book', p. 50, ISBN 978-0-7506-8164-3

- Prior to the installation of the amorphous metal core in transformers and its application of the windings, it must be conditioned. The metal has to be heated to above its Curie temperature and then gradually cooled in the presence of a conditioning DC magnetic field, which orientates the magnetic domains in the amorphous materials. This is a costly procedure, but the ’wound core’ technology in the case of amorphous material needs field anneal to optimise its performance. Thus, heat treatment of the cores takes place at 340 – 360°C. This cycle involves a heat up phase, soak time for 1 hour, and a cooling phase (not forced cooling) for 5 – 6 hours (depending on core size and oven load).
- Amorphous metal has low resistance to external stresses. The magnetic circuit in silicon sheet technology is rigid once it is installed, acting as a mechanical support on which all the transformer elements rest. Amorphous technology involves closing the circuit elements at the bottom-end, making it a fragile area that must not be subjected to any stress, even the impact of its own weight on stress in the core[62].
- Due to the increased size of amorphous metal cores and the brittleness of it is why it is not used for large transformers.

#### 4.1.1.6 Comparing the performance of Grain Oriented Steel to Amorphous Core Material

In comparing transformers made from grain-oriented material to their amorphous equivalents, a model of a power transformer that is available in the JMAG library was used to define power and dimensions of the transformer. Similarly, the amorphous equivalent transformer was analysed assuming a 3-limbed transformer configuration. To achieve identical voltage and power ratings, the depth of the amorphous core is adjusted to accommodate its lower flux density and stacking factor compared to grain-oriented material. Consequently, more copper is required for the amorphous transformer due to its larger core depth.

The core materials differ; for grain-oriented transformers, a commercially available High Permeability Domain-Refined Grain-Oriented (HGO) steel with 0.23 mm thickness is used, while state-of-the-art amorphous material with a thickness of 0.025 mm is utilized for the amorphous transformers. The lower saturation level of amorphous material necessitates adapted magnetic polarizations: 1.75 T for HGO and 1.4 T for amorphous.

In terms of performance and bill of materials, the total mass of active materials (copper and iron) increases by 17% when transitioning from a grain-oriented to an amorphous core at constant power. While the amorphous transformer reduces no-losses by 74% compared to grain-oriented transformers under no-load conditions, at nominal load, copper losses are 18% higher for amorphous cores. These copper losses represent 92% of total losses for grain-oriented cores and 98% for amorphous cores. Overall, total losses are 11% lower with grain-oriented cores compared to amorphous ones[63].

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[62] CIRED (2009-1): Bertrand JARRY, Patrick LAUZEVIS, Pierre LAGACHE, Michel SACOTTE ‗AMORPHOUS SHEET CORE TRANSFORMERS UNDER EXPERIMENTATION ON THE ERDF NETWORK‘, CIRED 2009 conference proceedings.

[63] 2024 Stakeholder feedback.

#### 4.1.1.7 Voltage Regulating Distribution Transformers

Traditionally, distribution transformers achieved voltage regulation using off-circuit tap changers, adjusting in distinct steps when de-energized. In contrast, Voltage Regulating Distribution Transformers (VRDTs) feature on-load tap changers, ensuring stable voltage output under varying loads within ±5% of the nominal voltage as per ANSI C84 standards. VRDTs offer a notable advantage by decoupling medium voltage (MV) from low voltage (LV) grids, crucial for grid stability. Unlike conventional transformers where primary voltage fluctuations affect secondary voltage, VRDTs break this link, providing consistent power to end-users regardless of primary voltage changes. ComEd, Illinois' largest electric utility, exemplifies VRDT impact on grid infrastructure, deploying ECOTAP® VPD® in next-gen ‘DC In A Box’ to replace individual voltage regulators, significantly reducing substations' footprint. Operating within a regulating range of ±10%, these transformers benefit end-users in rural areas like Tonica, Illinois. With their compact design and decoupling capabilities, VRDTs offer a cost-effective solution for utilities modernizing distribution grids amidst electrification and regulatory pressures, ensuring grid stability, reliability, and meeting future energy demands. In summary, VRDTs represent a significant advancement in grid infrastructure modernization, stabilizing voltage, decoupling grids, and reducing costs, poised to play a pivotal role in the evolving energy landscape[64].

### 4.1.2 Best not yet available Technology

BNAT is defined as:

- "Best" and “Available” as defined before;

- "Not yet" available technology shall mean that not developed yet on a scale which allows implementation for the relevant product but that is subject to research and development.

#### 4.1.2.1 Superconducting transformers

Superconducting transformer technology involves the use of superconducting materials in the windings of transformers to achieve higher efficiency, smaller size, and lower losses compared to conventional transformers.

Superconductors, including high-temperature superconductors (HTS) and low-temperature superconductors (LTS), conduct electricity with zero resistance when cooled below a critical temperature. This characteristic allows superconducting windings to have significantly lower losses compared to conventional copper or aluminium windings, resulting in higher efficiency and reduced energy consumption during transformer operation. Superconductors, when designed appropriately can also carry much higher current densities than conventional conductors, enabling the design of compact and lightweight transformers suitable for space-limited applications like urban areas or onboard ships subject to bending radius of the material. However, superconducting materials typically require cryogenic cooling, often with liquid helium or liquid nitrogen, which can add complexity and cost to the operational setup. Despite these challenges, the elimination of resistance in superconducting windings allows for the construction of smaller and lighter transformers with similar or higher power ratings compared to conventional

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[64] Smart Transformers: Revolutionizing US Grid Infrastructure (powersystems.technology) _ Smart Transformers: Revolutionizing US Grid Infrastructure (powersystems.technology) Extracted {04/04/2024}

transformers, making them advantageous for applications with space constraints or where weight reduction is critical. Additionally, superconducting transformers offer improved power quality and stability, helping to reduce voltage drops, minimize harmonic distortion, and enhance grid stability, particularly in areas with fluctuating renewable energy sources. They can also operate at higher frequencies than conventional transformers, making them suitable for various applications such as high-frequency power distribution, grid interconnection, and power electronics. However, despite their advantages, superconducting transformers face challenges related to cost, cryogenic cooling requirements, material availability, and scalability, which have limited their widespread commercialization and deployment in utility-scale power systems[65].

#### 4.1.2.2 Flexible transformers

The conventional transformers utilized in grid infrastructure are bespoke in nature, leading to high costs and significant lead times for procurement. A ‘flexible transformer’ provides a solution to these challenges by enabling seamless reconfiguration to suit different locations, voltages, and power requirements. Additionally, its adjustable impedance feature allows for dynamic optimization of grid conditions, crucial for accommodating intermittent renewable energy sources and ensuring grid stability.

The flexible transformer introduces an adjustable "knob" mechanism, akin to adjusting the volume on a radio, which enables operators to manipulate impedance in real-time. This capability is essential for swiftly adapting to fluctuations in renewable energy output and ensuring grid stability during variable conditions. Moreover, it facilitates rapid grid isolation in the event of disruptions, safeguarding unaffected sections from cascading faults caused by severe weather events or equipment failures.

Remarkably, the flexible transformer technology is ingeniously integrated into the same footprint as conventional transformers, ensuring seamless deployment within existing substation infrastructure, even in space-constrained urban environments. Leveraging established materials such as copper, steel, and mineral oil expedites production, testing, and widespread adoption, ushering in a new era of resilient and sustainable grid management.

In conclusion, the introduction of flexible transformer technology marks a significant advancement in grid resilience and renewable energy integration. Its ability to adapt to varying conditions, optimize grid operations in real-time, and seamlessly integrate with existing infrastructure holds immense promise for the future of grid management. Further research and development in this field are crucial for realizing the full potential of flexible transformer technology in creating resilient and sustainable energy systems[66].

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[65] Superconducting transformers – Part I | Transformers Magazine (transformers-magazine.com)

[66] GE Research and Prolec GE Power Up World’s 1st Large Flexible Transformer to Enhance the Resiliency of America’s Grid | Cooperative Energy

## 4.2 Production, distribution and end-of-life

### 4.2.1 Bill of materials

Aluminium is the dominating material for transformers due to it being cheaper than copper. One stakeholder provided the bill of materials and dimensions for a 400 kVA aluminium base case distribution transformer as seen showcased previously in Table 2.7[67]. The base case 1 bill of materials from the 2011 preparatory study is used for the 'insulation', 'others' and 'coatings' materials[68].

Table 4.3 Bill of materials for the base case

| Transformer component | Weight (kg) |
|---|---|
| **Windings** | |
| Aluminium | 308 |
| **Core** | |
| Magnetic steel sheet | 782 |
| **Tank** | |
| Steel | 192 |
| **Insulation** | |
| Paper | 16 |
| Ceramic | 6.0 |
| Oil | 265 |
| Cardboard | 3.6 |
| **Others** | |
| Plastics | 2.0 |
| Wood | 4.4 |
| **Coatings (kg)** | 5 |

### 4.2.2 Primary scrap production

This section will hyperlink to the Phase 1 section which covers the item: i) material efficiency aspects; and m) strengthening potential of the existing MEPS and the potential of introducing material efficiency requirements (MMPS).

### 4.2.3 Means of transport employed

#### 4.2.3.1 Transportation on Roads

In European road transport, compliance with specific regulations governing weights and dimensions is imperative to ensure road safety and prevent damage to infrastructure such as roads, bridges, and tunnels. Directive (EU) 2015/719 sets the

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[67] 2024 stakeholder feedback

[68] Lot 2: Distribution and power transformers, VITO, BIO, 2011 preparatory study

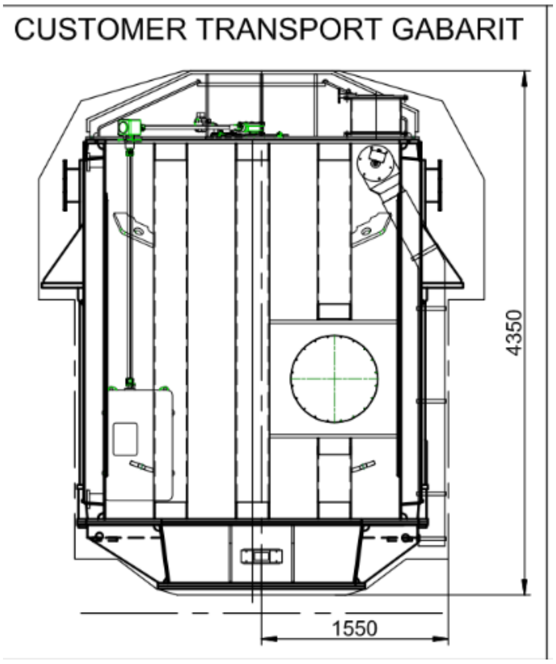
standards, restricting regular road transport vehicles to 40 tonnes (including the trailer), 2.6 meters in width, 4 meters in height (including the trailer), and 12 meters in length. Consequently, regular road transport is suitable only for smaller power transformers like distribution transformers. Larger and heavier products necessitate special road transports, with limits contingent upon local circumstances and permits.

The 2017 Transformers Study incorporated inquiries into the installer's questionnaire to ascertain the typical special transport limits in Europe. While some countries provided specific information on transportation limits, identifying commonalities proved challenging. For instance, Norway's special road transport limits are 10 meters in length, 3.7 meters in width, 4.5 meters in height, and a maximum weight of 250 tonnes. In contrast, Italy reported limits of 18.75 meters in length, 2.55 meters in width, and 4 meters in height, without any specified weight limits. Due to the limited time frame of this study and the incomplete information received on this subject, it was concluded that beyond the standard EU road transport limits (40 tons; 2.6 meters width; 4 meters high; 12 meters long), any power transformer could potentially encounter transportation restrictions. Notably, these limits also accommodate the transportation of standard containers (ISO 668), which are generally smaller.

