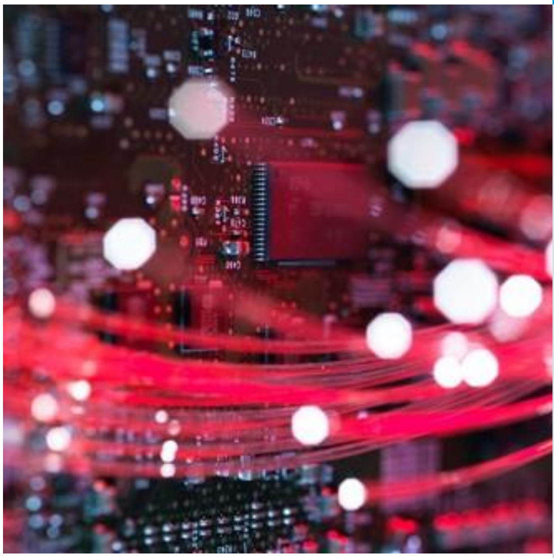

Study for the review of Commission Regulation 2019/1783 (Ecodesign of small, medium and large power transformers)

Phase 1 report – Technical Analysis (v2)

September 2024

Submitted to:

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

Phase 1 report – Technical Analysis (v2)

A report submitted by ICF S.A.

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1 Introduction

The study for the review of Commission Regulation 2019/1783 (Ecodesign of small, medium and large power transformers) has been commissioned to update the Ecodesign regulation on power transformers. The study covers a broad range of subjects, including, amongst others, the definitions used in the regulation, the scope and exemptions granted, the energy efficiency requirements, technological improvements in the technology, usage patterns and market changes.

1.1 Aims and objectives of this report

This report covers Phase 1 of the review study. This phase of the study seeks to answer specific questions raised in article 7 of Commission Regulation (EU) 2019/1783, and other points of interest to DG GROW and other Commission Directorates.

Listed below are the items set out in Article 7 of Regulation 2019/1783:

a) the extent to which requirements set out for Tier 2 have been cost-effective and the appropriateness to introduce stricter Tier 3 requirements;

b) the appropriateness of the concessions introduced for medium and large power transformers in cases where installation costs would have been disproportionate. In particular, the analysis should investigate concessions in concrete cases (e.g., manufacturers, electricity companies, market surveillance authorities) and determine their appropriateness;

c) the possibility of utilising the PEI calculation for losses alongside the losses in absolute values for medium power transformers;

d) the possibility to adopt a technology-neutral approach to the minimum requirements set out for liquid-immersed, dry-type and, possibly, electronic transformers;

e) the appropriateness of setting minimum performance requirements for small power transformers;

f) the appropriateness of the exemptions for transformers in offshore applications;

g) the appropriateness of the concessions for pole-mounted transformers and for special combinations of winding voltages for medium power transformers;

h) the possibility and appropriateness of covering environmental impacts other than energy in the use phase, such as noise and material efficiency.

Further items to be analysed:

i) material efficiency aspects;

j) an analysis of the standards, and of their relevance for regulatory purposes;

k) technological, market and regulatory evolutions affecting environmental performance;

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.

m) strengthening potential of the existing MEPS and the potential of introducing material efficiency requirements (MMPS);

n) impact of rising electricity prices on current and potentially stricter Ecodesign requirements.

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 2019/17834.

p) functional categorisation of power transformers (including conventional transformers, overload transformers and fire performant transformers and any others that the contractor may suggest).

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).

r) other topics, as emerged from consultations with stakeholders.

The subjects set out in this list of items, have been grouped in the report along the themes of:

- Regulation definitions and scope (items f, g and p)
- Ecodesign energy efficiency requirements (items a, e, and n)
- Existing standards and definitions (items j, k and l)
- Implementation of methodologies for Ecodesign requirements (items b, c, d, o and q)
- Material efficiency (items l and m)
- Environmental concerns (item h)
- Other topics (item r)

1.2 Methodology followed

To answer the queries set out in Phase 1, the research team used its extensive technical expertise and consulted with stakeholders through a stakeholder meeting, qualitative questionnaires, and direct 1-to-1 calls. The input from stakeholders was synthesised into answers for each item, illustrating the arguments set out by stakeholders. The research team then used their own expertise and independent research to corroborate the stakeholder inputs. For each theme, the report details the background to be aware of in the theme, develops the research results and stakeholder feedback, makes recommendations to policymakers on next steps for Ecodesign and sets out in which sections of Phase 2 the subject would be further developed in the update to the Ecodesign study.

2 Items for review

2.1 Existing standards and regulations

j) an analysis of the standards, and of their relevance for regulatory purposes;
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.

2.1.1 Background

International standards for transformers ensure the safe and effective functioning of the vital electrical grid that dictates everyday life. They provide a common framework for manufacturers, power utilities and others involved in the production and operation of transformers. Guaranteeing the reliability, efficiency and safety of these products and facilitating the international trade by harmonising the specifications of transformers. Therefore, adherence to international standards is essential to ensure these systems are kept running smoothly.

There are several different standards that exist across the world that cover many aspects such as the design, manufacture, installation, testing, commissioning, and operation of transformers. With different standards covering a wide range of power and distribution transformers.

The main standards that are adopted by regulations worldwide include the following:

- IEC 60076-X series (International Electrotechnical Commission)
- IEEE C57.12 series (Institute of Electrical and Electronics Engineers)
- EN 50708-X series Power transformers.
- National Electrical Manufacturers Association (NEMA) TP-1

Following extensive market research, our conclusion is that the two most specified international standards are IEC 60076 and IEEE C57.12[1]. With most economic blocs requiring the testing of energy performance of power transformers to be performed using the IEC 60076 standard[2]. The standard which is adopted is varies based on upon geographical location. At present, most major economic blocs (excluding North America) use IEC 60076 which covers power transformers, tap changers for use in transmission and distribution. There are now 26 parts to the standard covering many details, including energy performance testing. The IEC 60076 standard is one of the most widely used, with over 100 countries adopting it[3]. Meanwhile Canada, Chile and the United States are the three economies that use the IEEE standards as a basis for their own national standards for transformers. The US uses NEMA TP-1 which is closely aligned with the IEEE standard. Canada standards are also closely aligned with the US's NEMA TP-1 test methods.

In the EU, EN standards are fully aligned with the IEC standards while the IEEE has recently initiated alignment with the IEC standard. However, there remains some difference in certain assumptions and definitions between standard IEEE C57.12

[1] U4E_DT_Model-Procurement-Specs_Final_20191002_2.pdf (united4efficiency.org)
[2] lbnl-1005067-lbnl_international_review_on_dt_sl_programs.pdf
[3] https://www.daelimtransformer.com/iec-60076-standard.html

and the IEC standard[4]. For example, one of the major differences concerns the definitions of rated power and efficiency.

One of the main uses of the test standards is to determine the energy performance of transformers with each providing variations in how this is done. From research there are four main ways that the energy performance of a distribution transformers is measured[5]:

- Maximum no-load and load-losses
- Maximum combined losses
- Minimum efficiency requirements
- Peak Efficiency Index (PEI)

2.1.2 Feedback/ Research results

2.1.2.1 Standards

IEC 60076 series of standards

The IEC 60076 series was prepared by the IEC Technical Committee 14 (TC14) and covers various aspects related to power transformers, governing the safe and efficient operation of transformers. The scope of TC14 covers the standardisation of power transformers, tap-changers and reactors used in power generation, transmission and distribution[6].

The standard covers transformers with a power rating above 1 kVA single phase and 5 kVA polyphase with a higher voltage winding of 1000 Volts or more, excluding lower voltage transformers. Various types of transformers are covered including liquid-immersed, dry-type, gas-filled, self-protected and transformers for wind turbines[7]. It provides the specifications of different voltage levels and power ratings, while supplying guidelines for materials, insulation and construction methods.

The scope of TC 14 covers power transformers that are > 1000 V, which therefore, includes small power transformers as defined by the Regulation. However, after discussions with the TC 14 members it was discovered that this was not the intention of TC 14 because the IEC 60076 standard is only meant to apply to medium and large power transformers. With small power transformers as defined by the IEC being covered under the scope of TC 96, which covers the standard IEC 61558. The current scope of the Regulation states that it covers transformers power transformers which have a rated power > 1 kVA and a rated voltage > 1 kV. The Regulation also provides the following definition for small power transformers: "*as a power transformer with a highest voltage for equipment not exceeding 1,1 kV".* Therefore, under the scope of the regulation and this definition of small power transformers, technically small power transformers are defined as power transformers with highest voltage > 1 kV but < 1.1 kV.

TC 14 published specification PD IEC TS 60076-20, 2017 with the aim to promote a higher average level of energy performance for transformers. The standard provides

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

[5] lbnl-1005067-lbnl_international_review_on_dt_sl_programs (2).pdf

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

[7] https://collections.iec.ch/iec60076

a method for specifying a transformers energy efficiency according to the loading and operating conditions. It also presents the minimum efficiency and maximum loses which lead to a generally acceptable balance between loses and use of other resources. In addition, the IEC standard also provides guidelines for testing and performance evaluations.

The IEC standard proposes two methods of defining an energy efficiency index and three methods of evaluating the energy performance of a transformer. These measurements are based on the existing regional practices[8]:

- The Peak Efficiency Index (PEI) including a Total Cost of Ownership approach or any other means of specifying the load factor.
- The no-load and load losses at rated power for rationalisation of transformer cores
- The efficiency at a defined power factor and particular load factor (typically 50%).

The standard covers two levels of recommended requirements for each of these three methods: Level 1 is for modest energy performance; Level 2 is for high performance.

Another key aspect of the IEC 60076 standard is the transformer code system, which presents a standardised method of identifying and specifying transformers. The code specifies many parameters to describe transformers such as rated power, voltage level, frequency, winding connection, short circuit impedance, cooling method, and temperature rise[9].

ISO/EN 60076-X series are the harmonised standards used by the Ecodesign Regulation (EU) 2019/1783. Table 2.1 provides a full list of the standards prepared by TC 14.

Table 2.1 Full list of IEC 60076 standards developed by TC 14[10][11].

Standard	Title
IEC 60076-1: 2011	Power transformers – Part 1: General
IEC 60076-2: 2011	Power transformers – Part 2: Temperature rise for liquid-immersed transformers
IEC 60076-3: 2013	Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air
IEC 60076-4: 2002	Power transformers – Part 4: Guide to the lighting impulse and switching impulse testing – power transformers and reactors
IEC 60076-5: 2006	Power transformers – Part 5: Ability to withstand short circuit
IEC 60076-6: 2018	Power transformers – Part 6: Reactors
IEC 60076-7: 2018	Power transformers – Part 7: Loading guide for mineral-oil immersed power transformers
IEC 60076-8: 2018	Power transformers – Part 8: Application guide
IEC 60076-10: 2020	Power transformers – Part 10: Determination of sound levels
IEC 60076-11: 2018	Power transformers – Part 11: Dry-type transformers

8 https://webstore.iec.ch/preview/info_iects60076-20%7Bed1.0%7Den.pdf

9 https://www.linkedin.com/pulse/introduction-international-standard-power-iec-60076-muhammad-hanif/

10 INTAS_D2.1_Final_Annex_A.pdf (intas-testing.eu)

11 https://webstore.iec.ch/publication/606

Standard	Title
IEC 60076-12: 2008	Power transformers – Part 12: Loading guide for dry-type power transformer
IEC 60076-13: 2006	Power transformers – Part 13: Self-protected liquid-filled transformers
IEC 60076-14: 2013	Power transformers – Part 14: Design and application of liquid-immersed power transformers using high-temperature insulation materials
IEC 60076-15: 2015	Power transformers – Part 15: Transformers for wind turbine applications
IEC 60076-18: 2012	Power transformers – Part 18: Measurement of frequency response
IEC 60076-19: 2013	Power transformers – Part 19: Rules for the determination of uncertainties in the measurement of losses in power transformers and reactors
IEC 60076-20: 2017	Power transformers – Part 20: Energy efficiency
IEC 60076-21: 2006	Power transformers – Part 21: Standard requirements, terminology, and test code for step-voltage regulators
IEC 60076-22: 2019	Power transformers – Part 22: Power transformer and reactor fittings – protective devices
IEC 60076-23: 2018	Power transformers – Part 23: DC magnetic bias suppression devices
IEC 60076-24: 2020	Power transformers – Part 24: Specification of voltage regulating distribution transformers (VRDT)
IEC 60076-25: 2023	Power transformers – Part 25: Neutral grounding resistors
IEC 60076-26: 2020	Power transformers – Part 26: Functional requirements of insulating liquids for use in power transformers

The IEC 60076 series of standards are currently subject to a revision and update process, which will have implications on this technical analysis and review of the Transformers Commission Regulation No 2019/1783. The Commission closely follows the development of new IEC 60076 standards, therefore, once the new publication is released the EU will subsequently adopt it as the EU's version of the IEC standard which is EN 50708.

EN 50708 series

Previously the regulation adopted the harmonised standards from EN 50588-1 and EN 50629. EN 50588 covered medium power transformers while EN 50629 covered large power transformers with a highest voltage > 36 kV[12]. The EN 50708 series "Power transformers – additional European requirements" supersedes these two standards and now acts as the additional requirements for the EU regulation 2019/1783. These standards act as additional standards on top of the IEC 60078 requirements that are already in place. The technical requirements set out in EN 50708 supplement, modify or replace the requirements of the previous EN standards which were derived from the IEC standards. It should be noted that EN 50708 doesn't provide the testing procedures for power transformers in scope of the Regulation, with Table 2.2 demonstrating the elements covered by EN 50708. The technical requirements of EN 50708 are adopted from the IEC 60076 standard. These include elements such as the peak efficiency, fixed load and no-load losses.

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

Despite the development of these EN standards for medium and large power transformers the Regulation continues to utilise the IEC standard for the testing procedures of transformers. Since this is only standard other than the IEEE standard that provides a testing methodology for calculating a transformers efficiency. The IEC standard because it was determined that its testing methodology more closely aligned with the use of transformers in the EU. It should be noted that the IEC 60076 standard is only discussed at a global level rather than EU, therefore, the Regulation can be susceptible to any changes that are made to the testing procedures. The EN standards allow the EU to adopt their own version of the IEC standards for the aspects described in Table 2.2.

The EN 50708 series of standards is divided into three sections, as shown below. The parts of the standard which have been adopted by the Regulation are summarised further below in the Table 2.2.

- Part 1 series – Common requirements
- Part 2 series – Medium power transformers
- Part 3 series – Large power transformers

Table 2.2 Summary of the series of standards set out by EN 50708[13]

	Common part	Medium power transformers	Large power transformers
General requirements	**EN50708-1-1** Power transformers – Additional European requirements: Part 1-1 Common part – General requirements	**EN50708-2-1** Power transformers – Additional European requirements: Part 2-1 Medium power transformers – General requirements	**EN50708-3-1** Power transformers – Additional European requirements: Part 3-1 Large power transformers – General requirements
Assessment of energy efficiency	**EN50708-1-2** Power transformers – Additional European requirements: Part 1-2 Common part – Assessment of energy performance		
Accessories		**EN50708-2-3** Power transformers – Additional European requirements; Part 2-3 Medium power transformers - Accessories	
Special tests		**EN50708-2-4** Power transformers – Additional European requirements; Part 2-4 Medium power transformers – Special tests	**EN50708-3-4** Power transformers – Additional European requirements: Part 3-4 Large power transformers – Special tests
Single-phase power transformers		**EN50708-2-5**	

13 21-04-20_EU-Oekodesign-Verordnung_GB.pdf (sgb-smit.com)

	Common part	Medium power transformers	Large power transformers
		Power transformers – Additional European requirements; Part 2-5 Medium power transformers – Single phase	
Non-conventional technologies		**EN50708-2-6** Power transformers – Additional European requirements; Part 2-6 Medium power transformers – non-conventional technologies	

The scope of the standard includes large power transformers with a power rating above 3,150 kVA or highest voltage equipment greater than 36 kV. Medium power transformers 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. In addition, the standard also applies to medium power pole-mounted transformers with a rated power of up to 400 kVA, suitable for outdoor service and designed to be mounted on support structures of overhead power lines. Thus, aligning with the transformers in scope of the Regulation, unlike the IEC standard.

IEEE C57.12 series of standards

In the United States, the features and functionality of most power and distribution transformers fall under the IEEE standard C57.12. This set of US standards cover power transformers and was prepared by the IEEE Transformer Committee. Within this committee there were two subcommittees one for power transformers and another for distribution transformers.

The main IEEE standards and the latest versions that are related to power transformers are:

- IEEE C57.12.00 (2020) – for general requirements for liquid-immersed distribution, power and regulating transformers.
- IEEE C57.12.01 (2020) – for general requirements for dry-type distribution and power transformers.
- IEEE C57.12.10 (2017) – standard requirements for liquid-immersed power transformers.
- IEEE C57.12.20 (2017) – for overhead-type distribution transformers 500 KVA and smaller; high voltage, 34,500 V and below; low voltage, 7970/13 800Y V and below
- IEEE C57.12.40 (2017) – for network, three phase transformers, 2500 kVA and smaller; high voltage, 34,500 V and below; low voltage, 600 V and below; subway and vault types (liquid immersed)
- IEEE C57.12.90 (2021) – test code for liquid-immersed distribution, power and regulating transformers.

- IEEE C57.12.91 (2020) – test code for dry-type distribution and power transformers.

As described above, the IEEE standards split the testing methodologies for dry-type and liquid-immersed distribution and power transformers into two different standards.

The IEEE C57.12.91 standard provides a methodology for performing the tests that are specified in IEEE C57.12.01. It applies to all dry-type transformers except instrument transformers, step-voltage and induction voltage regulators, arc furnace transformers, rectifier transformers, specialty transformers, and mine transformers[14]. In addition, it also applies to liquid immersed distribution and power transformers, autotransformers, regulating transformers, single and polyphase transformers with a voltage in the highest winding of greater than 601 V[15]. Providing a description of the electrical and mechanical requirements of liquid immersed transformers.

The IEEE C57.12 series of standards is accredited by ANSI. The IEEE standard is fully adopted by ANSI and in the US the harmonised standard is referred to as the ANSI/ IEEE C57 standard[16]. Since the IEEE test standard is only applicable to 60 Hz transformers it is not relevant to the transformers used within the EU, where the grid operates at a frequency of 50 Hz.

NEMA TP 1

NEMA TP 1 was developed in January 2007 to promote the use of higher efficiency transformers within the US. This standard provides a guide for determining the energy efficiency of distribution transformers. This standard has been adopted by the US Department of Energy (DOE) as the national energy efficiency rule for low voltage dry-type distribution transformers, medium-voltage dry type distribution transformers and liquid filled distribution transformers[17]. It was developed following a DOE study into transformer efficiency, which revealed on average that low-voltage dry-type transformers are loaded to only 35% of its maximum rating[18]. Prior to this study transformers were usually designed for maximum peak demand. Therefore, this standard defines the efficiency of distribution transformers at 35% loading to encourage industry to improve efficiency at this loading[19]. Please note that NEMA TP1 is a manufacturer association best practice, solely agreed among the manufacturers without the input of the users.

Comparison of IEC 60076 v IEEE C57 standards

While both the IEC and IEEE standards are widely used across the world for the design and testing of transformers, there are subtle differences that distinguish them. The study team is aware of the difficulties in comparing the IEC standard and IEEE standard. Although these differences can make it difficult to compare the two standards a comparison between these standards was requested by the Commission in this review study.

[14] https://ieeexplore.ieee.org/document/6152116

[15] https://standards.ieee.org/ieee/C57.12.00/5268/

[16] https://ieeexplore.ieee.org/document/4504732

[17] 2013-ewg-meps-vol-1.pdf (unepccc.org)

[18] Increasing transformer efficiency | Consulting - Specifying Engineer (csemag.com)

[19] TP-1 product launch issues; (jeffersonelectric.com)

As discussed previously there are regional preferences for the two standards, with IEC used in Europe and across Asia, while IEEE is more common in North America. There are general alignments on the design and testing of transformers however, there are certain add-ons that each makes each standard unique, as shown in Table 2.3 these differences cover aspects such as reference temperature, waveform correction, loss tolerances and excitation current. Table 2.3 describes the differences between the standard's methodology for calculating load losses of a transformers.

Table 2.3 Comparison of IEC and IEEE for the measurement of load and no-load losses[20]

Aspect	IEC 60076-1	IEEE C57.12.00
Reference Temperature	Load loss reference temperature is 75ºC. Correction equation available for load loss. No-load loss reference temperature is 75ºC. No correction equation available for no-load loss.	Load loss reference temperature is 85ºC. Correction equation available for load loss. No-load loss reference temperature is 20ºC. Correction equation available for no-load loss.
Waveform Correction equation	$P_0 = P_m$ Where: P_m = measured no-load loss And d = (U'-U)/U' U = measured average voltage U' == is the measured r.m.s. voltage	$P_c(T_m) = \frac{P_m}{(P_1+kP_2)}$ Where: k = r.m.s. voltage/ average voltage T_m = average oil temperature P_m = measured no-load loss P_1 = per unit hysteresis loss P_2 = per unit eddy-current loss
Maximum waveform correction	3%	5% or less
Loss tolerances	+10 % for no load loss and load loss, provided total losses don't exceed +5%	No limit for load loss measurements. No load losses shall not exceed 10% Total losses shall not exceed 6%
Excitation current	30% of the design value	Not specified.

In addition, to the contrasts illustrated by Table 2.3 there are further terminological differences across the two standards. Table 2.4 illustrates these differences which cover certain components and tests used by the IEC and IEEE standards[21].

Table 2.4 Terminology differences between IEC and IEEE standards

IEC 60076 Terminology	IEC C57.12 Terminology
Oil level indicator	Oil level gauge
On-load tap changer	Load tap changer
Terminal box	Terminal chamber
Type tests	Design tests

The definition of the rated power is another major difference between the IEC and IEEE standards. The IEC standard considers rated power on the primary windings

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

[21] Differences between IEC and IEEE standards of transformers | LinkedIn

while the IEEE considers it on the secondary. Therefore, this is the reason countries that adopt the IEC standard such as the EU, do not use the rated power in the calculation methods for efficiency. The IEC standard calculates efficiency based on the input power, whereas, the IEEE standard calculation is based on the output power, as shown below:

$$IEC\ Definition\ of\ Efficiency = \frac{(Power\ Input - Losses)}{(Power\ Input)}$$

$$IEEE\ Definition\ of\ Efficiency = \frac{(Power\ Output)}{(Power\ Output + Losses)}$$

Although these calculations are different ultimately, if the kVA rating is consistent then the two equations will yield the same value. However, it demonstrates the different methods that exits in these two standards to calculate the efficiency.