### 4.2.3.2 Transportation on Railways

Similar to road transport, railways impose specific dimension and weight limits (Figure 4.4). However, these limits lack harmonisation across Europe or within individual countries, as they are contingent on local railway infrastructure, including considerations for bridges. To gain insights into the typical railway limits in Europe, inquiries on this subject were included in this study. Unfortunately, responses were obtained from only a limited number of countries, rendering them unrepresentative of the entire EU.

Figure 4.4 Comparison between railway gauge and the actual size of a 170 MVA transformer in France[69]



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[69] Source: RTE feedback

# 5 Task 5: Environment & Economics

## 5.1 Overview of base case

This section will cover how the Ecoreport methodology covers the considerations for transformers. This section will hyperlink to the Phase 1 section which covers the item: *o) existing methodologies for assessing technoeconomic aspects of Ecodesign for power transformers (especially in terms of technology neutrality, circularity, MEPS and MMPS), as well as for the assessment of the costs for replacement/installation of transformers, based on the principles laid down in Regulation 2019/1783;*

This section aims to define and elaborate on the base-case derived from prior tasks, stakeholder inputs, and a thorough literature review. This base-case, an intentional abstraction of reality, is crucial in encompassing the diverse range of distribution transformers across the European market. Guided by the MEErP methodology, the objective is to define a base-case for a distribution transformer that effectively encapsulate the study's scope. The base-case's characteristics allow for the multiplication of its impacts during the use phase, production and distribution, and end-of-life stages with the respective total number of products in use, sold, and discarded, thereby providing a holistic representation of the environmental impact of this product.

The justification for the chosen base case, BC1, is presented in the sections below.

### 5.1.1 Data on European transformer types and ratings

During the inquiry phase, manufacturers and operators provided technical and economic information. Feedback from two stakeholders indicated that the load on a 400 kVA transformer may grow or exceed 400 kVA. Therefore, the existing transformer may be replaced by a larger rated unit, i.e. a 400 kVA unit is replaced by a 630 kVA or 1 MVA unit.

Despite this demand trend, most existing transformers are installed in packaged substations of minimal dimensions. It can be difficult to install larger packaged substations, as the physical sites and existing footprints would constrain the replacement installation size to fit current substation format. Five stakeholders submitted data for 400 kVA distribution transforms, indicating that this will remain to be the most common power rating for a distribution transformer.

Furthermore, the lifecycle of transformers is 20-40 years. The previous preparatory study in 2011 referenced 400 kVA distribution transformer as base case 1. The market landscape has not changed drastically since then, and thus the assumptions made are still relevant and representative of the technological spectrum of transformers in European markets[70].

### 5.1.2 Flat distribution transformer sales

According to the 2021 EIA report, as illustrated in Figure 2.10 and Table 2.4, the year-on-year growth of 400 kVA distribution transformer sales is linear (6-7%). DER transformers are growing more rapidly, demonstrating higher adoption rates in the renewable energy space. While distribution transformers maintain steady sales

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[70] 2023 stakeholder feedback

growth, DER transformers are leading towards a greener and more sustainable energy future, and thus no rapid infrastructure updates are required to meet the electricity demand for distribution transformers[71].

### 5.1.3 Electricity demand

With regards to electricity demand, the IEA electricity analysis 2024 indicates that electricity demand in the European Union has fallen to levels last seen two decades ago[72]. This is predominantly due to lower consumption in the industrial sector amid the economic malaise. With a gradual recovery in the industrial sector, EU electricity demand would return to 2021 levels by 2026. Electricity demand is expected to increase steadily in Europe, at a CAGR of about 1.7 percent until 2035. This is consistent with the growth rate observed over 2015-2019 period which again implies that no rapid infrastructure upgrades are required to meet the growing demand.

### 5.1.4 Conclusion

From the above data and stakeholder feedback, it can be inferred that 400 kVA is still representative of the stock of distribution transformers that will be deployed across Europe to meet the electricity demand. Therefore, it is deemed that the 400 kVA distribution transformer is best choice of base case.

## 5.2 Definition of base-case

### 5.2.1 General inputs and assumptions

#### 5.2.1.1 Discount Rate and Escalation Rate

The discount and escalation rates used for the base case were provided in the MEErP and are presented in Table 5.1.

Table 5.1 Discount rate and escalation rate

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Escalation rate (annual growth of running costs) | 3% | Per year | MEErP, 2024 |
| Discount Rate | 3% | Per year | MEErP, 2024 |

#### 5.2.1.2 Electricity Rate

The electricity rate used for the base case was calculated based on the values and methodology provided in the MEErP and are presented in Table 5.2.

Table 5.2 Electricity rate

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Electricity prices | 0.6 | € / kWh | MEErP, 2024 |

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[71] https://op.europa.eu/en/publication-detail/-/publication/392bc471-76ae-11ed-9887-01aa75ed71a1/language-en [extracted on 04/04/2024]

[72] https://www.iea.org/reports/electricity-2024/executive-summary [extracted on 04/04/2024]

### 5.2.1.3 Distribution

The main regions of manufacturing origin with regards to transport are as follows, based off stakeholder feedback[73]:

- Europe (a mix of France, Germany, Netherlands, Portugal, Spain and Austria)
- Turkey
- South Korea
- China
- India
- Japan

Considering the detail provided of the European response, the manufacturing origin was assumed as: 50% EU, and 50% out of EU (with an equal split between those, resulting in 10% of each non-EU country).

For the products coming from within Europe, the average road transport was assumed to be from Rotterdam to Stuttgart (approximately 600 km). This is taken as the average distance travelled from the main European port to another EU city.

For international travel, the road travel of 600 km is included, as well as shipping distance to the port of Rotterdam from:

- Istanbul
- Seoul
- Tokyo
- Shanghai
- Mumbai

The weighted average of the shipping distance was taken, resulting in an assumed distance of 15,000 km. These figures are tabulated in Table 5.3 below:

Table 5.3 Distribution values

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Transport mean 1 | Ship | - | ICF, assumption |
| Weight of the transported product | 1.584 | t | |
| Distance 1 | 15000 | Km | ICF, assumption |
| Transport mean 2 | Lorry | - | ICF, assumption |
| Weight of the transported product | 1.584 | t | |
| Distance 2 | 600 | Km | ICF, assumption. Average distance by road from major ports to Rotterdam |

### 5.2.1.4 Electricity consumption

The calculated electricity consumption of the base case is showcased in Table 5.4 below.

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[73] 2024 stakeholder feedback

Table 5.4 Electricity consumption

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Electricity Consumption | 7858.72 | kWh / year | Calculated |

### 5.2.1.5 Product Life

The product life and percentage of the products that are repaired annually are presented below in Table 5.5.

Table 5.5 Product life information

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Percentage of products that are repaired | 1% | - | Based on Intel report, referred to in Task 3 |
| Average product service life | 40 | Years | Stakeholder insights |

### 5.2.1.6 End of life

Based on the average service life, the production year for the transformers that reached their end of life in 2023 is calculated to be as follows in Table 5.6.

Table 5.6 End of life values

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Present Year | 2023 | - | ICF |
| Lifespan Years Ago Year | 1983 | - | Calculated |

### 5.2.1.7 Stocks and Sales

The stocks and sales information for the base case transformers, as covered in Section 2.2, is presented below in Table 5.7.

Table 5.7 Stocks and sales information

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| BC1 EU Stock | 2.54 | Million units | ICF, calculated from the Task 2 annual sales growth |
| BC1 Annual Sales | 0.103 | Million units | ICF, calculated from the Task 2 annual sales growth |
| Weibull shape parameter (b) | 1.5 | - | ERT tool-default |

### 5.2.1.8 Costs and Prices

The cost of BC1, cost of installation of a BC1 unit, and average repair and maintenance cost per unit over its lifetime is showcased in Table 5.8 below.

Table 5.8 Costs and prices

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| BC1 unit price | 12008 | € / unit | Stakeholder insights |
| Cost of installation of a BC1 unit | 0.00 | € | Stakeholder insights |
| Average Repair & Maintenance cost per unit over its lifetime | 4202.80 | € | Assumed |

### 5.2.1.9 Ratio of efficiency stock to efficiency new

The default EcoReport tool value for the ratio of efficiency stock to efficiency new is showcased in Table 5.9 below.

Table 5.9 Ratio of efficiency stock to efficiency new

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Ratio efficiency STOCK: efficiency NEW | 0.90 | Ratio | ERT tool-default |

### 5.2.1.10 Base-case 1 inputs: Distribution transformer

The bill of materials for the base case is presented below in Table 5.10. This data has been obtained from and aggregated from several industry stakeholders and internet research. The total weight of the base case amounts to 1.584 tonnes.

Table 5.10 Bill of Materials of BC1

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Windings | | | |
| Aluminium | 308 | Kg | MEErP, 2024 |
| Core | | | |
| Magnetic steel sheet | 782 | Kg | MEErP, 2024 |
| Tank | | | |
| Steel | 192 | Kg | MEErP, 2024 |
| Insulation | | | |
| Paper | 16 | Kg | MEErP, 2024 |
| Ceramic | 6 | Kg | MEErP, 2024 |
| Oil | 265 | Kg | MEErP, 2024 |

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Cardboard | 3.6 | Kg | MEErP, 2024 |
| Others | | | |
| Plastics | 2 | Kg | MEErP, 2024 |
| Wood | 4.4 | Kg | MEErP, 2024 |
| Coatings | 5 | Kg | MEErP, 2024 |

The base case values for packaging, distribution, the direct and in-direct use-phase values, maintenance and repair, and input values for EU totals and economic life cycle costs, are presented in Table 5.11 to Table 5.15, respectively.

Table 5.11 Distribution of BC1

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Transport mean 1 | Ship | | ICF, assumption |
| Weight of the transported product | 1.584 | t | |
| Distance 1 | 15000 | km | ICF, assumption. "Weighted average ship distance from the port of non-EU countries such as Turkey, South Korea, China, India, Japan to the Rotterdam port" |
| Transport mean 2 | Lorry | | ICF, assumption |
| Weight of the transported product | 1.584 | t | |
| Distance 2 | 600 | km | ICF, assumption Average distance by road from major ports to Rotterdam |

Table 5.12 Use Phase Direct of BC1

| Input / Assumption | Value | Unit |
|---|---|---|
| ErP Product service Life in years (see comment) | 40 | years |
| Electricity | | |
| Electricity mix (Click & select) | 243-Electricity grid mix 1kV-60kV technology mix consumption mix, to consumer 1kV - 60kV | |

| Input / Assumption | Value | Unit |
|---|---|---|
| On-mode: Consumption per hour, cycle, setting, etc. | 7859 | kWh |
| On-mode: No. of hours, cycles, settings, etc. / year | 1 | # |
| Standby-mode: Consumption per hour | | kWh |
| Standby-mode: No. of hours / year | | # |
| Off-mode: Consumption per hour | | kWh |
| Off-mode: No. of hours / year | | # |
| TOTAL over ErP Product Life | 314.36 | MWh (=000 kWh) |
| Heat | | |
| Type (click & select) | | |
| Avg. Heat Power Output | | kW |
| No. of hours / year | | hrs. |
| Efficiency (insert the value manually) | | please choose your item in cell D284 |
| TOTAL over ErP Product Life | 0 | GJ |

Table 5.13 Use Phase Indirect of BC1

| Input / Assumption | Value | Unit |
|---|---|---|
| ErP Product (service) Life in years | 40 | years |
| Electricity | | |
| Electricity mix (Click & select) | 243-Electricity grid mix 1kV-60kV technology mix consumption mix, to consumer 1kV - 60kV | |
| On-mode: Consumption per hour, cycle, setting, etc. | 7859 | kWh |
| On-mode: No. of hours, cycles, settings, etc. / year | 1 | # |
| Standby-mode: Consumption per hour | | kWh |
| Standby-mode: No. of hours / year | | # |
| Off-mode: Consumption per hour | | kWh |

| Input / Assumption | Value | Unit |
|---|---|---|
| Off-mode: No. of hours / year | | # |
| TOTAL over ErP Product Life | 314.36 | MWh (=000 kWh) |
| Heat | | |
| Boiler dataset (click & select) | | |
| Avg. Heat Power Output (when saving use a negative value) | | kW |
| No. of hours / year | | hrs. |
| Efficiency (insert the value manually) | | please choose your item in cell D314 |
| TOTAL over ErP Product Life | 0 | GJ |

Table 5.14 Maintenance & Repair of BC1

| Input / Assumption | Value | Unit | Source |
|---|---|---|---|
| Spare parts % of product materials | 15840 | g | ICF, assumption |

Table 5.15 Inputs for EU-Totals & economic Life Cycle Costs of BC1

| Input / Assumption | Value | Unit |
|---|---|---|
| Product expected lifetime | 40 | years |
| Latest Annual sales | 0.103 | mln. Units/year |
| EU Stock | 2.54 | mln. Units |
| Product price | 12008 | Euro/unit |
| Installation/acquisition costs (if any) | 0 | Euro/unit |
| Fuel rate (gas, oil, wood) | 0 | Euro/MJ |
| Electricity rate | 0.6 | Euro/kWh |
| Water rate | 1 | Euro/m3 |
| Auxiliary material 1 | 0 | Euro/kg |
| Auxiliary material 2 | 0 | Euro/kg |
| Auxiliary material 3 | 0 | Euro/kg |
| Auxiliary material 4 | 0 | Euro/kg |
| Auxiliary material 5 | 0 | Euro/kg |
| Repair & maintenance costs | 4202.8 | Euro/ unit |
| Discount rate (interest minus inflation) | 0.03 | % |
| Escalation rate (project annual growth of running costs) | 0.03 | % |

| Input / Assumption | Value | Unit |
|---|---|---|
| Present Worth Factor (PWF) (calculated automatically) | 40 | (years) |
| Ratio efficiency STOCK: efficiency NEW, in Use Phase | 0.9 | |

## 5.3 Base-case Environmental Impact Assessment

Using the EcoReport tool and the above inputs, it is possible to calculate environmental impacts for the following phases of a product life cycle:

- Raw Materials Use and Manufacturing;
- Distribution;
- Use phase;
- End-of-Life Phase.

This chapter provides the environmental impacts of the Base Case throughout all the life cycle stages. The results were calculated using the Ecoreport tool of the MEErP, based on the inputs presented in the previous section. The MEErP tracks 16 impact categories used in the EF method by using the Circular Footprint Formula (CFF).

**Circular Footprint Formula (CFF) parameters**
The simplified version of the CFF (material part only) is as follows:

$$\boxed{(1 - R_1)E_V + R_1 \times \left(AE_{recycled} + (1 - A)E_V\right)}$$

Where:

- $R_1$ (recycled content): it is the proportion of material in the input to the production that has been recycled from a previous system.
- $R_2$ (recycling output rate): it is the proportion of the material in the product that will be recycled (or a component to be reused) in a subsequent system. R2 shall therefore consider the inefficiencies in the collection and recycling processes. R2 shall be measured at the output of the recycling plant.
- A (allocation factor): allocation factor of burdens and credits between supplier and user of recycled materials.
- $E_v$: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.
- $E_{v*}$: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials. It will be set by default equal to Ev.
- $E_{recycled}$: specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled material (or reused component), including collection, sorting and transportation process.

### 5.3.1 Base-case: Distribution transformer

**Error! Reference source not found.**0 below presents the results of the environmental analysis of the base case distribution transformer. According to this, the energy consumption during the use phase is the predominant aspect contributing to the environmental impacts from the product's entire life cycle.

Figure 5.1 Distribution of the base case environmental impacts by life cycle phase

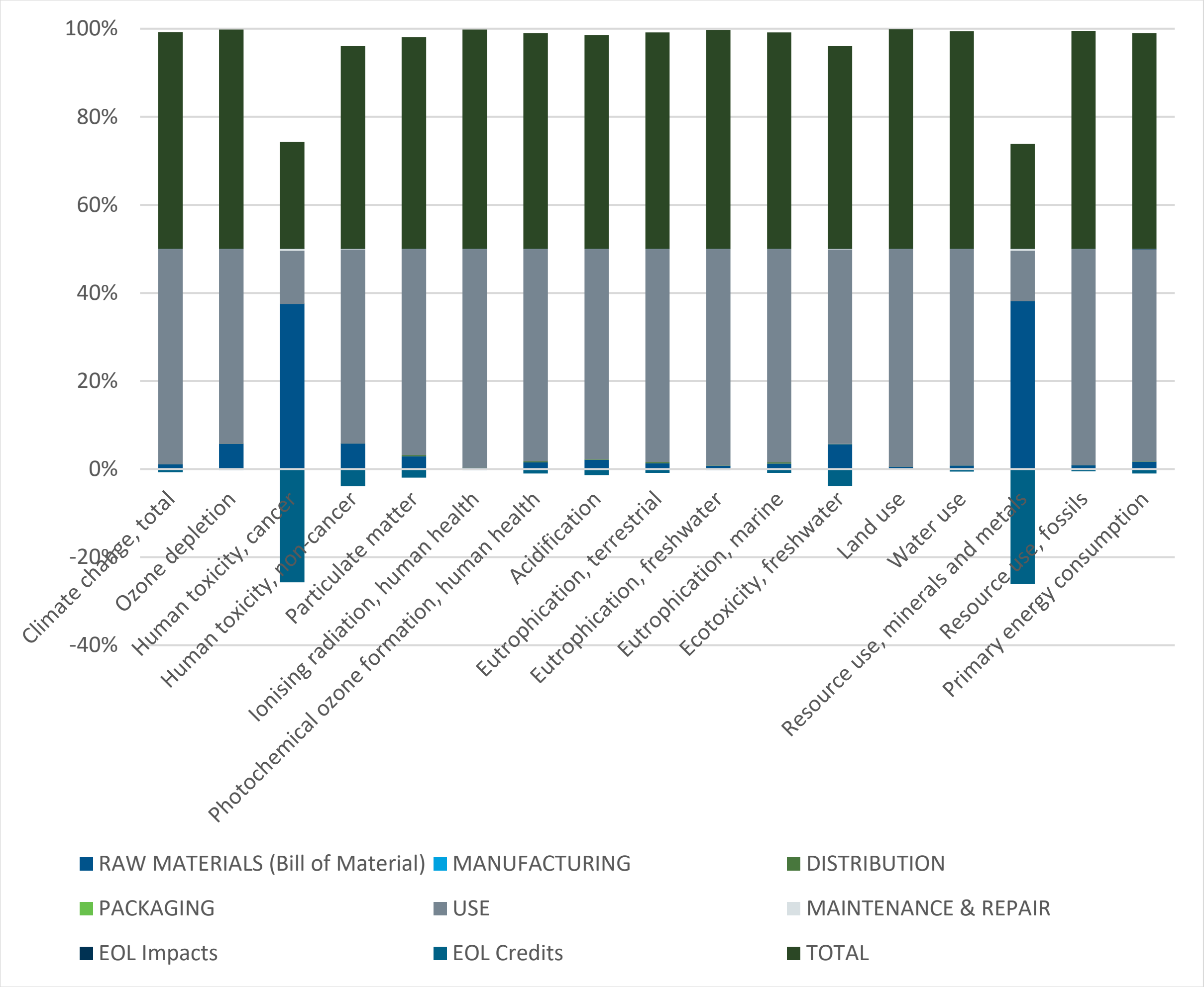


Table 5.16 below presents the Life Cycle Impacts (per unit) of the base case.

Table 5.16 Life Cycle Impacts (per unit) of Distribution Transformer

| Life Cycle phases --> | | **RAW MATERIALS (Bill of Material)** | **MANUFACTURING** | **DISTRIBUTION** | **PACKAGING** | **USE** | **MAINTENANCE & REPAIR** | **EOL** | | **TOTAL** |
|---|---|---|---|---|---|---|---|---|---|---|
| Resources Use and Emissions | | | | | | | | **Impacts** | **Credits** | |
| **PEF Impact categories** | **unit** | | | | | | | | | |
| Climate change, total | kg CO2 eq | 5.9E+03 | 0.0E+00 | 1.8E+02 | 0.0E+00 | 2.6E+05 | 5.9E+01 | 2.5E+02 | -4.0E+03 | **2.7E+05** |
| Ozone depletion | kg CFC-11 eq | 1.3E-05 | 0.0E+00 | 7.7E-11 | 0.0E+00 | 9.8E-05 | 1.3E-07 | 5.7E-08 | -4.2E-07 | **1.1E-04** |
| Human toxicity, cancer | CTUh | 1.4E-04 | 0.0E+00 | 4.6E-08 | 0.0E+00 | 4.4E-05 | 1.4E-06 | 4.0E-08 | -9.3E-05 | **8.8E-05** |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Human toxicity, non-cancer | CTUh | 1.2E-04 | 0.0E+00 | 8.8E-07 | 0.0E+00 | 8.8E-04 | 1.2E-06 | 9.9E-07 | -7.8E-05 | **9.2E-04** |
| Particulate matter | disease incidence | 5.2E-04 | 0.0E+00 | 5.1E-05 | 0.0E+00 | 8.4E-03 | 5.2E-06 | 1.1E-05 | -3.5E-04 | **8.6E-03** |
| Ionising radiation, human health | kBq U235 eq | 6.5E+02 | 0.0E+00 | 6.8E-01 | 0.0E+00 | 1.1E+05 | 6.5E+00 | 6.7E+01 | -4.6E+02 | **1.1E+05** |
| Photochemical ozone formation, human health | kg NMVOC eq | 1.3E+01 | 0.0E+00 | 2.4E+00 | 0.0E+00 | 4.3E+02 | 1.3E-01 | 6.0E-01 | -8.8E+00 | **4.4E+02** |
| Acidification | mol H+ eq | 3.5E+01 | 0.0E+00 | 3.3E+00 | 0.0E+00 | 8.0E+02 | 3.5E-01 | 8.9E-01 | -2.4E+01 | **8.2E+02** |
| Eutrophication, terrestrial | mol N eq | 4.3E+01 | 0.0E+00 | 1.0E+01 | 0.0E+00 | 1.6E+03 | 4.3E-01 | 2.1E+00 | -2.9E+01 | **1.6E+03** |
| Eutrophication, freshwater | kg P eq | 7.8E-03 | 0.0E+00 | 6.2E-04 | 0.0E+00 | 5.4E-01 | 7.8E-05 | 4.6E-04 | -2.5E-03 | **5.4E-01** |
| Eutrophication, marine | kg N eq | 3.9E+00 | 0.0E+00 | 9.2E-01 | 0.0E+00 | 1.5E+02 | 3.9E-02 | 1.9E-01 | -2.6E+00 | **1.5E+02** |
| Ecotoxicity, freshwater | CTUe | 1.5E+05 | 0.0E+00 | 1.9E+03 | 0.0E+00 | 1.2E+06 | 1.5E+03 | 1.6E+03 | -1.0E+05 | **1.3E+06** |
| Land use | pt | 1.2E+04 | 0.0E+00 | 7.8E+02 | 0.0E+00 | 1.1E+06 | 1.2E+02 | 1.0E+03 | -3.5E+03 | **1.1E+06** |
| Water use | m3 water eq. of deprived water | 1.5E+03 | 0.0E+00 | 8.7E+00 | 0.0E+00 | 9.0E+04 | 1.5E+01 | 8.1E+01 | -1.0E+03 | **9.0E+04** |
| Resource use, minerals and metals | kg Sb eq | 2.2E-01 | 0.0E+00 | 6.6E-05 | 0.0E+00 | 6.7E-02 | 2.2E-03 | 7.5E-05 | -1.5E-01 | **1.4E-01** |
| Resource use, fossils | MJ | 7.9E+04 | 0.0E+00 | 2.3E+03 | 0.0E+00 | 4.6E+06 | 7.9E+02 | 4.4E+03 | -4.6E+04 | **4.6E+06** |
| **Additional technical information** | | | | | | | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Primary energy consumption | MJ | 7.9E+04 | 0.0E+00 | 2.3E+03 | 0.0E+00 | 2.3E+06 | 7.9E+02 | 4.4E+03 | -4.6E+04 | **2.3E+06** |

## 5.4 Base Case Life Cycle Cost For Consumers

This section presents the results of the Life Cycle Cost (LCC) analysis of the base case using the Ecoreport tool. In the analysis, all the consumer expenditures throughout the life span of the product are considered, which include:

- Average sales prices of the base case (in EUR);
- Average installation costs (in EUR);
- Average repair and maintenance costs (in EUR);
- Average electricity rates (in EUR cent/kWh)
- Average lifetime of the base case (in years);
- Average annual energy consumption (in kWh).