Ultimately, countries or economic blocs will decide whether to align more closely with the IEC or IEEE standards based on the use of transformers within their respective areas. For example, the measurement and determination of the load losses is always at 100% rated capacity however, the calculation of the efficiency index may differ since this is dependent on the load factor.

Global comparison of power transformer testing and measurement standards

It is clear from the research conducted that the majority of countries favour the use of IEC 60076 as the standard to harmonise their own national standard to. From country to country the efficiency requirement that is set does vary with some favouring measuring losses at 50% load (E.g., the USA) while other opt for 100% load (e.g., the EU). Table 2.5 gives a summary of dry-type transformer standards that are in place around the world. While Table 2.6 provides a summary of the liquid-filled transformer standards across the world. Essentially the requirements across the countries and economic blocs cluster together within 0.5% on the efficiency scale at any kVA power rating, with the slope of the curves being fairly consistent. Despite this tight cluster it should be noted that losses of just 0.1% can have a significant impact on the amount of energy lost by the transformer. Therefore, although the percentage values observed for each country's efficiency requirements are very low, the impact on energy savings can be dramatically larger. Especially when looking at the larger power transformers.

Table 2.5 Summary of coverage of dry-type distribution transformer standards[22]

Country/ Economy	Scope	Load Measurement Point	Date Launched	Standard	Adopted from (IEC or IEEE)
Australia	1 phase: 10-50 kVA 3 phase: 25-2500 kVA Voltage: 11 and 22 kV	Efficiency at 50% load	April 2004	AS 2374.1.2-2003	IEC 60076
Canada	1 phase: 15-833 kVA	35% loading for low voltage	April 2012	CAN/ CSA C802.2-06	IEEE C57.12

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

Country/ Economy	Scope	Load Measurement Point	Date Launched	Standard	Adopted from (IEC or IEEE)
	3 phase: 15-7500 kVA Voltage: 20-45, >45-95; >-199 kV BIL	(1.2kV) and 50% for >1.2 kV			
China	3 phase: 30-2500 kVA Class B, F and H	Maximum core and coil losses at 100% load	2013	GB 20052:2020	IEC 60076
European Union	3 phase: 50-40,000 kVA ≤12 kV, 17.5 and 24 kV, ≤ 36 kV	Maximum core and coil losses at 100% load	2015	EN 50588 replaced by EN 50708:2020	IEC 60076
Israel	100-2500 kVA Voltage: 22 kV or 33 kV	Maximum W losses 100%	2011	IS 5485	IEC 60076
Japan	1 phase: 5-500 kVA 3 phase: 10-2000 kVA Both 50 & 60 Hz Voltage: 3 and 6 kV	<500 kVA: 40% load >500 kVA:50% load	March 2008	Top Runner	IEC 60076
Republic of Korea	1 and 3 phase: 3.3-6.6 kV, 50-3000 kVA 1 and 3 phase: 22.9 kV, 50-3000 kVA	Efficiency at 50% load	July 2012	KS C4311	IEC 60076
US	1 phase, LV, 25-333 kVA 3 phase, LV, 30-1000 kVA 1 phase, MV, 15-833 kVA 3 phase, MV, 15-2500 kVA MV: 20-45 kV, 46-95, >96kV BIL	35% loading for low voltage (LV) (<600V) and 50% for medium voltage (MV)	Jan 2010	10 CFR 431	IEEE C57.12

Table 2.6 Summary of the coverage of liquid-filled distribution transformer standards[23]

Country/ Economy	Scope	Load Measurement Point	Date Launched	Standard	Adopted from (IEC or IEEE)
Australia	1 phase: 10-50 kVA 3 phase: 25-2500 kVA Voltage: 11 and 22 kV	Efficiency at 50% load	April 2004	AS 2374.1.2-2003	IEC 60076
Canada	1 phase: 15-833 kVA	Efficiency at 50% load	April 2012	CAN/ CSA C802.2-06	IEEE C57.12

[23] SEAD-Distribution-Transformers-Report_Part-1_Comparison-of-Efficiency-Programs.pdf (clasp.ngo)

Country/ Economy	Scope	Load Measurement Point	Date Launched	Standard	Adopted from (IEC or IEEE)
	3 phase: 15-3000 kVA				
China	1 phase: 5-160 kVA 3 phase: 30-2500 kVA Class B, F and H	Maximum core and coil losses at 100% load	2013	GB 20052:2020	IEC 60076
Europe	3 phase: 50-3150 kVA Voltage 24 and 36 kV	Maximum core and coil losses at 100% load	2015	EN 50464 replaced by EN 50708:2020	IEC 60076
Israel	100-2500 kVA Voltage: 22 kV or 33 kV	Maximum W losses at 100%	2011	IS 5484	IEC 60076
Japan	1 phase: 5-500 kVA 3 phase: 10-2000 kVA Both 50 & 60 Hz	<500 kVA: 40% load >500 kVA:50% load	March 2008	Top Runner	IEC 60076
Republic of Korea	1 phase: 10-100 kVA' 1 and 3 phase: 3.3-6.6 kV, 50-3000 kVA 1 and 3 phase: 22.9 kV, 50-3000 kVA	Efficiency at 50% load	July 2012	KS C4306, C4316. C4317	IEC 60076
US	1 phase, LV, 25-333 kVA 3 phase, LV, 30-1000 kVA 1 phase, MV, 15-833 kVA 3 phase, MV, 15-2500 kVA MV: 20-45 kV, 46-95, >96kV BIL	Efficiency at 50% load	Jan 2010	10 CFR 431	IEEE C57.12

Table 2.5 and Table 2.6 demonstrate that there are varying methods of regulation adopted across the world for both dry-type and liquid-filled transformers. This can be observed by the different kVA ratings that each country defines. In addition, the requirements of each regulation vary from country to country, with some measuring efficiency at 50% load while others look at efficiency at 100% load. As presented previously, the USA and Canada are the two major economies adopting a different international test standard methodology to rest of the economies listed in Table 2.5 and Table 2.6. Both nations adopt the IEEE methodology for testing distribution transformers.

2.1.2.2 Regulatory Comparison: EU vs. Rest of the world

It was communicated with the study team that it is not suitable to compare the MEPS for a 50 Hz electrical grid against a 60 Hz. The main reason why comparing electrical grids with different frequencies is difficult is because transformers that operate at a higher frequency tend to have a greater inductive resistance and hence incur more no-load losses. Therefore, the core must be adapted in order to operate under different frequencies. Despite these issues the comparison of MEPS from Japan, the US and the EU has been specifically requested by the commission for this review study.

Regulations for transformers have evolved in many countries around the world during the last two decades. Although each country or economic bloc has specific requirements that are unique to that place they do share a lot of similarities. The main differences are where the energy efficiency requirements are set at. Table 2.7 provides a comparison of the MEPS for the EU's Tier 1 and Tier 2, Japan's Top Runner Programme, and the US's 10 CFR Part 431.

Table 2.7 Comparison of the MEPS from the EU (Tier 2), Japan and the USA[24]

Efficiency at 50% Load							
Power	**Tier 2 Dry**	**Tier 2 Liquid**	**Japan 50 Hz Dry**	**Japan 50 Hz Liquid**	**Power**	**USA Dry**	**USA Liquid**
800	99.21	99.48	99.31	99.38	**300**	98.81	99.27
1000	99.27	99.48	99.35	99.41	**500**	98.99	99.35
1250	99.30	99.48	99.39	99.43	**750**	99.12	99.40
1600	99.35	99.49	99.43	99.46	**1000**	99.20	99.43
2000	99.37	99.49	99.47	99.48	**1500**	99.30	99.48
2500	99.40	99.50	99.50	99.50	**2000**	99.36	99.51
3150	99.43	99.51	99.53	99.52	**2500**	99.41	99.53

MEPS for Liquid-Filled Transformers

Worldwide each country or economic bloc has set minimum energy performance requirements (MEPS) which aim to increase the energy efficiency of transformers within their electrical network. As previously discussed, geography plays a significant role in how a transformer is utilised. Thus, for each countries regulation there are varying MEPS that a transformer must meet, some more stringent than others.

A comparison of the regulations has been conducted for liquid-filled distribution transformers. It should be noted that this data has been normalised to all show 50% loading, 50 Hz operation and using the IEC definition of rated power (kVA). In addition, since the US's efficiency calculation is based on the IEEE measurement method, these values have also had their load losses corrected and reference temperature altered to 75ºC to align with the IEC reference temperature.

The UN environment, United for Efficiency programme, published a report in 2017 presenting how the highest efficiency curve for the small power ratings (up to 50 kVA) is set by the US's 10 CFR Part 431 2016 MEPS, which has been in effect since January 2016. The report shows this comparison graph under Figure 6 on the *efficiency at 50% load (IEC) for three-phase liquid-filled transformers,* on page 36 of the report. For transformers larger than 50 kVA the EU's Tier 2 requirements are set a higher efficiency rating. Meanwhile, the Republic of Korea and Brazil have the lowest MEPS, with both showing the lowest efficiency curves. Both the EU's Tier 1 and Tier 2 MEPS clearly demonstrate that the EU is looking at very small power rating transformers between 5 and 25 kVA. However, the other countries observed

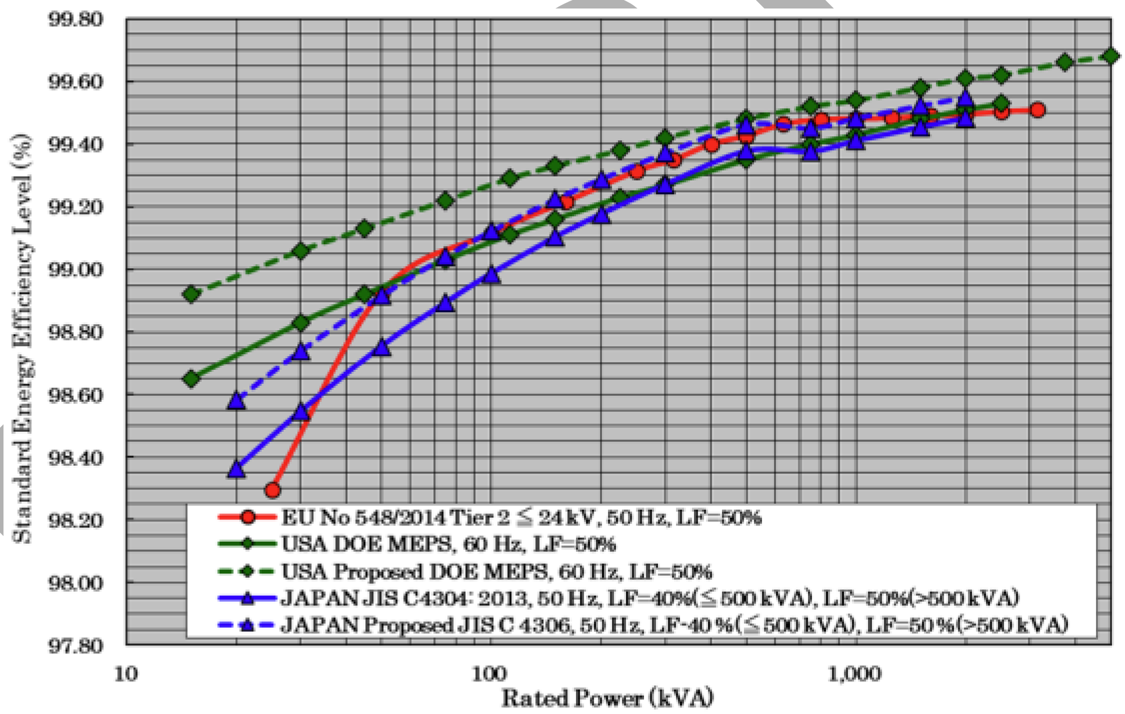
[24] Communicated via stakeholder feedback in the qualitative questionnaire.

don't consider transformers that are rated at this level. Therefore, it is difficult to compare these efficiency curves for small transformers. It does illustrate that the EU covers the broadest range of three-phase liquid filled transformers.[25]

As demonstrated by the United for Efficiency programme, the EU's Tier 2 requirements sit above both the US and Japanese MEPS at present.[26] However, the US DOE and Japanese JIS standards (Top Runner) are currently under revision and the proposed amendments are illustrated below with the dashed lines in Figure 2.1. It should be noted that the values presented in Figure 2.1 are at 50% load factor for EU Tier 2 are calculated using the Method A of IEC 60076-20. While the Japanese JIS Standard levels are calculated using the Method B of IEC 60076-20, with a load factor of 40% for 500 kVA or less and 50% load factor for over 500 kVA.