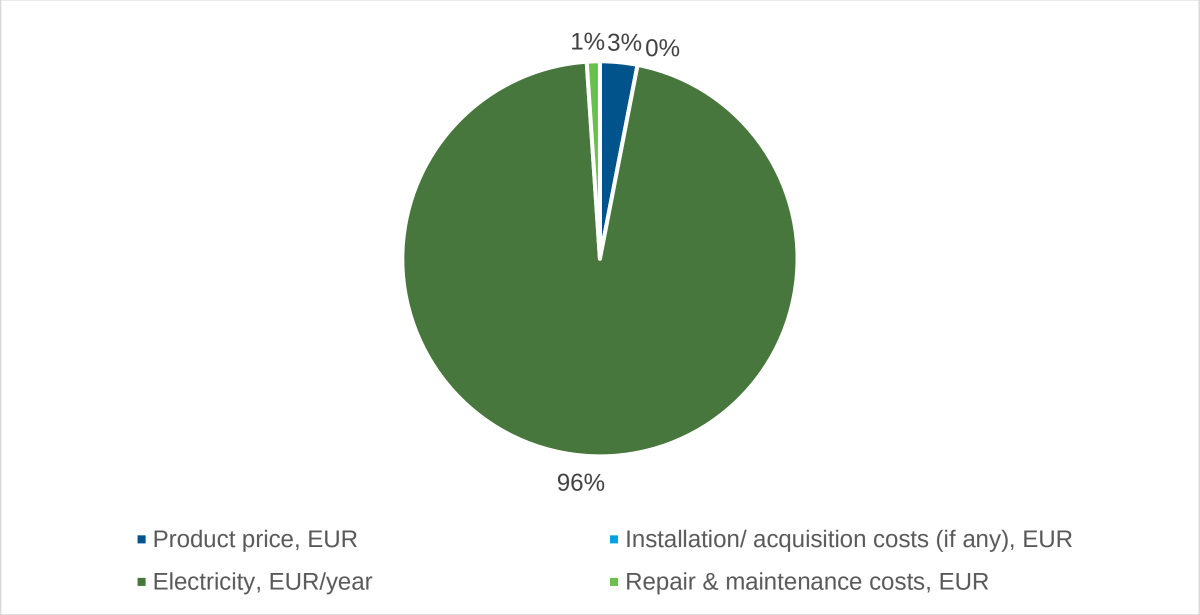
Table 5.17 below presents the Ecoreport outcomes of the LCC calculations for the Base Case.

Table 5.17 Life Cycle Costs for the Base Case

| | BC Distribution Transformer |
|---|---|
| Product price, EUR | 12,008 |
| Installation/ acquisition costs (if any), EUR | 0 |
| Electricity, EUR/year | 377,232 |
| Repair & maintenance costs, EUR | 4,203 |
| **Total, EUR/year** | **377,637** |

**Error! Reference source not found.** below visually presents the distribution of the values represented in Table 5.17 for the base case. It is clear that the largest cost comes from the electricity costs per year to operate the product.

Figure 5.2 Base case distribution transformer costs



## 5.5 Base Case Life Cycle Costs For Society

The societal life cycle costs is a sum of direct environmental costs, externalities and other indirect costs. The calculations are based on the following formula:

Societal LCC = LCC consumer + LCC ext.damages

Where:

LCC ext.damages = PP damages + N* OEdamages+ EoLdamages

And:

- PPdamages = Impacts (GWP in kg CO2 eq., AP in kg SO2 eq., etc.) in Production and Distribution phase x Damage unit value (in €/kg)
- OEdamages = Impacts in Use Phase x Damage unit value
- EoLdamages = Impacts in End of Life Phase x Damage unit value

Table 5.18 below presents the life cycle costs for society calculated by the Ecoreport tool.

Table 5.18 Total Societal Life Cycle Costs

| | **BC Distribution Transformer** |
|---|---|
| PP damages (€) | 1,217 |
| N*OE damages (€) | 35,269 |
| EoL damages (€) | -744 |
| Total External Damages (€) | 35,741 |
| **LCC (excl. ext. damages) (€)** | **377,637** |
| **Total Societal LCC (€)** | **378,531** |

## 5.6 EU totals

### 5.6.1 Lifecycle Environmental Impact at EU-27 Level

In this section, the environmental impact data is aggregated at the EU-27 level using stock and market data from Task 2. The aggregated results of the life cycle environmental impacts per year corresponding to the EU stock of products are presented in Table 5.19.

Table 5.19 EU Total Annual Impact of Stock of Products

| Main life cycle indicators<br>PEF Impact categories | Unit | Value |
|---|---|---|
| **Climate change, total** | **kg CO2 eq** | 674,913 |
| Ozone depletion | kg CFC-11 eq | 2.8E-04 |
| Human toxicity, cancer | CTUh | 2.2E-04 |
| Human toxicity, non-cancer | CTUh | 2.3E-03 |
| Particulate matter | disease incidence | 2.2E-02 |
| Ionising radiation, human health | kBq U235 eq | 2.8E+05 |
| Photochemical ozone formation, human health | kg NMVOC eq | 1.1E+03 |
| Acidification | mol H+ eq | 2.1E+03 |
| Eutrophication, terrestrial | mol N eq | 4.2E+03 |
| Eutrophication, freshwater | kg P eq | 1.4E+00 |
| Eutrophication, marine | kg N eq | 3.9E+02 |
| Ecotoxicity, freshwater | CTUe | 3.2E+06 |
| Land use | Pt | 2.9E+06 |
| Water use | m3 water eq. of deprived water | 2.3E+05 |
| Resource use, minerals and metals | kg Sb eq | 3.5E-01 |
| Resource use, fossils | MJ | 1.2E+07 |
| Additional technical information | | |
| **Primary energy consumption** | MJ | 5957116.05281512 |

Table 5.20 below presents the life cycle environmental impacts of the new products:

Table 5.20 EU Total Impact of New Products over their lifetime

| Main life cycle indicators<br>PEF impact categories | Unit | BC Distribution Transformer |
|---|---|---|
| **Climate change, total** | **kg CO2 eq** | 27,411 |
| Ozone depletion | kg CFC-11 eq | 1.1E-05 |
| Human toxicity, cancer | CTUh | 9.0E-06 |
| Human toxicity, non-cancer | CTUh | 9.5E-05 |

| Main life cycle indicators<br>PEF impact categories | Unit | BC Distribution Transformer |
|---|---|---|
| Particulate matter | disease incidence | 8.9E-04 |
| Ionising radiation, human health | kBq U235 eq | 1.2E+04 |
| Photochemical ozone formation, human health | kg NMVOC eq | 4.5E+01 |
| Acidification | mol H+ eq | 8.4E+01 |
| Eutrophication, terrestrial | mol N eq | 1.7E+02 |
| Eutrophication, freshwater | kg P eq | 5.6E-02 |
| Eutrophication, marine | kg N eq | 1.6E+01 |
| Ecotoxicity, freshwater | CTUe | 1.3E+05 |
| Land use | Pt | 1.2E+05 |
| Water use | m3 water eq. of deprived water | 9.3E+03 |
| Resource use, minerals and metals | kg Sb eq | 1.4E-02 |
| Resource use, fossils | MJ | 4.8E+05 |
| Additional technical information | | |
| **Primary energy consumption** | MJ | 237,665.93 |

### 5.6.2 Life Cycle Costs for Consumers at EU-27 Level

Table 5.21 below presents the aggregated results of the annual consumer expenditure per Base Case in the EU-27. This represents the total expenditure at EU level per year, assuming that the Base Case represents the entire installed stock in the EU-27.

Table 5.21 Total Annual Consumer Expenditure in the EU-27 million €

| Expenditure category | Annual consumer expenditure (EU-27 million) |
|---|---|
| Product price,mln. EUR/year | 1,239 |
| Installation/ acquisition costs (if any), EUR | 0 |
| Electricity, mln. EUR/year | 958,021 |
| Repair & maintenance costs, mln. EUR/year | 267 |
| **Total, mln. EUR/year** | **959,527** |

### 5.6.3 Life Cycle Costs for Society at EU-27 Level

Table 5.22 below presents the total annual social life-cycle costs at EU-27 level. Adding the external costs to society to the LCC gives the total annual social life cycle costs.

Table 5.22 Total annual social life-cycle costs at EU-27 level

| Expenditure category | Annual consumer expenditure (EU-27 million) |
|---|---|
| PP damages (m €) | 125.50 |
| N*OE damages (m €) | 2,239.23 |
| EoL damages (m €) | -76.77 |
| Total External Damages (m €) | 2,287.96 |
| **LCC (excl. ext. damages) (m €)** | **959,527** |
| **Total Societal LCC (m €)** | **961,815** |

# 6 Task 6: Design Options

## 6.1 Identification of design options

### 6.1.1 Recovery and regeneration of oil

#### 6.1.1.1 DO1: Replacing mineral oil with ester

The team recommends the usage of esters to increase the lifetime of assets, diminish environmental concerns in case of leaks, and improve fire safety considerations.

This measure would consider the effects of replacing mineral oil with esters. These esters are capable of performing at higher temperatures and are environmentally safer. The model would need to consider the following aspects:

- An increase in cost for ester compared to mineral oil. It is estimated by transformer manufacturers that units filled with ester dielectric fluid would price at 5 -10% more[74].
- The improved lifetime of assets due to the better cooling properties of ester. It is conservatively estimated that new transformers would experience a 33% life extension if filled with ester-based dielectric fluids. Furthermore, the cellulose paper used to insulate windings in fluid-filled transformers degrades at a significantly slower rate in the presence of ester dielectric fluids than in conventional mineral transformer oil. The time to end of life for a transformer with paper submersed in ester oil at 110°C is estimated to be ≥ 2.5 that of a transformer with paper submersed in mineral oil[74].
- The potential for higher capacities to be run on transformers with the same metal structure, but with ester instead of mineral oil, thanks to their higher thermal protection capability.
- The environmental benefits that an ester leak is not as damaging to the environment compared with mineral oil, due to esters being biodegradable and less flammable than mineral oil. Ester fluids have a flash point as defined by ISO 2719 of 330°C and fire point defined by ISO 2592 of 360°C, versus typically 160-180°C for mineral oil. Ester fluids also will not sustain a flame in the absence of a high-energy source of ignition. Ester fluid combustion byproducts are water, carbon dioxide and carbon monoxide, which are less toxic than the carbon, nitrogen and sulphur oxide byproducts from mineral oil combustion[74].
- Change the environmental impacts of ester from mineral oil in the tool, due to ester fluids not containing petrochemicals, siloxanes or halogens, and its less toxic combustion by-products[74].

Ester Dataset utilised for Design Option 1 modelling of environmental impacts is at Annex 2.

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[74] PGE-FR3-report.pdf (nwppa.org)

#### 6.1.1.2 DO2: Recovering and regenerating mineral oil

Transformers with oil are bunded, such that if there is ever a leak, the oil is captured within the transformer enclosure and does not spread to the local environment.

To improve the sustainability of the mineral oil, the research team recommends reviewing if the recovery and regeneration of oil can be encouraged. Mineral oil captured within the transformer enclosure can be cleaned and regenerated to be reused in a transformer. IEC 60296 catalogues recycled oils as equivalent to virgin oils. Stakeholders have indicated that 5% of transformer failures are due to poor oil quality. Thus, encouraging the recovery and regeneration of the captured oil to virgin oil quality would minimise the number of failures from this.

It is worth noting however that this bunded system is not used for certain setups with a lack of space, such as pole-mounted transformers. Therefore, DO1 using non-toxic, biodegradable esters may be a better fitting for these products to limit environmental risks.

### 6.1.2 Material efficiency measures

#### 6.1.2.1 DO3: Ability to disassemble requirement and information sharing to disassemble

It is recommended that Ecodesign includes a requirement that transformers need to be disassembled without destruction to allow for repair. This requirement would be set up such that an expert (class C, with specific training and/or experience related to the product category) can perform the repair with tools of class C (commercially available tools). Epoxy resin, which is difficult to separate from the coils when used as an insulation material to allow for the metal recycling of the coils, may need exemption from this. A recommendation can be made to enquire for the use of silicone rubber, which has been indicated as a good insulator and can be separated from winding conductors, instead of epoxy to facilitate reuse.

Technical documents with instructions for disassembly and the winding plans shall be made available to registered repair staff to ensure that products can be adequately repaired. The percentage of encountered defects for components within a liquid immersed distribution transformer is showcased in Table 3.2, which highlight the improved repair potential of individual components.

It is recommended that no changes are made to article 1.3, as it is only in effect when both core components (core and windings) are replaced. This is in place to ensure that there is no loophole to the Ecodesign Regulation, where a product is remanufactured under the realm of ‘repair’ and resold at lower performance metrics.

### 6.1.3 Measures which need including in the revised regulation but will not be modelled

#### 6.1.3.1 Updates to the definitions of small and medium

It is recommended that we update the definitions of small, medium and large power transformers in the regulation. The following definitions will be adopted:

- A small power transformer would be defined as: “a power transformer with a highest voltage for equipment <= 1 kV”.

- A medium power transformer would be defined as “a power transformer with all windings having rated power lower than or equal to 3 150 kVA, and highest voltage for equipment greater than 1 kV and lower than or equal to 36 kV”

These definitions ensure that all small power transformers are covered by the scope of TC 96 and that only medium and large power transformers are covered by TC 14, as intended by the IEC technical committees.

#### 6.1.3.2 Update to the scope of the regulation

Currently the regulation defines small power transformers as *“a power transformer with a highest voltage for equipment not exceeding 1,1 kV”.* Based on this definition and the scope of the regulation, which states that all power transformers > 1 kV and > 1 kVA are in scope, small power transformers are those that are > 1 kVA and < 1.1 kV. Meanwhile the scope of TC 14 covers power transformers that are > 1 kV and > 1 kVA. Therefore, small power transformers as defined by the regulation are technically included in the scope of TC 14. This is not the intention of TC 14 because there is another working group which covers small power transformers separately, TC 96, which also has its own set of standards.

This misalignment has caused some confusion in the industry because technically small power transformers are supposed to be covered by TC 96, whose scope states it includes transformers < 1000 V. As a result, the study team has looked at the possible resolution of this matter to ensure there is more clarity. The study team recommends that we align the scope of the regulation with that of TC 14. This update, alongside the updated definition of small power transformers described in Section 6.1.3.1 will ensure that small power transformers will no longer overlap with the scope of TC 14.

### 6.1.4 Measures considered but not taken forward

#### 6.1.4.1 Implementation of Tier 3

Although it is technically feasible to reach higher efficiency values, this is done by using more materials. This increases the weight and size of the transformers, which can have complications such as increasing installation costs if it cannot fit into an existing substation. Furthermore, increasing energy efficiency standards would increase the costs and delays that the transformer supply chain currently experiences.

For medium sized transformers, reaching Tier 3 performance would require the use of amorphous steel cores. Since no country in the EU currently manufactures amorphous steel, as covered in Section **Error! Reference source not found.**, this is a difficult material to source. The infrastructure and supply chains for manufacturing with amorphous steel are still not established. Furthermore, amorphous steel is more expensive than regular steel, especially when operating at low saturation levels to mitigate excessive noise. This leads to the production of pricier transformers. Therefore, it is recommended to not increase the standard performance from Tier 2 to Tier 3.

#### 6.1.4.2 Small power transformers energy efficiency metric

After discussions with members of the TC 14 it was discovered that it is not the intention of this TC to include small power transformers within its scope. As a result, there is currently no energy efficiency testing method present for small power transformers, since TC 14 only covers transformers > 1000 V. It was also mentioned that it was not the intention of TC 14 to cover small power transformers, because all small power transformers are to be covered by TC 96.

Therefore, it is not recommended to take this small power transformer energy efficiency metric forward because of the lack of a standard containing a methodology for testing small power transformers efficiency. The study team is aware of TC 96 which covers small power transformers < 1000 V. However, this series of standards (IEC 61558) does not provide a testing methodology for the efficiency of small power transformers. As discussed in Section 6.1.3.1 we will be recommending that the definition of small power transformers is adopted from TC 96.

#### 6.1.4.3 PEI usage for medium transformers

It is recommended to keep only absolute values of losses for medium transformers without PEI.

Medium transformers affect the EU-27 grid losses to a significant extent, due to them making up one of the largest market shares in the EU out of the existing transformer types.

Using only PEI may give several combinations of no-load loss (P0) and load loss (Pk) with different optimum equivalent load factor (kPEI). Hence, the absolute value of losses for medium transformers is recommended. However, out of several combinations of P0 and Pk, only one might be compliant with losses in absolute numbers as set out in the regulation. Absolute values of losses are also important for market standardisation.

#### 6.1.4.4 Additional considerations when using reversed power flow transformers

The need for reverse power flow transformers is expected to continue to increase as more green/renewable sources are connected to the grid. It is recommended that Reverse Power Flow (RPF) is defined to ensure manufacturers can accommodate appropriate protection and control systems, minimising the effects of RPF. This helps their operation to be safe and reliable. This action is not for Ecodesign, but for the technical standards body to define RPF and its other modalities as deemed necessary for safe and reliant operation.

#### 6.1.4.5 Offshore transformer exemption

##### *Within the nacelle*

It is recommended that these exemptions are kept. These transformers have more than double the capacity on average than those used for onshore wind turbines. Without exemptions, compliant transformers would struggle to fit into the nacelle, resulting in the nacelle and overall turbine needing to be bigger. Onshore turbines are smaller on average, more accessible, and cheaper to maintain and install, and hence a like-for-life comparison between onshore and offshore turbines is not deemed appropriate. It is recommended that these exemptions are kept, but are worth reviewing in future as the market share grows.

***On platforms***

It is recommended to keep these concessions. Larger, more efficient transformers would require an increased amount of structural material, making costs very high and increasing the environmental impact when considering the additional steel. Increasing regulatory pressure on offshore transformers may also be seen as a barrier to develop offshore wind resources, inhibiting renewable energy policies.

#### 6.1.4.6 Pole-mounted transformer exemption

It is recommended that these concessions are kept for like-for-life replacements. The cost for replacements are estimated to be significantly more than what would be saved from a more efficient transformer due to the pole being likely to not be able to withstand a heavier transformer. An FAQ document is recommended to be created to state the conditions when this concession can be used and the process for applying for it. A mark on a transformer indicating that it is specifically for a like-for-like replacement would provide clarity and mitigate the risk of the concession being used as a loophole. Future considerations could be given to reducing the concession limit to 100 kVA or 200 kVA as higher loads (typically for >250 kVA) are being moved to ground based setups.

#### 6.1.4.7 Concessions to medium transformers with special combinations of winding voltages

Concessions for these are deemed necessary due to larger, more efficient transformers often unable to fit into the same space that the original transformer was in, increasing installation costs by 10-20%. The concessions allow for the gradual conversion of the grid to a higher voltage in an economically favourable way, as well as for effectively handling intermittent power sources for the growing renewable energy sector. It is recommended that an FAQ document is created to state the conditions when this concession can be used and the process for applying for it.

#### 6.1.4.8 Technology neutral and functional categorisation

Since the regulation currently aligns its power transformer definition with that provided in EN/ISO 60076-1:2011, which is also harmonised with IEC 60076-1:2011, it is likely that any update that is made to the definition in the upcoming amendment of IEC 60076-1 will be adopted by the regulation. However, because the revised IEC standard will not be published until after the results of this study are published the regulation should not adopt a new definition. Thus, from an Ecodesign perspective, it is recommended not to change the definition of power transformers at this point. The regulation should only align with the definitions provided by the standard once these have officially been published. This will also mean that the current reference temperatures used by the regulation for oil-immersed transformers will continue to be used until the IEC 60076-1:2011 standard is updated. As a result, no action is to be taken on this matter during this review study.

#### 6.1.4.9 Noise as a measure for Ecodesign

It is recommended not to include noise as a measure for Ecodesign. The increase in efficiency from Ecodesign is already having an effect on reducing the noise of transformers. Additionally, there are separate standards and regulations from national and local governments which provide a maximum noise requirement. Furthermore, transformers with more efficient amorphous steel cores are much louder than ones with grain-oriented steel cores, making noise a potentially conflicting metric to include. Stakeholders have also indicated that noise testing would provide an additional charge for testing at certified laboratories.

#### 6.1.4.10 Temperature and climate considerations

It is recommended to not make further requirements in the Ecodesign regulation with regards to temperature and climate adaptation. This is due to the IEC and CENELEC standards already providing temperature requirements. IEC 60076-1 already states the operating ranges for transformers. IEC 60076-2 also sets out the cooling measures, temperature rise limits and the corresponding verifications tests. For dry-type transformer, IEC 60076-11 defines climate classes, covering transformer storage down to -60ºC and transformer energization down to -50ºC. Furthermore, the PEI methodology for large power transformers also considers the cooling systems operation within the test procedure. Mandating temperature operating ranges for transformers may be counterproductive, as it may go against the existing standards and would not allow utilities the flexibility to adapt to changing climate conditions.

## 6.2 Assessment of environmental impacts, life cycle costs and purchase price

### 6.2.1 BC1

Task 5 identified the Life Cycle cost and Environmental Impacts of BC1. Within Task 6, different design options applicable to Base Case 1 and their impact analysis was performed.

Table 6.1 below shows the primary energy consumption and life cycle cost of all design options compared to the Base Case 1.