Figure 2.1 illustrates that the Tier 2 requirements are currently equivalent to the current US 10 CFR Part 431 regulation and superior to Japan's. The revisions proposed by Japan would mean that their MEPS would now align with the EU's Tier 2 requirements. Meanwhile, the revisions proposed by the US's DOE display that these requirements will be superior to the EU's Tier 2 requirements.

Figure 2.1 Comparison of EU Tier 2, US 10 CFR Part 431 Regulation and Japan's Top Runner (JIS Standard) MEPS levels for three-phase liquid-filled medium power transformers[27].



The UN's United for Efficiency report also reviews the MEPS comparison for single-phase liquid-filled transformers. The report shows this comparison graph under figure 7 on the *efficiency at 50% load (IEC) for single-phase liquid-filled transformers,* on page 37 of the report. There are far fewer economies that adopt single phase transformers, because most electric networks are three-phase. The UN report shows that the US's 10 CFR Part 431 2010 MEPS are the most stringent MEPS, with these closely aligned with Japan. These nations MEPS almost mirror

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

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

[27] Graph provided in Proterial qualitative feedback calculated from publicised standards and IEC definitions

each other until it gets to the larger >250 kVA transformers, where Japan's MEPS become more ambitious. Like the three-phase comparison, the Republic of Korea and Brazil have significantly less stringent MEPS, with efficiency levels set between 1.0 to 1.5% less that Japan or the US at some kVA ratings[28].

MEPS for Dry-type Transformers

As with the liquid-filled distribution transformer comparison the data for dry-type distribution transformers has been normalised to allow comparison. The data has been normalised to 50% loading, 50 Hz operation and using the IEC definition of rated power (kVA) and efficiency. However, as dry-type transformers require insulation which has an impact on the performance the transformers have been grouped with similar voltages and insulation ratings[29]. In addition, Brazil, Mexico, and India do not have efficiency requirements for dry-type transformers.

The UN's United for Efficiency report shows how the efficiency curves of dry-type transformers cluster within approximately 1% on the efficiency scale for each power rating (kVA). The report shows this comparison graph under Figure 8 on the *efficiency at 50% load (IEC) for three-phase dry-type distribution transformers,* on page 39 of the report. From around 50 kVA the efficiency curves for all countries are consistent. However, below 50 kVA the Tier 1 and Tier 2 EU MEPS have a steep slope, this is also seen for liquid-filled transformers[30]. This indicates that the EU has set less stringent requirements for smaller power transformers. .

Similar to liquid-filled transformers the Republic of Korea has the least stringent efficiency requirements for dry-type transformers. Meanwhile the Japanese Top Runner programme sets the highest MEPS, and the US's 10 CFR Part 431 2016 MEPS sit within the middle of the field. Furthermore, there are similarities between the US and Canada's requirements for MEPS as their efficiency curves align. Canada's efficiency requirements cover a wider range of larger dry-type distribution transformers.[31]

However, as mentioned the US and Japan are currently revising their regulations and this has meant a change in the positioning of the efficiency curves. Via stakeholder feedback, the study team have been able to analyse that following the revised criteria for these regulations, Japan's Top Runner will remain the superior standard while the US's 10 CFR Part 431 and the EU's Tier 2 MEPS fall closely behind. Figure 2.2 demonstrates that neither the EU's Tier 2 MEPS nor the US's proposed MEPS will match those set by Japan. With Japan's proposed MEPS at some power ratings being 0.2-0.4% higher than the US and EU's MEPS. However, it should also be noted that the Japanese regulation only applies to cast resin dry-type transformers.

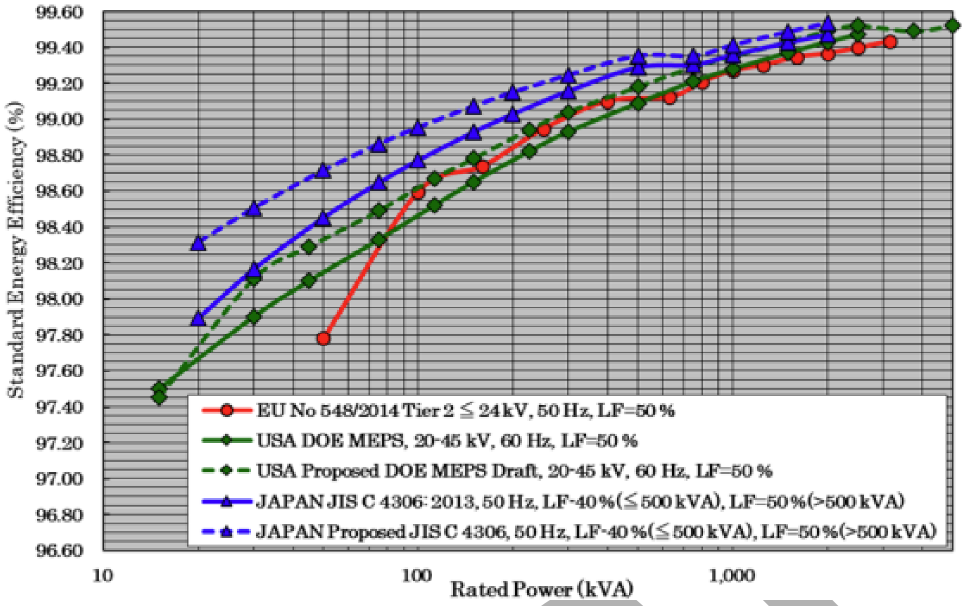
[28] https://united4efficiency.org/wp-content/uploads/2017/11/U4E-TransformersGuide-201711-Final.pdf

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

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

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

Figure 2.2 Comparison of EU Tier 2, US 10 CFR Part 431 Regulation and Japan's Top Runner (JIS Standard) MEPS levels for three-phase dry-type medium power transformers[32]



US Regulation – 10 CFR Part 431

The first regulation that covered transformers in the USA was laid down by the Energy Policy and Conservative Act (EPCA). This regulation adopted the testing standard NEMA TP-2 1998 – "Standard Test Method for Measuring the Energy Consumption of Distribution Transformers". Subsequently, in 2005 the Department for Energy (DOE) introduced efficiency standards in the Energy Act (EPACT). This implemented the first efficiency standards for low voltage dry-type transformers in the USA[33]. EPACT 2005, also adopted the updated version of the NEMA test method, NEMA TP-2-2005 and the latest versions of IEEE C57.12.90 and IEEE C57.12.91.

The standard was then further extended to include liquid-immersed and medium voltage dry-type transformers in 2010[34]. The legislation covering distribution transformers was later redefined in 2016 by the Code of Federal Regulations (CFR), 10 CFR Part 431[35]. The most recent edition of this legislation was published in 2022 and contains the following key sections:

- The Purpose and scope of the MEPS (431.191)
- Definitions (431.192)
- Test procedures (431.193)
- Energy conservation standards and their effective dates (431.196)
- The uniform test method that has been adopted by the legislation to calculate the energy consumption of distribution transformers (Appendix A)

[32] Graph provided in Proterial qualitative feedback calculated from publicised standards and IEC definitions

[33] https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=200610&RIN=1904-AB08

[34] 2013-ewg-meps-vol-1.pdf (unepccc.org)

[35] CFR-2022-title10-vol3-sec431-192.pdf (govinfo.gov)

10 CFR Part 431 applies to the following types of transformers: all low-voltage dry type three-phase ventilated transformers from 15 kVA through 1000 kVA and harmonic mitigating transformers[36]. The DOE determines that all transformers manufactured after 2016 must meet the efficiency levels with a 35% per-unit load and temperature of 75°C. These transformers must also have grain oriented, non-aging silicon steel cores. The regulation doesn't apply to machine-tool transformers, rectifier transformers, regulating transformers, sealed transformers, special-impedance transformers, testing transformers, transformers with tap range of 20% or more, uninterruptible power supply transformers and welding transformers.

Using the above-mentioned standards, the DOE determined the percentage energy efficiency that distribution transformers must meet, using the measurements of no-load and load losses. The standards specify the temperature, current voltage, extent distortion in voltage waveform and DC resistance of the windings[37].

Prior to the adoption of 10 CFR Part 431 the EPCA implemented the test procedure of NEMA TP-1 2002 on the 1st of January 2007. This followed the adoption of TP-1 by the Energy Act (EPACT), 2005. From 2007, EPACT established NEMA TP-1 as the measurement standard for the national MEPS levels for low voltage dry type transformers[38]. The test method provides a guide for determining the energy efficiency of distribution transformers, the requirements of this standard were made mandatory efficiency requirements for low voltage dry-type distribution transformers. The introduction of NEMA's TP 1 test procedure into EPACT meant minimum efficiency requirements for transformers were set in the USA. Its introduction meant the conclusion of the Energy Star programme for transformers in 2007 because the MEPS set by NEMA TP-1 meant that the Energy Star become obsolete. This is determined on the DOE Test Method for Measuring the Energy Consumption specified in 10 CFR 431.193. As discussed, the test method used by the DOE are aligned with the IEEE and NEMA test methods. It should be noted that in 2006 NEMA TP-2 2005 was rescinded, therefore, the DOE no longer use this standard as a method of testing[39]. In addition, the DOE is seeking to more closely align the legislation to incorporate the most recent revisions of the IEEE standards[40].

Unlike the current Ecodesign transformers regulation, the MEPS specified by part 431 are based on the minimum efficiency values at 50% of the rated capacity and not 100% as in the Ecodesign regulation.

The efficiency is determined from the total transformer losses, which are determined from the measured value of the no-load loss and load loss power components[41]. Table 2.8 provides an example of the MEPS that low voltage dry type distribution transformers placed on the market in the United States after January 1st, 2007, but before January 1st, 2016, have to meet.

[36] CFR-2022-title10-vol3-sec431-192.pdf (govinfo.gov)

[37] lbnl-1005067-lbnl_international_review_on_dt_sl_programs.pdf

[38] lbnl-1005067-lbnl_international_review_on_dt_sl_programs.pdf

[39] Federal Register :: Energy Conservation Program: Test Procedure for Distribution Transformers

[40] Federal Register :: Energy Conservation Program: Test Procedure for Distribution Transformers

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

Table 2.8 MEPS set by CFR Part 431 for low voltage dry-type distribution transformers[42].