Table 6.1 Primary energy consumption & LCC of design options compared to BC1

| | **Base Case 1** | **Design option 1** | **Design option 2** |
|---|---:|---:|---:|
| Primary Energy Consumption (MJ) | 2.30E+06 | 3.04E+06 | 2.44E+06 |
| % change with BC | | 32 | 6 |
| Life Cycle Cost (Euro) | 377,637 | 502,039 | 400,271 |
| % change with BC | | 33 | 6 |

Figure 6.1 shows the relative impact on the primary energy consumption for each of the design options compared to the Base Case 1.

Figure 6.1 Primary energy consumption for design options compared to BC1 (%)

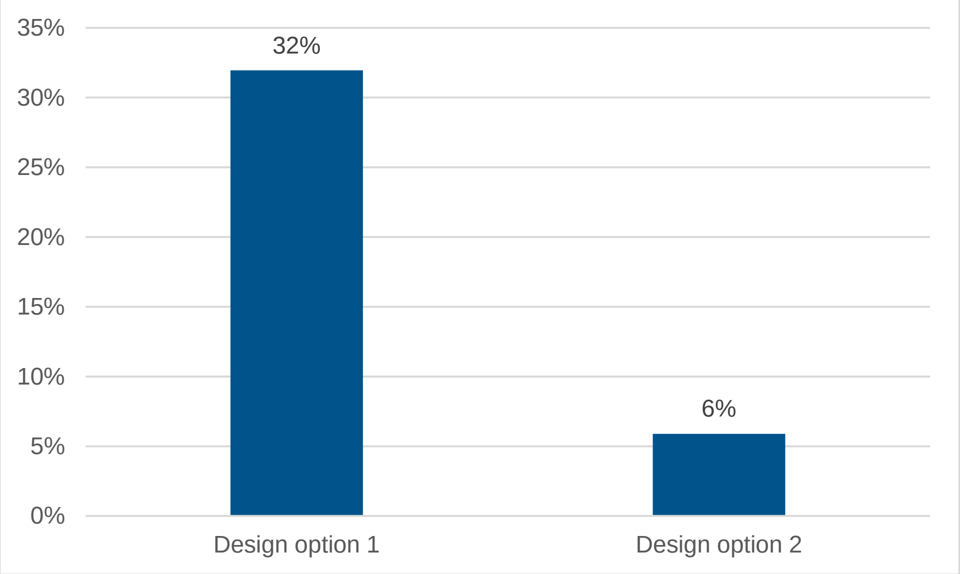
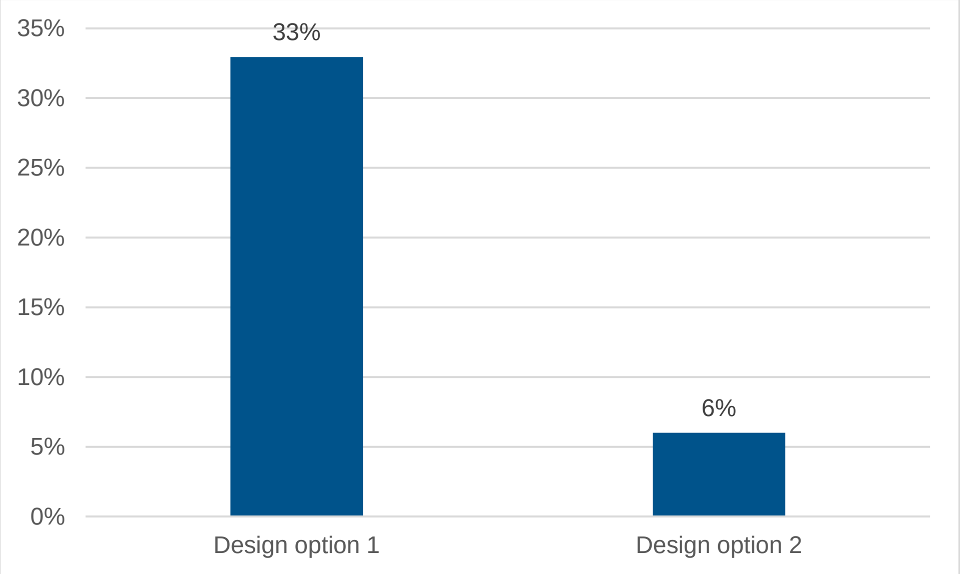


Figure 6.2 shows the relative impact on the life cycle cost for each of the design options compared to the Base Case 1.

Figure 6.2 Life cycle cost as compared with BC1 (%)



Each of the design options applicable to Base Case 1 and its relative impact on climate change, resource use (minerals and metals) and resource use (fossils) compared the base-case are shown in Table 6.2.

Table 6.2 Impact on climate change, resource use (minerals and metals) and resource use (fossils) of each design option compared to BC1

| Life-cycle indicators per unit | Unit | Base Case 1 | Design option 1 | Design option 2 |
|---|---|---|---|---|
| **Climate change, total** | kg CO2 eq | 2.66E+05 | 3.53E+05 | 2.82E+05 |
| | % change with BC | | 33 | 6 |
| **Particulate Matter** | disease incidence | 8.63E-03 | 1.14E-02 | 9.14E-03 |
| | % change with BC | | 32 | 6 |
| **Acidification** | mol H+ eq | 8.17E+02 | 1.08E+03 | 8.65E+02 |

| | | | | |
|---|---|---|---|---|
| | % change with BC | | 33 | 6 |
| **Resource use, minerals and metals** | kg Sb eq | 1.39E-01 | 1.62E-01 | 1.43E-01 |
| | % change with BC | | 16 | 3 |
| **Resource use, fossils** | MJ | 4.62E+06 | 6.12E+06 | 4.90E+06 |
| | % change with BC | | 32 | 6 |

## 6.3 Analysis BAT and Least Life Cycle Cost (LLCC)

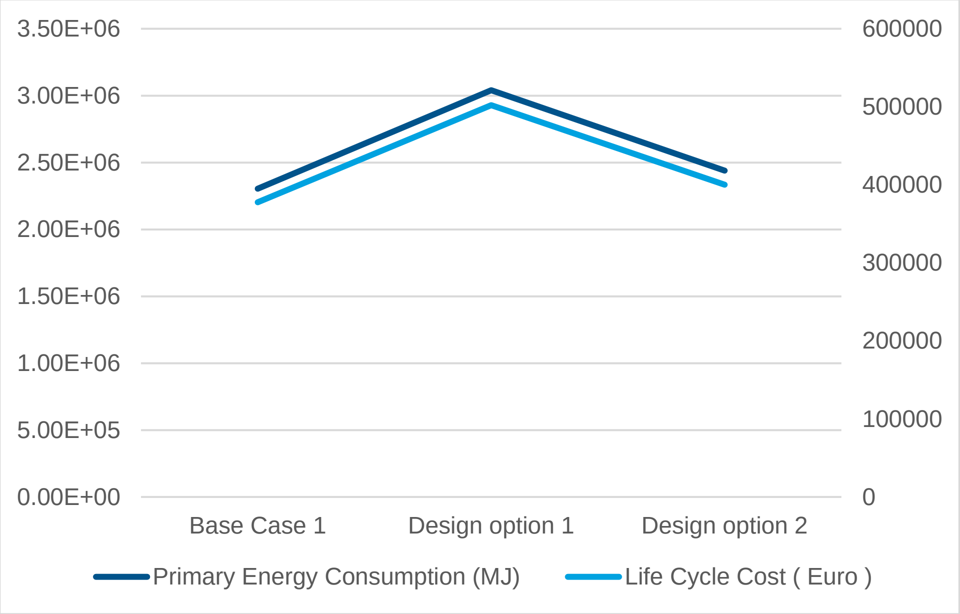
The design options are ranked to identify improvement options with the least cycle environmental impacts (BAT) and the Least Life Cycle Costs (LLCC). Energy-LCC curve (Y-axis = energy consumed and LCC, X-axis = options) allows the LLCC and BATs to be identified.

The performance of each Design Option is compared with the base case. The comparison is done in terms of primary energy consumption and Life Cycle cost (LCC) as described in Task 5.

### 6.3.1 BC1

Figure 6.3 shows the LLCC curve for Base Case 1. The comparison is done in terms of primary energy consumption and Life Cycle cost (LCC).

Figure 6.3 LLCC curve for Base Case 1



# 7 Task 7: Scenarios

## 7.1 Policy analysis

### 7.1.1 Stakeholders

Since commencing in June 2023, the research team has consulted with stakeholders across industry. This includes stakeholders from SMEs to large multi-national manufacturers, grid operators, energy companies, Member State government bodies, trade association for transformer and materials as well as international testing organisations. Trade associations that were engaged in the study include T&D Europe, European Copper Institute, Eurelectric, E.DSO, SIRMELEC and BEAMA.

The research team has undertaken two stakeholder meetings to present their work to industry. The first stakeholder meeting on the 26th September 2023 introduced the main activities of the study and a timeline requesting feedback via a qualitative questionnaire. Following this the Phase 1 Technical Analysis report was released, and feedback requested during the second stakeholder meeting. The research team also requested stakeholders to complete a quantitative questionnaire to provide inputs for the Phase 2 report (updated of Tasks 1-7 of the MEErP). The second stakeholder meeting was held on 16th January 2024 which discussed the results of the Phase 1 report and the next steps for the publication of the Phase 2 report and requested completion of the quantitative questionnaire.

## 7.1.2 Barriers & Opportunities

### 7.1.2.1 Barriers

The research team considered implementing a higher tier of energy efficiency thresholds. The team concluded that meeting the raised thresholds would result in more material consumption, which increases the weight and size of the transformer, resulting in complications such as increasing installation costs. Increasing the energy efficiency thresholds would also increase the costs and delays that the transformer supply chain currently experiences.

Amorphous steel cores would be required for medium-sized transformers to reach a higher tier performance. The study team's research found no country in the EU currently manufactures amorphous steel, making it a difficult material to source. The infrastructure and supply chains for manufacturing with amorphous steel are not yet sufficiently established, and it is a more expensive material than regular steel, increasing the price of the transformers. Therefore, although it is technically feasible to reach higher efficiency values, it is recommended not to increase the efficiency thresholds above the current Tier 2.

### 7.1.2.2 Opportunities

An opportunity identified by the research team is replacing mineral oil with esters. This increases the lifetime of the transformers, diminishes environmental concerns associated with leaks, and improves fire safety considerations. Although it would increase the price of transformers by 5 – 10%, it would increase the lifetime by approximately 33%. Other benefits include the transformers being able to run at a higher capacity with the same metal structure due to their higher thermal protection capability, and that ester fluid combustion byproducts are less toxic than mineral oil combustion.

Another opportunity identified is to recover and regenerate the mineral oil that is captured within the bunded transformer enclosure to virgin oil quality. This would minimise the amount of failures that are due to poor oil quality. It is worth noting that not all transformers are bunded, such as pole-mounted transformers, due to a lack of space.

### 7.1.3 Scope

The general scope of Regulation (EU) 2019/1783 has been defined by the European Commission to cover power transformers with a minimum power rating of 1 kVA used in 50 Hz electricity transmission and distribution networks or industrial applications.

Small, medium, and large power transformers have been regulated since 2014 within the Ecodesign Regulation (EU) 548/2014. This regulation introduced the definitions for: power transformers, small power transformers, medium power transformers, large power transformers, liquid-immersed transformer, dry-type transformers, medium power pole mounted transformers, and Voltage Regulation Distribution Transformer. The full definitions for the amended regulation are covered in Task 1, Section 1.2.2.