Single Phase		Three-phase	
kVA	%	kVA	%
15	97.7	15	97.0
25	98.0	30	97.5
37.5	98.2	45	97.7
50	98.3	75	98.0
75	98.5	112.5	98.2
100	98.6	150	98.3
167	98.7	225	98.5
250	98.9	300	98.6
333	98.9	500	98.7
		750	98.8
		1000	98.9

Japan's Top Runner Programme

The Japanese Top Runner Programme is a mandatory scheme that is regulated by the Energy Efficiency Act. The programme requires each manufacturer to surpass a weighted average value for all of their products per category for a predetermined year[43]. The transformers standard has been defined by the Japan Electrical Manufacturers' Association (JEMA) and has been in effect since 2006.

The most recent update to the requirements set out in the Top Runner scheme for power transformers are from 2013[44]. This meant that Top Runner more closely aligned with the IEC standard. Top Runner applies to both 50 and 60 Hz units (there are two types of electrical distribution systems in Japan), single phase and three phase transformers[45]. Both dry-type and liquid-immersed transformers are also covered by the program. Within Top Runner transformers are classified according to their physical quantities and functions as these are both closely related to the total loss. These are classed using roman numerals (I to VIII-2). For example, class I is a single phase, 50 Hz transformer with a rated capacity of 500 kV or less.

The efficiency values specified in Top Runner are determined from aggregate core losses derived from the following equation. This is based on the transformer rating at a specific loading point.

The Top Runner program provides the maximum total losses for a transformer at 40% load and 50% load. Since the testing standards are aligned to the IEC standards, the kVA ratings are also based on the power input rather than the output. The energy consumption efficiency of transformers is considered as the 'total loss' (W)[46]. With the no-load loss and load loss measured according to the Japanese

[42] CFR-2022-title10-vol3-sec431-192.pdf (govinfo.gov)

[43] Top Runner Programme – Policies - IEA

[44] https://www.eccj.or.jp/top_runner/pdf/tr_transformers_dec2011.pdf

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

[46] https://www.eccj.or.jp/top_runner/pdf/tr_transformers_dec2011.pdf

harmonised standards with IEC which are JIS C 4304 and JIS C 4306. The equation is defined as:

$$Total\ loss\ (W) = No\ load\ loss(W) + [\frac{m}{100}]^2 \times Load\ loss\ (W)$$

Where ‘m’ is the standard load ratio which is one of the following:

- For transformers with a capacity of 500 kVA or less: 40%
- For transformers with a capacity of more than 500 kVA: 50%

The standards JIS C4304-2013 “6kV oil-immersed distribution transformers” and JIS C4306-2013 “6k V sealed winding distribution transformers” are the two standards adopted by the Top Runner program. These specify the total loss limits of 6kV class single phase 50 Hz and 60 Hz, 10 kVA to 500 kVA distribution transformers and 6 kV class three-phase 50 Hz and 60 Hz, 20 kVA to 2000 kVA distribution transformers[47].

The United Kingdom

The Energy Networks Association (ENA) published the Technical Specifications (TS) 35-1 for distribution transformers known as ENA TS 35-1. This standard sets the UK’s minimum efficiency requirements for transformers, with it closely aligning with the requirements set by the EU’s Regulation 2019/1783. This standard has four parts which are broken into the following:

- Part 1 – Common clauses (published 2020)
- Part 2 – Ground-mounted transformers – not close coupled (published 2021)
- Part 3 – Ground-mounted transformers – closed-coupled (published 2021)
- Part 4 – Pole-Mounted transformers (published 2022)

The specification applies to transformers in the range 16 kVA to 2000 kVA for continuous service at 50 Hz, for highest voltage equipment 7.2 kV, 12 kV, 24 kV and 36 kV, equipment voltage above 24 kV is considered for use on pole-mounted transformers only[48].

ENA TS 35-1 amplifies the requirements that are set in IEC 60076 and therefore, should be analysed in conjunction with this standard. The IEC standard has been adopted by the UK as the standard BS EN 60076.

Australia and New Zealand

Australia and New Zealand jointly operate the Equipment Energy Efficiency (E3) programme, which is co-funded by the Australian Department of Climate Change and Energy Efficiency and the New Zealand government. Both countries have adopted the same energy efficiency requirements to encourage the flow of trade between the two nations. For distribution transformers the first standard was introduced by Australia in 2003 called the AS 2374.1.2-2003[49]. The AS 2374.1.2 provided MEPS for dry-type and oil immersed, three-phase and single-phase power transformers with a rating from 10 kVA to 2500 kVA and a system highest voltage

[47] Energy Efficiency Standard For Transformer In Various Countries (daelim-electric.com)

[48] ENA Document Catalogue (ena-eng.org)

[49] AS 2374.1.2-2003 Power transformers - Minimum Energy Performance Standard (MEPS) requirements for distribution transformers (saiglobal.com)

up to 24 kV. New Zealand then quickly adopted the same standard to align with Australia on these MEPS for distribution transformers.

The AS 2374.1.2 standard set the minimum power efficiency levels at 50% load that all transformers in Australia and New Zealand had to meet. Alongside the mandatory MEPS, the programme also identifies voluntary higher energy performance standards (HEPS) to encourage innovation[50].

The test standard for the MEPS is based on the power loss measurements that are specified in the Australian and New Zealand standard AS/NZS 60076.1, which has been adopted from the IEC 60076 standard. There are some specific variations that are specific to the AS/NZS standard, such as the commonly used power ratings and preferred methods of cooling, connections in general use and details of connection designation[51].

Brazil

Brazil has adopted MEPS for liquid-immersed distribution transformers, this regulation has been set by the Ministry of Mines and Energy and is called the Inter-Ministerial Ordinance 104/2013[52]. The legislation covers single-phase liquid-filled distribution transformers from 5 to 100 kVA, and three-phase liquid-filled distribution transformers from 15 to 300 kVA both with voltage classes of 15 kV, 24.2 kV and 36.2 kV[53]. These transformers are designed to operate at 60 Hz.

The national test standard that has been published is the ABNT NBR 5440: 2014 standard which closely aligns with the test requirements set out in the IEC 60076.1 standard. The requirements of the MEPS are presented as maximum losses in the core and coil at 100% loading[54].

In addition to the MEPS covered by the abovementioned legislation Brazil also has an energy labelling program for transformers. The label includes the following information: the manufacturer, model, type, kVA rating, and voltage class, the watts of losses at no load and total watts of loss at full load, temperature rise and basic-impulse insulation level of the transformer at both the nominal tap and the ‘critical’ tap[55].

Canada

The Office of Energy Efficiency at Natural Resources Canada created Canada’s mandatory regulations covering dry-type transformers only with voluntary efficiency levels also being set for liquid-immersed distribution transformers. The mandatory dry-type regulation applies to single-phase or nominal power of 15 to 833 kVA, or three-phase with nominal power of 15 to 7500 kVA, a nominal frequency of 60 Hz and a high voltage winding of 35 kV or less[56]. The most recent update to the MEPS was in 2019, with this regulation applying to dry-type transformers that were placed on the market after January 1st, 2016.

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50 1364440 (osti.gov)

51 1364440 (osti.gov)

52 Portal de Serviços do Inmetro — INMETRO (www.gov.br)

53 1364440 (osti.gov)

54 SEAD-Distribution-Transformers-Report_Part-1_Comparison-of-Efficiency-Programs.pdf (clasp.ngo)

55 1364440 (osti.gov)

56 Dry-type transformers (canada.ca)

In 2010 the Canadian regulation adopted the same MEPS levels as the US's 10 CFR Part 431 for dry-type distributions transformers. Therefore, it also sets the minimum power efficiency levels at 50% load. The national standard CAN/CSA C802.2-06 provides the test requirements and refers to the NEMA TP 2-2005 standard. However, since TP 2 is no longer an active standard the Canadian MEPS quote that the testing standard used by the regulation is aligned with 10 CFR Part 431 Appendix A, subpart K. Which as described previously is closely aligned to the IEEE C57 standard for dry type distribution transformers[57].

Chile

Chile has a voluntary labelling programme which covers single-phase distribution transformers from 10 kVA to 833 kVA and three-phase distribution transformers from 15 kVA to 2500 kVA, both dry and liquid-immersed distribution transformers with a primary voltage of 34.5 kV or less and a secondary voltage of 600 V or less, at a frequency of 50 Hz[58].

The test standards are defined by two national standards NCh2660 and NCh2661 which are closely aligned to and refer to NEMA TP-2-2005. Chile is yet to develop any MEPS for distribution transformers however, research is being conducted for Chiles to have MEPS in the near future.

China

The Chinese mandatory MEPS are applicable for liquid-immersed three-phase distribution transformers with a voltage level of 10 kV and a rated capacity of 30 kVA to 2500 kVA, dry-type distribution transformers with a rated capacity of 30 kVA to 2500 kVA, and oil-immersed three-phase transformers with a rated frequency of 50 Hz, a voltage class of 35 kV to 500 kV, and a rated capacity of 3150 kVA and above[59].

The MEPS which provides the minimum allowable values of energy efficiency are specified by the standard GB 20052-2020 & JB/T 10317-02[60]. Similar to the Ecodesign regulation's EN standards these Chinese standards broadly align with the standards set by the IEC 60076 standard series. China sets their distribution transformer MEPS in terms of maximum permitted no load and full load power loss limits[61].

India

India has adopted a mandatory labelling scheme which applies to liquid-filled distribution transformers that are oil immersed, naturally air cooled, three phase, and double wound non-sealed type outdoor distribution transformers up to 2500 kVA, 11 kV specifications[62]. The national standard IS 1180 (Part 1 and Part 2) provides the testing procedure for the distribution transformers. These standards are based on the IEC 60076 standards.

[57] Dry-type transformers (canada.ca)

[58] 1364440 (osti.gov)

[59] http://www.gbstandards.org/index/standards_search.asp?word=Transformer

[60] Energy-Efficiency-EN.pdf (ececp.eu)

[61] Energy-Efficiency-EN.pdf (ececp.eu)

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

The labelling scheme in India adopts a star system to differentiate between models at the same rating, with 1 star being low efficiency and 5 stars being the highest. From 2010 the Central Electricity Authority (CEA) required all distribution transformer purchased by the utilities to have at least 3-star rating to ensure the purchase of more efficient transformers by the government [63]. The energy label indicates both total losses at 50% and 100% and are used to rate the product accordingly.[64]

Israel

Israel have adopted both MEPS and labelling requirements for distribution transformers. The ISI Standard 5484 provides the energy efficiency requirements for distribution transformers with a nominal input of 22 kV or 33 kV and a nominal output voltage of 400 V, with power rating up to 2500 kVA, operating at 50 Hz[65]. The test standard is closely aligned to the IEC 60076 series of standards.

The efficiency of distribution transformers is measured using the maximum coil losses that are measured at 100% of rated capacity. Similar to Australia and New Zealand, Israel has published a set of MEPS and HEPS both of which use the maximum losses at 100% rated capacity[66].

The Republic of Korea

Korea's MEPS programme covers both liquid-immersed and dry-type transformers. The Korean regulations covers single-phase distribution transformers between 10 and 3000 kVA and three-phase transformers between 100 and 3000 kVA[67].

The program also has target energy performance standards (TEPS) which attempt to drive innovation in the field to push industry to improve their energy efficiency. Both the MEPS and the TEPS set energy efficiency requirements at a 50% load which is calculated using the measurement methodologies in the national standards KS C 4306, KS C 4311, KS C 4316, and KS C 4317[68]. All of these standards cross reference the standards published by the IEC 60076 series, which has been adopted without modification by the Korean national standard KS C IEC 60076-1[69].

2.1.3 Recommendations

Standards used

Concluding from the in-depth analysis undertaken on the current standards present across the world for transformers and their relevance for the EU's regulatory process, the IEC 60076 standard is the most commonly used standard. Therefore, it is recommended that the EU continues to closely align to this standard with the EN 50708 standard. IEC 60076 is currently undertaking a revision which may see several changes to the standard, such as the re-defining small, medium and large

63 https://ksei.gov.in/pdf/Acts%20&%20Rules/TechStd.pdf

64 Bureau of Energy Efficiency (beestarlabel.com)

65 Ministry of Energy and Infrastructure (www.gov.il)

66 International Review of Standards and Labeling Programs for Distribution Transformers (Technical Report) | OSTI.GOV

67 http://www.kemco.or.kr/web/kem_home_new/new_main.asp

68 INTAS_D2.1_Final_Annex_A.pdf (intas-testing.eu)

69 1364440 (osti.gov)

transformers. It is recommended Ecodesign align with the EN standard, but also verify that the new standard definitions do not alter the scope of the regulation.

It is evident from Section 2.1.2.2 that EU's Tier 2 requirements closely align with the US and Japan's regulations. However, both the US and Japan's regulations are currently under revision, and which may uplift requirements for both dry and liquid filled transformers. This would see both either align or overtake the EU Tier 2 requirements. It can be very difficult to compare the efficiency levels of transformers located in different geographies. This is because the levels of efficiency can depend on the carbon intensity of the local grid and the costs incurred for producing more efficient transformers in that specific market. For example, if the electricity mix is more carbon intensive, then requirements for more energy efficient transformers are justifiable and vice versa. One stakeholder mentioned that the most important factor in assessing transformer efficiency is the overall benefit to society brought by the chosen efficiency level compared to the opportunity costs to society incurred for investing in the improved efficiency level. Therefore, it is important that many factors such as geography are considered as well as efficiency level to ensure the changes are suitable for that region.

Definition update

Since the Regulation's definition and scope mean that small power transformers fit within the scope of TC 14 this has caused some confusion in industry as to whether small power transformers are supposed to be covered by TC 14. 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 more closely align the definition of small power transformers with that of TC 14 and TC 96. 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 "*as 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.

2.2 Ecodesign energy efficiency requirements

a) the extent to which requirements set out for Tier 2 have been cost-effective and the appropriateness to introduce stricter Tier 3 requirements;
e) the appropriateness of setting minimum performance requirements for small power transformers.
n) impact of rising electricity prices on current and potentially stricter Ecodesign requirements.

2.2.1 Background

2.2.1.1 Effectiveness of Tier 2, and implementation of Tier 3

Ecodesign Tier 1 and Tier 2 requirements for transformers from Commission Regulation (EU) 2019/1783 refer to the EU's energy efficiency standards and requirements for transformers used in electrical power systems. Below is a brief overview of Ecodesign Tier 1 and Tier 2 requirements for transformers:

- Ecodesign Tier 1 (2015): This initial phase of requirements, implemented in 2015, established minimum energy efficiency requirements for transformers with power ratings between 1 kVA and 2,500 kVA, as well as certain specific transformers used in special applications. The regulation set energy efficiency requirements based on loss measurements, such as no-load losses and load losses, which transformers had to meet. Transformers were classified into three efficiency classes: low-loss (Tier 1), medium-loss, and high-loss.

- Ecodesign Tier 2 (2021): The Tier 2 requirements, which came into effect in 2021, expanded the scope of the regulation and included more transformer categories. Currently it now covers transformers with power ratings from 1 kVA to 5,000 kVA. Tier 2 levels tightened energy efficiency requirements for transformers, promoting further reductions in energy losses and improvements in energy efficiency.

Not only Medium Power Transformers (MPT) of less than 5 000 kVA are regulated, but also larger transformers. The MPT are regulated with fixed losses as they represent mass production, the larger units are tailored to their usage and therefore defined by minimum efficiency index.

2.2.1.2 Energy efficiency metrics for small power transformers

The scope of the transformer's regulation is for power transformers with a minimum power rating of 1kVA used in 50Hz electricity transmission and distribution networks or for industrial applications. Within this scope, the "small power transformers" are defined as those more than 1kVA power transformers with a highest winding voltage not exceeding 1.1kV. Small power transformers as defined by the EU are not compliant with the EN/IEC 60076-1, they mainly concern safety transformers and are not under the control of CLC TC14.

Small transformers have lower power ratings resulting in a relatively smaller contribution to total power network losses compared to larger transformers. Small power transformers are commonly used in industrial power systems, including drives, rectifiers, and power converters for renewable energy applications like wind and solar. They can also serve as isolating transformers for safety on construction sites.

Very small transformers (50-100W, and hence out of scope of this power transformers regulation) are used in electronic equipment, although many modern devices no longer require transformers. Some of these electronic equipment (e.g. displays), and the transformers within external power supplies, are covered by separate Ecodesign regulations.

Small transformers are used for LV (low voltage) to LV grid transitions and network compensators, particularly in the context of the energy transition, addressing issues like over- or undervoltage caused by photovoltaics and electric vehicles.

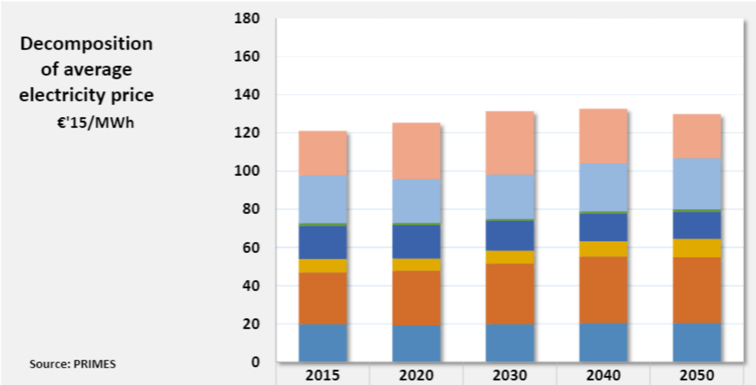
The efficiency of large transformers can be as high as 99.75% while typically small transformer efficiency is lower at around 97.5%. Considering that the suggested ideal efficiency limit lies between 98 and 99.5% for an electrical transformer[70], efficiency improvements are possible for small transformers. Small power transformers can present technical challenges related to measuring and enforcing energy efficiency standards. These transformers may have more variable and less standardised designs, making it more complex to establish uniform regulations.

[70] https://www.electricalindia.in/how-to-enhance-transformer-efficiency/#:~:text=Large%20power%20transformers%20attain%20efficiency,98%20and%2099.5%20per%20cent

2.2.1.3 Effect of rising electricity prices

Understanding the development of electricity prices is crucial for appreciating the savings associated with loss reduction. The price of a kilowatt-hour (kWh) for consumers is structured to cover fixed costs related to network and generation investments, the variable cost of generator fuel linked to kWh output, and operational costs associated with running the network and systems (unrelated to kWh). It's essential to note that while improved transformer efficiency reduces kWh losses, resulting in less fuel consumption and associated savings, it does not impact fixed costs or operational costs, as these remain unaffected by a reduction in losses. This aspect was thoroughly investigated in Tier 2, based on an EU report.

Figure 2.3 Cost components of average electricity price[71]



	2015	2020	2030	2040	2050
Annual capital cost	23	29	33	29	23
Fixed costs	25	23	23	25	27
Variable costs	1	1	1	1	1
Fuel costs	18	17	16	15	14
Tax on fuels and ETS payments	7	6	7	8	10
Grid costs	27	29	32	35	34
Excise tax and VAT on electricity	20	19	20	21	20
Average price of electricity (after tax)	146	151	158	159	161

The graph illustrates that the price of electricity is predominantly comprised of fixed costs related to network investment, generation plants, and associated debt servicing costs, with additional taxes. In addition, variable costs related to the fuel used for electricity generation contribute to the overall price, and although these variable costs are considerably lower than the fixed costs, they are an essential component.

Capitalisation of losses takes a long-term perspective, typically spanning several decades, to assess the financial implications and performance of an investment. This extended timeframe is particularly relevant when considering the lifespan of energy infrastructure. Capitalisation of losses is a valuable tool for assessing the financial viability and sustainability of energy investments in the context of Net Zero goals. By looking at costs over a long-term horizon, it can help investors and policymakers make informed decisions about the economic feasibility and long-term value of energy projects. As technology advances, economies of scale are achieved, and more efficient energy generation methods are developed, the cost per unit of energy (kWh) typically decreases.

[71] EU reference scenario 2020 - Publications Office of the EU (europa.eu)

2.2.2 Feedback/ Research results

2.2.2.1 Effectiveness of Tier 2, and implementation of Tier 3

There is consensus among some respondents that improving energy efficiency is essential. They emphasise looking at energy efficiency from a Total Cost of Ownership (TCO) perspective rather than just the initial transformer cost. The focus of Tier 2 is seen as reducing environmental impact by addressing power losses in power transformers. One stakeholder noted that in line with the goals set by EU climate law to reach net-zero emissions by 2050 and the resulting increase in renewable energy generation, the benefits of increasing the efficiency requirements will decrease. It is therefore important to perform a thorough analysis of the life cycle impact of transformers with different efficiency levels in regional and varying electricity mixes.

A simplified formula for the TCO is as follows:

$$TCO = IC + A \cdot (P_0 + P_{C0}) + B \cdot (P_k + P_{cs} - P_{c0})$$

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).

Opinions regarding the cost-effectiveness of Tier 2 energy performance requirements for transformers are divided. While some stakeholders view Tier 2 as cost-effective, others express concerns about the strain it places on the supply chain and advise caution against exceeding certain limits. The principal concern over supply chain is that the more efficient transformer technologies rely on amorphous steel cores, and there does not seem to be any amorphous steel manufacturing in the EU. Per feedback, challenges in the supply chain will also compel transformer manufacturers to use existing e-steel grade instead of opting for higher grade e-steels to meet stricter Tier 3 requirements. This situation would cause a decrease in material usage efficiency and an increase of costs. Between Tier 1 and Tier 2, the mass of power transformers has increased by an average of 30%, and their volume by 15 to 20%. The increase in the mass is not equal for all materials for medium power transformers. On average, the detailed increases by material are as follows[72]:

- Aluminium windings: +80%
- Steel tank: +30%
- Magnetic core: +30%
- Dielectric fluid: +20%

The assessment of cost-effectiveness is contingent on various factors, including the load and lifespan of the transformers in question. While there is acknowledgment of the importance of addressing no-load losses, there is also a strong emphasis on

[72] Stakeholder feedback

considering load losses. Additionally, the economic viability of Tier 2 has been impacted by significant increases in raw material prices, further complicating the assessment of its cost-effectiveness.

According to another stakeholder, Tier 2 is widely regarded as a positive step forward in terms of enhancing efficiency in the transformer industry. However, there are concerns about the economic and ecological payback times, particularly in relation to CO_2 emissions reduction, which remain uncertain in some cases. Notably, Tier 2 had minimal effects on the design of large power transformers for Transmission System Operators (TSOs), indicating that larger transformers, especially those above 100MVA, inherently exhibit greater cost-effectiveness in complying with these regulations.