Small, medium and large power transformers are separately defined within Regulation (EU) 2019/1783 because they are used in different applications. Medium power transformers are defined as having a rated power < 3,150 kVA and a highest voltage of > 1.1 kV and < 36 kV.  Within the scope of the regulation "small power transformers" are defined as those more than 1 kVA power transformers with a highest winding voltage not exceeding 1.1 kV. Small power transformers as defined by the EU are not compliant with the EN/IEC 60076 series and are not within the scope of TC14. However, due to the current regulation’s definition of small power transformers they technically fit within the scope of TC 14. After discussions with members of TC 14 it was discovered that it is not the intention of TC 14 to include small power transformers within its series of standards (IEC 60076). Primarily because TC 96 is supposed to cover small power transformers, with its scope covering transformers < 1000 V (see Table 1.2 for a comparison of the scopes of TC 14, TC 96 and the regulation).

As a result, the research team has looked at the possible resolution of this matter to ensure there is more clarity. The research team recommends that we more closely align the definition of small power transformers with that of TC 14. This will ensure that the regulation’s definition of small power transformers does not allow it to be covered by the IEC 60076 standard. It is recommended that we update the definition of small power transformers to “*a power transformer with a highest voltage for equipment <= 1 kV.* This ensures that all small power transformers are covered by the scope of TC 96 and that medium and large power transformers are covered by TC 14.

### 7.1.4 Measures Considered

The measures considered for the transformer’s product groups are presented and discussed below.

#### 7.1.4.1 Replacing mineral oil with ester

Design Option 1 from Task 6, this measure would consider the effects of replacing mineral oil with esters. Esters are capable of performing at higher temperatures and are environmentally safer. The usage of esters increases the lifetime of assets, diminishes environmental concerns in case of leaks, and improves fire safety considerations.

#### 7.1.4.2 Recovering and regenerating mineral oil

Design Option 2 from Task 6, this measure would improve the sustainability of the mineral oil used with transformers by considering if the recovery and regeneration of oil can be encouraged. Mineral oil captured within the transformer enclosure can be cleaned and regenerated to be reused in a transformer. Currently, transformers with oil are bunded, such that if there is ever a leak, the oil is captured within the transformer enclosure and does not spread to the local environment. Stakeholders have indicated that 5% of transformer failures are due to poor oil quality. Thus, encouraging the recovery and regeneration of the captured oil to virgin oil quality would reduce the overall number of failures.

### 7.1.5 Standards

Transformers within the scope of the regulation adopt the standards developed by the IEC TC 14. The scope of TC14 covers the standardisation of power transformers, tap-changers and reactors used in power generation, transmission and distribution[75]. TC 14 has developed the IEC 60076 series of standards which covers transformers with a power rating > 1 kVA single phase and 5 kVA polyphase with a higher voltage winding of > 1000 Volts. The standard IEC 60076-20:2017 provides a method for specifying a power transformers energy efficiency according to the loading and operating conditions. This is utilised by the regulation to test the performance of transformers in the EU.

Since the IEC standards are only discussed on a global level, the EU developed its own set of standards which were adopted from the IEC 60076, these are covered in the EN 50708 series of standards. Developed by the CLC/ TC 14 the scope of EN 50708 aligns with the EU regulation. It defines large power transformers as those with a power rating above 3,150 kVA or highest voltage equipment greater than 36 kV. Additionally, medium power transformers are defined as those with a rated power lower than 3,150 kVA and highest voltage for equipment greater than 1.1 kV or lower than or equal to 36 kV. It should be noted that EN 50708 does not provide the testing procedures for power transformers in scope of the regulation. Scenario analysis – resource use and environmental impacts.

### 7.1.6 Inputs & Assumptions

#### 7.1.6.1 Stock & Sales

The stock and sales assumptions from Tasks 2 and 5 are used for modelling the BaU and MEPS scenarios.

In the MEPS scenario, the total stock and sales figures are the same as those in the BaU scenario.

There is further detail on the assumptions used to model stock and sales in the Task 2 and Task 5 reports.

Table 7.1 Estimated stock of BC1 in the EU between 2010 and 2050.

| Year | BC1 (thousands) |
|---|---|
| **2010** | 2230 |

---

[75] INTAS_D2.1_Final_Annex_A.pdf (intas-testing.eu)

| | |
|---|---|
| **2015** | 2501 |
| **2020** | 2784 |
| **2025** | 3076 |
| **2030** | 3376 |
| **2035** | 3683 |
| **2040** | 3992 |
| **2045** | 4294 |
| **2050** | 4598 |

#### 7.1.6.2 BaU Scenario

In the BaU scenario, the energy consumption in the use phase and the consequent environmental impacts are calculated considering the technical inputs used to model the Base Case in Task 5. Environmental impacts are also calculated using the EcoReport tool 2024, as per Task 5.

#### 7.1.6.3 MEPS Scenario

In the MEPS scenario, the energy consumption in the use phase and the consequent environmental impacts are calculated considering the technical inputs used to model the Base Cases in Task 5 and Design Option 1 in Task 6 for BC1 . Environmental impacts are also calculated using the EcoReport tool 2024, as per task 5.

Between 2010 and 2023, there is no difference between the BaU and the MEPS scenario. The MEPS scenario comes into effect from 2024. The stocks and sales remain same as BaU scenario.

### 7.1.7 Results

The energy consumption of the stock of BC1 in the EU for the **two** different scenarios were calculated

#### 7.1.7.1 Base Case 1

Figure 7.1 shows the Primary Energy Consumption for the two scenarios between 2010 and 2050 for EU27 for BC1

Figure 7.1 BC1 Primary Energy Consumption, two scenarios, 2010-2050 (EU27)

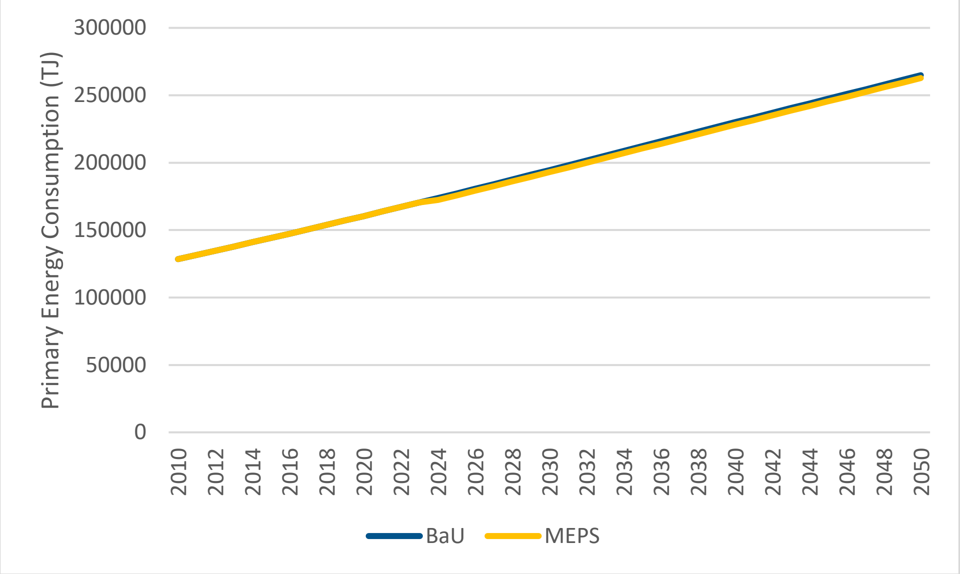


Figure 7.2 shows the Energy Cost for the two scenarios between 2010 and 2050 for EU27 for BC1.

Figure 7.2 BC1 Energy Cost for the two scenarios, 2019-2050 (EU27)

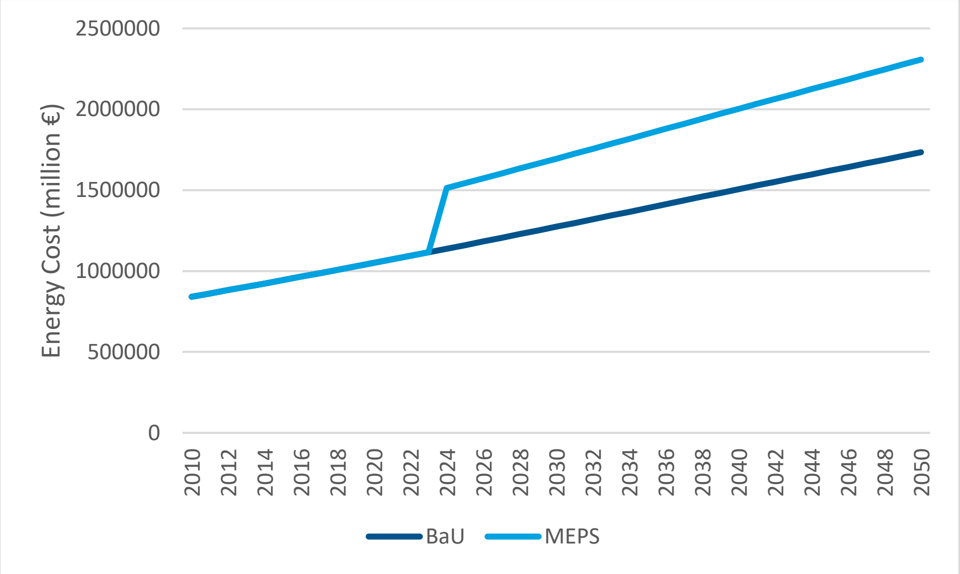
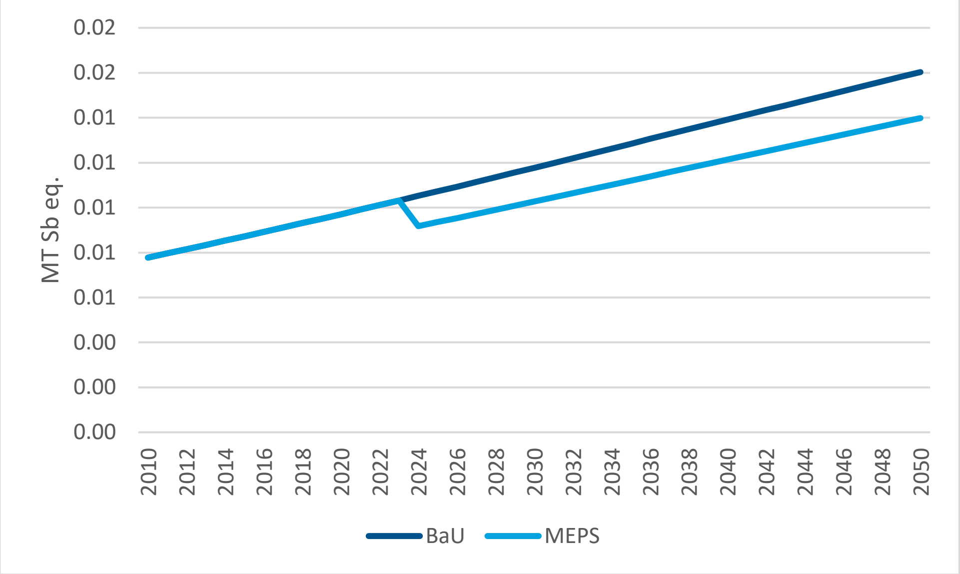


Figure 7.3 shows the Resource use (minerals & metals) for the two scenarios between 2010 and 2050 for EU27 for BC1.

Figure 7.3 BC1 Resource use, two scenarios, 2010-2050 (EU27)



## 7.2 Scenario analysis – Socio-economic impacts

The objective of this sub-task is to discuss the socio-economics impacts created by the different policy scenarios proposed (i.e. BaU and MEPS).

The same sales and stock model used previously to calculate resource use and environmental impacts is used to estimate the following outputs in all four scenarios:

- Consumer expenditure with purchase and installation.
- Running costs to the consumer, cost of electricity, cost of repair, and maintenance cost.
- Societal costs of the environmental impacts created.