However, there's a notable call for improved management of various factors such as raw materials extraction, transportation costs, and civil engineering. Additionally, concerns have been voiced regarding the effective handling of variable cooling and the management of real load conditions. Despite these challenges, some respondents believe that the transition to Tier 2 is entirely sustainable, citing the combination of rising material costs and increased energy prices across Europe as factors that support this transition.

Per the stakeholder feedback, the implementation of Tier 2 requirements resulted in higher transformer costs primarily due to the use of higher-grade materials. However, this cost escalation was partially mitigated by the increase in electrical energy costs. The future remains uncertain, particularly in terms of electricity pricing trends influenced by renewable and nuclear energy sources. This uncertainty necessitates a delicate balance between ensuring affordability and enhancing energy efficiency.

The introduction of Tier 2 requirements resulted in substantial price hikes for medium-power transformers, driven by the increased mass of these transformers and rising raw material costs, which ranged from 15% to 25%[73]. Despite these cost increases, the savings achieved through reduced electrical losses helped maintain the total cost of ownership at levels like those seen in 2014 (i.e., compared with Tier 1). Large power transformers had already been moving towards Tier 2 requirements due to a strong focus on loss reduction in their procurement processes. Nonetheless, the weight constraints imposed by Tier 2, especially for 36MVA transformers, resulted in higher prices and had implications for transportation and material selection.

Respondents expressed concerns about the difficulty of achieving further efficiency improvements beyond Tier 2, especially when it comes to reducing losses by 5%. One stakeholder stated that the efficiency levels introduced in Tier 1 and Tier 2 are now at a stage where any further increases will produce rapidly decreasing returns to scale. Some manufactures have privately indicated a figure of an increase of up to 50% in cost for a further 10% in efficiency, or for a 5% increase in efficiency. Iron and copper losses would need to be reduced by 10% each from Tier 2 levels, resulting in an increase in weight of up to 30%[74]. Scarcity of high-quality magnetic steel and difficulties in sourcing the best-quality materials are highlighted. ICF's concerns also extend to the impact on transformer dimensions and weights, particularly in large power transformers.

[73] Stakeholder feedback

[74] Stakeholder feedback

The objective concerning 'high-performance materials' is not aimed at minimizing losses but rather at lowering embedded carbon emissions by extending the lifespan of existing transformers, thus decreasing the replacement rate. This strategy enhances 'circularity' and boosts the resilience of supply chains by prolonging the 'useful economic life' of transformers. The approach involves the utilization of new ester transformers with Nomex papers to enable higher power density, resulting in lower average iron losses but higher peak copper losses. However, it's important to note that this option is currently not feasible.

Some stakeholders suggest that Tier 3 requirements should focus more on material efficiency, emphasising the use of high-performance materials and reevaluating rated power selection. They believe that Tier 3 could disproportionately increase material consumption, posing environmental challenges.

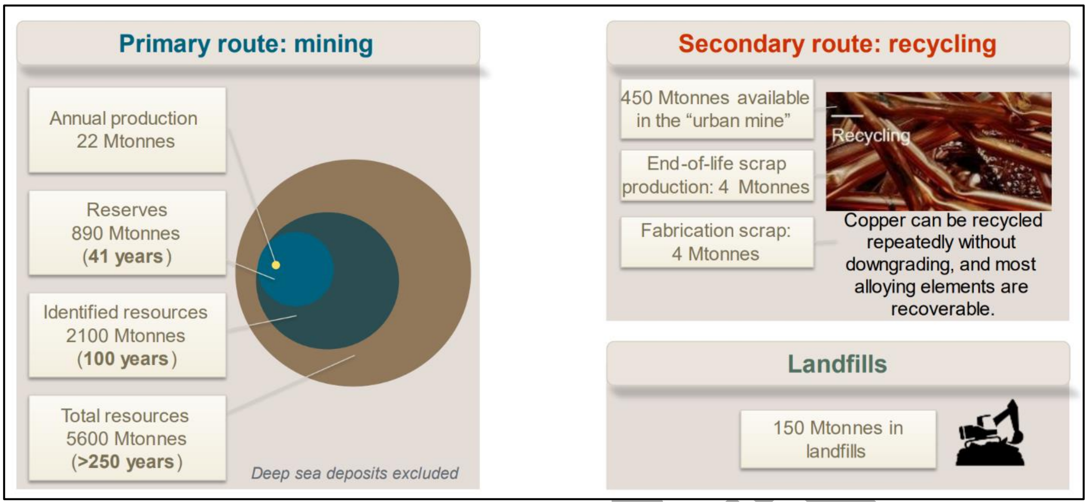
Respondents raised concerns about the substantial increase in raw materials that stricter Tier 3 requirements would demand, potentially out of proportion to the efficiency gains achieved. They also highlight potential challenges related to manufacturing capacity, supply chain flexibility, and the environmental consequences of higher material consumption. Additionally, they point out difficulties in integrating larger and heavier transformers into certain applications, such as solar and battery storage systems. A stakeholder further added that a system perspective should be adopted when it comes to assessing the net balance of material use.

Some respondents suggest that rather than strict Tier 3 requirements, the focus should remain on the repair and remanufacturing market for older transformers. They stress the importance of considering the carbon footprint associated with material extraction and the need for new, more efficient materials.

The feedback highlights the need for high-performance materials to reduce losses, which could lead to increased material costs and concerns about raw material availability. The environmental and supply chain implications of these materials are discussed. The International Copper Study Group (ICSG) mentions that a theoretical annual capacity of around 10.8 million tonnes of copper resides in mining projects not yet in operation[75]. A stakeholder suggested that Copper demand is expected to grow primarily due to energy transition, population growth and economic development. The same stakeholder mentions that there are enough copper resources to support the energy transition.

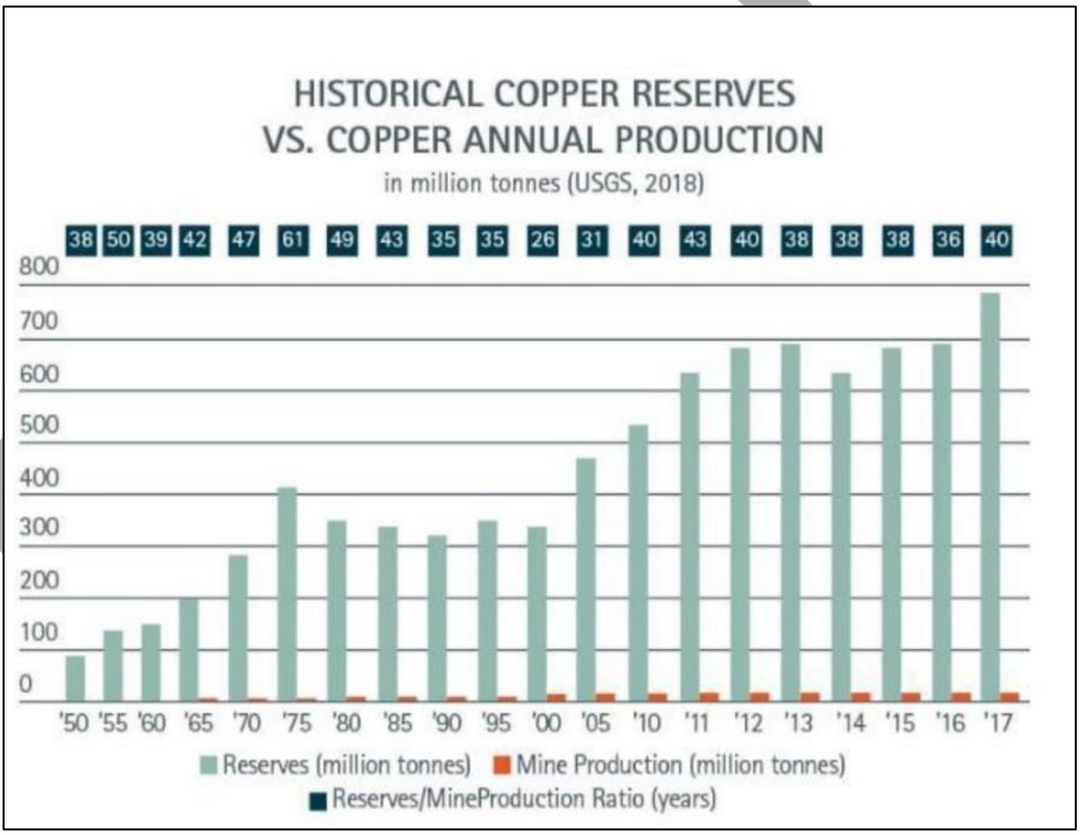
[75] The World Copper Factbook 2023: https://icsg.org/copper-factbook/

Figure 2.4 Copper sources from mining and recycling[76] [77] [78] [79]



Since 1950, there has always been, on average, 40 years of copper reserves and over 200 years of resources remaining, as showcased in Figure 2.5 below.

Figure 2.5 Historical copper reserves versus copper annual production [80]



[76] The World Copper Factbook 2023: https://icsg.org/copper -factbook/

[77] Dynamic Analysis of Global Copper Flows: https://pubs.acs.org/doi/10.1021/es400069b

[78] US Geological Survey (USGS), 2023: https://www.usgs.gov/

[79] Meeting Future Copper Demand: https://internationalcopper.org/

[80] https://copperalliance.org/sustainable -copper/about-copper/cu-demand-long-term-availability/

For medium-power transformers, it is noted that Tier 2 transformers have already reached the limits of existing substations in terms of size and load. Implementing stricter Tier 3 requirements could necessitate costly replacement of substations, with significant environmental and economic implications per stakeholder feedback.

The feedback emphasises the need to establish a fixed reference temperature for assessing losses in transformers, as the current regulation allows user discretion and potential manipulation. The stakeholder recommendation is to define the reference temperature as the yearly average winding temperature, calculated at 20°C plus the guaranteed temperature rise, leading to 85°C for AN or OF cooled transformers and 90°C for OD transformers. Currently, a common reference temperature of 75°C is in use and increasing it by 10°C results in approximately a 4% rise in losses. The suggestion is to adopt the reference temperature described, in line with EN 60076-1, without modifying the PEI or loss level[81].

ICF understands that stricter Tier 3 requirements for large power transformers could complicate transportation and installation due to increased size and weight, posing challenges for existing infrastructure and costs.

The feedback suggests that introducing material efficiency requirements (MMPS) alongside Tier 3 MEPS could encourage more compact designs while maintaining Tier 3 efficiency standards.

Amorphous core transformers are experiencing substantial market adoption, particularly in developing countries like China and India, driven by their superior energy efficiency and competitive pricing compared to traditional core transformers. These transformers have been in production for over thirty years, with growing demand, primarily due to their successful deployment in China and Japan, as well as the increasing need for more durable transformers. Notably, in China, there is a tiered system for maximum losses, with Grade 1 being the most efficient and Grade 3 the least efficient for silicon-core steel transformers. Furthermore, amorphous-core distribution transformers, which have significantly lower losses, are classified under separate product classes within Grades 1 and 2, reflecting their remarkable energy efficiency[82]. Figure 2.6 shows the maximum no load loss (W) for different kVA ratings for both Cold Rolled Grain Oriented (CRGO) core and Amorphous Core (Grade 1 in China).