The inputs and assumptions used in the modelling as well as the results are presented in the following sub-sections.

### 7.2.1 Inputs & Assumptions

#### 7.2.1.1 Purchase Price

The purchase price inputs for the BaU scenario were used as per the Base Case model from Task 5 for the whole 2010-2050 period.

In the MEPS scenario, the average price per unit is expected to increase in 2024 due to the proposed measures as described in Task 6 for DO1.

The purchase price of units used in the scenarios are detailed in Table 7.2.

Table 7.2 Purchase price of units used in the two scenarios

| Base Case | BaU purchase price (€) | MEPS purchase price (€) |
|---|---|---|
| BC1 | 12,008 | 12,849 |

#### 7.2.1.2 Installation cost

The installation cost inputs were used as per the Base Case models from Task 5 for the whole 2010-2050 period in two scenarios.

The installation cost of units used in the scenarios are detailed in Table 7.3.

Table 7.3 Installation cost of units used in the two scenarios

| Base Case | 2 scenarios installation cost (€) |
|---|---:|
| BC1 | 0 |

#### 7.2.1.3 Maintenance & repair

The repair and maintenance cost inputs for the BaU scenario were used as per the Base Case model from Task 5

The repair and maintenance cost of units used in the scenarios are detailed in Table 7.4.

Table 7.4 Repair and maintenance cost of units used in the two scenarios

| Base Case | 2 scenarios repair and maintenance cost (€) |
|---|---:|
| BC1 | 4,202 |

#### 7.2.1.4 Inflation

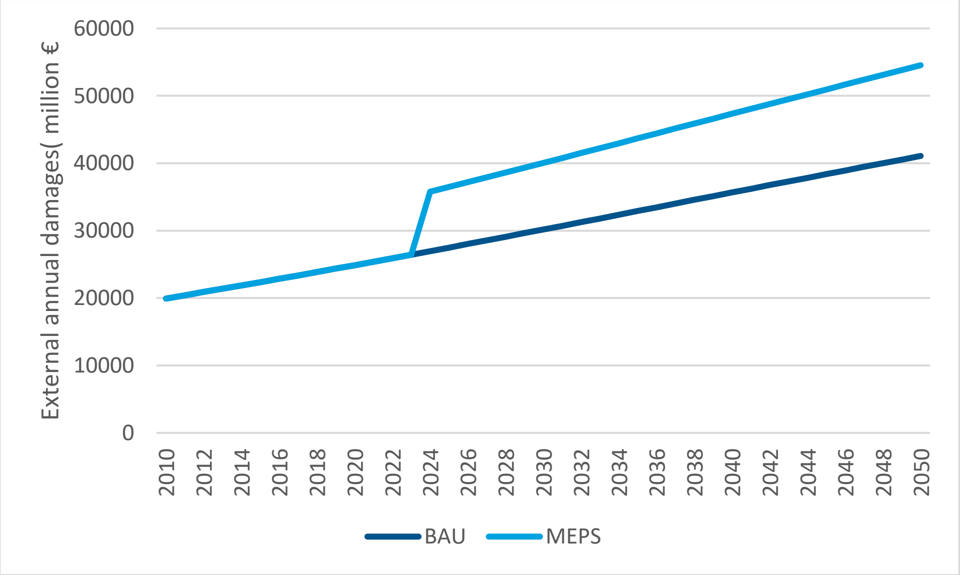
Socio-economic impacts were first calculated in terms of real value (i.e. current €) for an analysis of the effect of the assumptions and policies.

### 7.2.2 Results

#### 7.2.2.1 Base Case 1

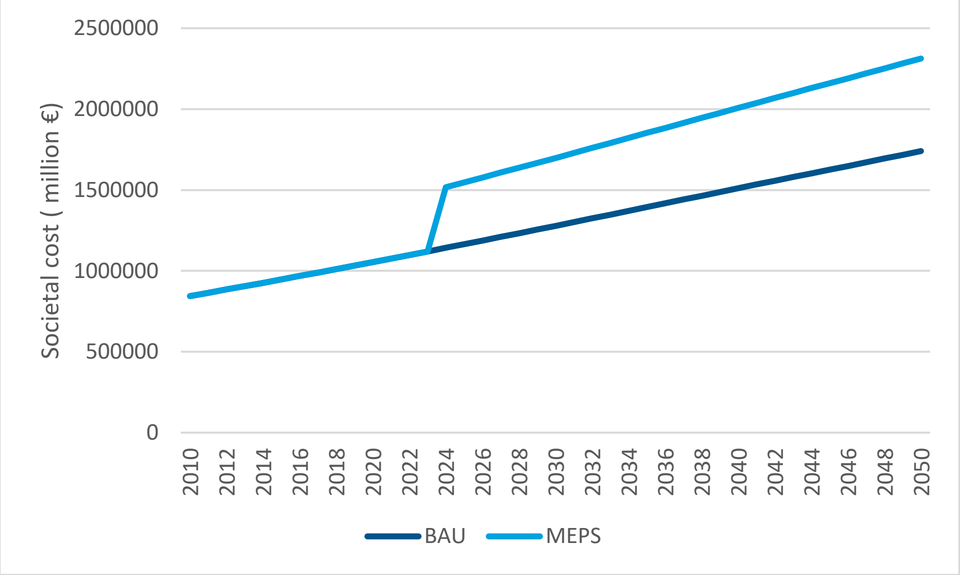
Total annual external damages of the stock between 2010 and 2050 in the EU for the two different scenarios is presented in Figure 7.4 below.

Figure 7.4 BC1 External annual damages, EU27



Total societal cost of the stock between 2010 and 2050 in the EU for the two different scenarios is presented below in Figure 7.5

Figure 7.5 BC1 Total Societal cost, EU27



## 7.3 Conclusions

The Life cycle cost for Design Option 1 and Design Option 2 were calculated using the MEErP tool 2024. The LCC for both of the Design Options is greater than the Base Case.

For Design Option 1, the LCC is greater than the Base Case because there is an increase in the lifetime of the transformer and increase in the cost due to esters. Also, the availability and supply chain of esters also has to be factored in.

For Design Option 2, the LCC is greater than Base Case because recovery and regeneration of mineral oil will increase the cost of the transformer by around 6%. Also, the responsibility of the recovery and regeneration of mineral oil also has to be factored in.

In considering the practical implementation possibilities of replacing mineral oil with esters (i.e. Design Option 1), it would not be feasible to implement a ban, within the scope of the Ecodesign Framework 2009/125/EC, of mineral oil. Therefore, this measure will be taken forward as a proposed Information Requirement only. The information requirement would require manufacturers to specify if their transformer can be operated using esters.

It would be desirable to encourage the recovery and regeneration of used mineral oil from power transformers (i.e. Design Option 2). However, similarly to the replacement of mineral oil with esters, it is difficult to consider practically how the Ecodesign Framework 2009/125/EC can bs used to implement this measure.

# Annex 1 All Life Cycle Indicators per unit for design options

## A1.1 Base Case 1

Table A1.1 All Life Cycle indicators per unit of the different design options for BC1

| Life-cycle indicators per unit | Unit | Base Case 1 | Design option 1 | Design option 2 |
|---|---|---|---|---|
| **Energy Consumption** | | | | |
| **Electricity** | kWh | 628,720 | 836,198 | 666,443 |
| | % change with BC | | 33% | |
| **Thermal Energy** | MJ | 0 | 0 | 0 |
| | % change with BC | | 0% | |
| **PEF Impact Categories** | | | | |
| **Climate change, total** | kg CO2 eq | 2.66E+05 | 3.53E+05 | 2.82E+05 |
| | % change with BC | | 33% | 6% |
| **Ozone depletion** | kg CFC-11 eq | 1.10E-04 | 1.42E-04 | 1.16E-04 |
| | % change with BC | | 29% | 5% |
| **Human toxicity, cancer** | CTUh | 8.77E-05 | 1.02E-04 | 9.03E-05 |
| | % change with BC | | 17% | 3% |
| **Human toxicity, non-cancer** | CTUh | 9.22E-04 | 1.25E-03 | 9.75E-04 |
| | % change with BC | | 36% | 6% |
| **Particulate Matter** | disease incidence | 8.63E-03 | 1.14E-02 | 9.14E-03 |
| | % change with BC | | 32% | 6% |
| **Ionising radiation, human health** | kBq U235 eq | 1.12E+05 | 1.49E+05 | 1.19E+05 |
| | % change with BC | | 33% | 6% |
| **Photochemical ozone formation, human health** | kg NMVOC eq | 4.39E+02 | 5.81E+02 | 4.65E+02 |
| | % change with BC | | 32% | 6% |
| **Acidification** | mol H+ eq | 8.17E+02 | 1.08E+03 | 8.65E+02 |
| | % change with BC | | 33% | 6% |
| **Eutrophication, terrestrial** | mol N eq | 1.64E+03 | 2.18E+03 | 1.74E+03 |
| | % change with BC | | 33% | 6% |
| **Eutrophication, freshwater** | kg P eq | 5.43E-01 | 7.70E-01 | 5.76E-01 |
| | % change with BC | | 42% | 6% |
| **Eutrophication, marine** | kg N eq | 1.54E+02 | 2.05E+02 | 1.64E+02 |
| | % change with BC | | 33% | 6% |
| **Ecotoxicity, freshwater** | CTUe | 1.25E+06 | 1.64E+06 | 1.33E+06 |
| | % change with BC | | 31% | 6% |
| **Land use** | pt | 1.14E+06 | 1.58E+06 | 1.21E+06 |
| | % change with BC | | 38% | 6% |
| **Water use** | m3 water eq. of deprived water | 9.05E+04 | 1.20E+05 | 9.59E+04 |

| | | | | |
|---|---|---|---|---|
| | % change with BC | | 33% | 6% |
| **Resource use, minerals and metals** | kg Sb eq | 1.39E-01 | 1.62E-01 | 1.43E-01 |
| | % change with BC | | 16% | 3% |
| **Resource use, fossils** | MJ | 4.62E+06 | 6.12E+06 | 4.90E+06 |
| | % change with BC | | 32% | 6% |
| **Primary energy consumption** | MJ | 2.30E+06 | 3.04E+06 | 2.44E+06 |
| | % change with BC | | 32% | 6% |

# Annex 2 Ester Dataset utilised for Design Option 1 modelling of environmental impacts

Table A2.1 Ester dataset utilised for Design Option 1 modelling

| Impact Categories | Unit | Value |
|---|---|---|
| **Climate change, total** | kg CO2 eq | 8.37E-01 |
| **Ozone depletion** | kg CFC-11 eq | 4.56E-13 |
| **Human toxicity, cancer** | CTUh | 1.03E-09 |
| **Human toxicity, non-cancer** | CTUh | 1.62E-07 |
| **Particulate Matter** | disease incidence | 6.90E-08 |
| **Ionising radiation, human health** | kBq U235 eq | 1.39E-02 |
| **Photochemical ozone formation, human health** | kg NMVOC eq | 1.85E-03 |
| **Acidification** | mol H+ eq | 8.05E-03 |
| **Eutrophication, terrestrial** | mol N eq | 3.60E-02 |
| **Eutrophication, freshwater** | kg P eq | 1.85E-04 |
| **Eutrophication, marine** | kg N eq | 1.35E-03 |
| **Ecotoxicity, freshwater** | CTUe | 4.74E+00 |
| **Land use** | pt | 2.26E+02 |
| **Water use** | m3 water eq. of deprived water | 1.77E-01 |
| **Resource use, minerals and metals** | kg Sb eq | 8.64E-07 |
| **Resource use, fossils** | MJ | 8.77E+00 |
| **Primary energy consumption** | MJ | 8.77E+00 |