[81] Stakeholder feedback

[82] https://www.clasp.ngo/research/all/international-review-of-standards-and-labeling-programs-for-distribution-transformers/

Figure 2.6 Maximum no load losses for different kVA ratings for different cores[82]

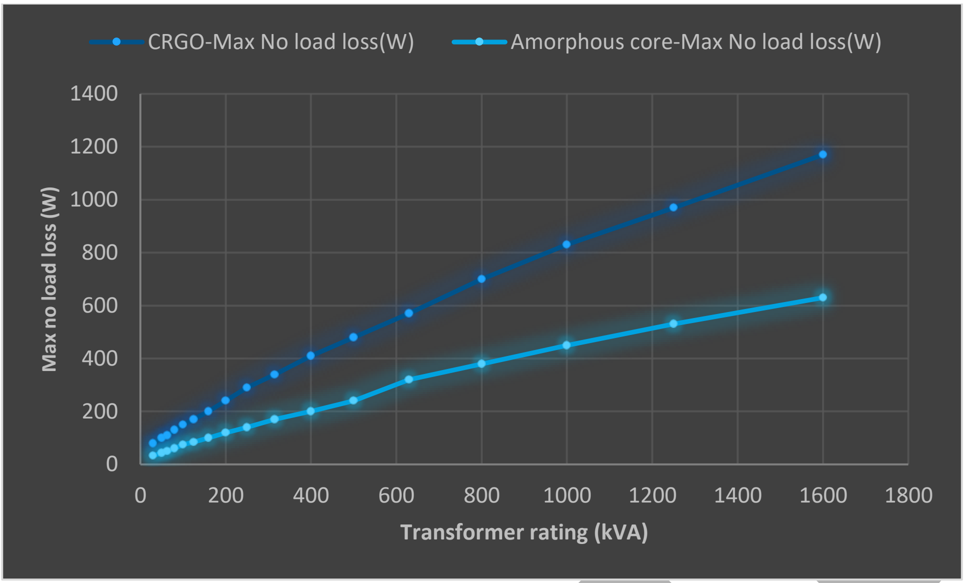
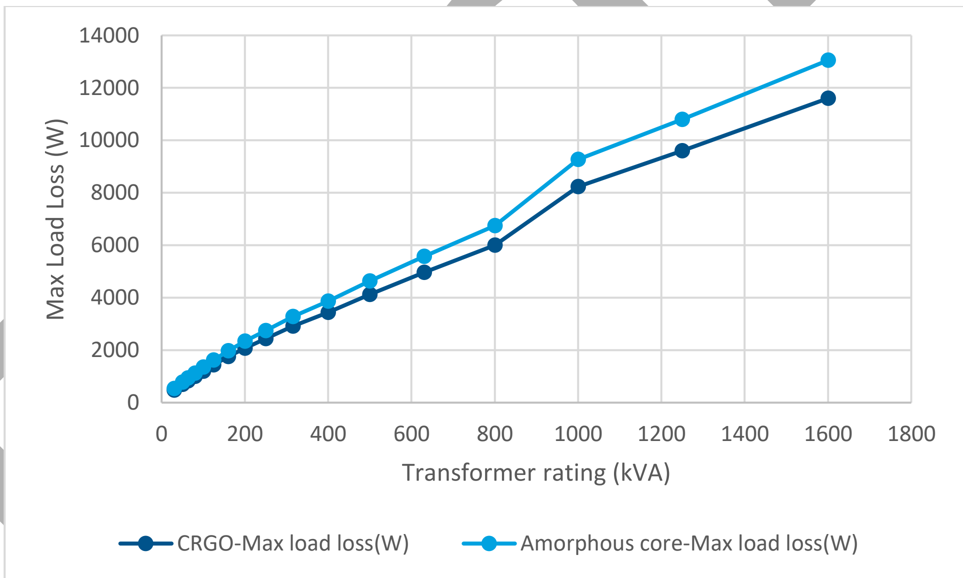


Figure 2.7 below shows the Max load loss(W) for different kVA ratings for both CRGO core and Amorphous Core.

Figure 2.7 Maximum load losses for different kVA ratings for different cores[82]



This comparison shows there is a significant scope in energy efficiency improvement when amorphous core is used in transformers. Tier 3 implementation will require a shift to amorphous core but there are certain arguments that should be considered:

- Supply of amorphous material, cost impact, industry readiness.

The European Copper Institute (ECI), an advocate for the copper industry within the EU, published a paper on the revision of the Ecodesign regulation[83] on the impact of potential Tier 3 MEPS for transformers. The paper discusses about the following areas:

  – Cost of transformer

83 "Revision of Ecodesign Regulation for Transformers

– Losses
– Material usage & efficiency

To analyse the impact of a potential Tier 3 MEPS, ECI carried out a modelling exercise. ECI developed various design options for a 630 kVA distribution transformer using professional design software and based on a particular set of parameters: Root Mean Square load: 30%. Lifetime: 40 years. Electricity price: 0.13 €/kWh. Interest rate (calculation of Net Present Value of future losses): 2%. Raw material prices: aluminium winding wire 6€/kg, copper winding wire 12€/kg, magnetic steel M070 5.5€/kg, oil 2€/kg, steel for tank and cover 4.5€/kg. The key findings from the ECI paper on implementation of a Tier 3 are as follows:

– Shifting to Tier 3 energy efficiency thresholds for transformers may involve an upfront cost increase due to the use of more or higher-quality materials, but this is offset by a significant reduction in net present value of energy losses, resulting in the total cost of ownership (TCO) fluctuating within a narrow +/- 5% range. The transition to Tier 3 can affect material use, but this should be assessed at a system level, including both the transformer and the energy generation infrastructure required to compensate for losses. Reduced losses mean less renewable generation capacity is needed, leading to material savings. This translates to a 4% to 8% reduction in material use when moving to Tier 3 compared to Tier 2. Transformer replacements should consider the impact on existing substations, as it may necessitate costly upgrades. Compact units, achieved through specific materials and design flexibility, can mitigate this. At the EU scale, Tier 3 MEPS for distribution transformers could yield substantial electricity savings and reduce material usage. The introduction of material efficiency requirements (MMPS) aligns with Tier 3 MEPS, encouraging more compact designs while respecting efficiency standards.

The use of amorphous steel would not be in line with the EU policy on Critical Raw Materials as this is only manufactured outside the EU in India, China, Japan and the US. Furthermore, European transformer manufacturers do not have the manufacturing capability to slit amorphous steel and optimise transformer design. Considering the need for volume production, the supply chain does not exist and manufacturers are not industrially ready particularly in a period of time when the grid electrification is generating volume increases. Hence, transformer designs are limited to standard sizes. One stakeholder also mentioned that amorphous technology is not available for large power transformers and presents weakness when it comes to short circuit for installations up to 5MVA. Another stakeholder stated that the use of amorphous is normally only justified in low load factor applications when it is most critical that iron losses are minimised, yet with electrification it is copper losses that are likely to be most critical as load factors will be high due to EV Charging, Heat Pumps and other forms of electric heating. EU factories do not have the specialised slitting machinery required to deal with amorphous and consequently would only be able to use standard sizes of amorphous to produce a restricted set of iron losses. Amorphous is also heavier and more expensive than normal steel, particularly where it has to be operated at low saturation levels to avoid excessive noise. This results in heavier and more expensive transformers.

As society becomes more electrified, the average load for which a house is designed has increased. Previously, houses were designed for an average load of 1-2 kW, with occasional peaks that were much higher. Now, with the installation of 7kW Electric Vehicles (EVs) and 3.5kW Heat Pumps that are expected to run for several hours, the average loading factor has increased. The design now accommodates an average load of 5.5kW, with an option to upgrade the substation to provide 8kW. The number of cables offloading each unit substation has increased from 4 to 6, each with a capacity of 1,200kVA. This reduces the load per cable from 25% to 16%, resulting in cable losses being reduced by more than half. However, transformer designs with fixed losses are only optimally efficient at a 30% load factor. This means they are not as efficient at the actual load factor and become increasingly inefficient at any higher future load factors[84].

Furthermore, considering the substantial size of renewable generation sources due to their low load factor, it becomes imperative to activate loads when the sun is shining, or the wind is blowing to maximize usage. Consequently, this leads to a considerable increase in copper losses due to loading. While this is acceptable, as an alternative would be to waste the renewable energy, it emphasizes the point that any reduction in losses with renewables translates to savings in renewable energy. However, such savings must be considered since storing this excess energy is not cost-effective. The key point to emphasize in evaluating losses is the value derived from avoiding the additional cost of not producing a kilowatt-hour (kWh). Although this area has not been thoroughly investigated, the feedback suggests that load should not be restricted to fit within the capabilities of the plant. Instead, the plant should be sized to prevent restrictions on the load, ensuring optimal utilization of generation when it is available.

In conclusion, the feedback indicates a consensus on the importance of improving energy efficiency in transformers, especially by considering TCO rather than just the initial transformer cost. Tier 2 thresholds are viewed as a positive step in enhancing efficiency, but opinions about their cost-effectiveness are mixed, influenced by factors like supply chain disruptions, material cost fluctuations, and shifts in energy prices. However, the potential transition to Tier 3 standards raises concerns about the difficulty of achieving further efficiency gains, especially in reducing losses by 5%, driven by issues like the scarcity of high-quality magnetic steel and material sourcing challenges, as well as implications for transformer dimensions and weights, especially in large power transformers. Additionally, the feedback highlights the positive market adoption of amorphous core transformers, driven by their energy efficiency and competitive pricing, particularly in countries like China and India.

2.2.2.2 Energy efficiency metrics for small power transformers

Small power transformers fall outside the standardisation framework of CENELEC TC14 but align more with TC96. Some stakeholders suggest that all transformers should be included in regulation efforts, emphasising the importance of energy efficiency in transformer designs. Small power transformers are numerous but priced lower than medium and large power transformers, resulting in a smaller market in terms of value. For example, in France, around 30,000 small power transformers are traded annually[85]. Transformers used for temporary solutions, such as during grid upgrades, may not be very cost-effective over extended periods due to high initial costs and operational expenses per the feedback. Some argue that small power transformers used in domestic appliances or building applications should be regulated differently from other transformers due to variations in users and producers. In the context of the energy transition, small power transformers find applications in charging stations and coupling PV (photovoltaic) inverters. Sales

[84] Stakeholder feedback

[85] Stakeholder feedback

volumes in Europe for transformers below 1.1 kV is estimated to be around 100,000 units per year, accounting for approximately 5-7% of total transformer sales in Europe[86].

Another subset of smaller industrial transformers includes Isolation (Separation) Transformers or Safe Extra Low Voltage (SELV) transformers for control purposes (e.g., 24 VAC). Initial assessments suggest that these smaller industrial transformers have a minimal impact, accounting for less than 0.4 terawatt-hours (TWh). This finding is consistent with results from other studies, such as those conducted in Australia. It's important to note that these smaller industrial transformers adhere to different standards and are not linked to the medium voltage system.

ICF understands that the efficiency of small transformers is noted to depend on factors like load rating and utilisation, which can be low for intermittently used electronic equipment. Setting a general efficiency level for small transformers is considered challenging due to the varied use-cases and potential ancillary costs. Per stakeholder feedback, small transformers (50-100W) are often produced outside the EU for a worldwide market and embedded as components in other products, making it difficult to impose sanctions on manufacturers through current legislation. However, these should be noted to be outside of the scope of the transformers Ecodesign regulation as the scope is only for transformers with a kVA larger than 1.

Furthermore, grid decarbonisation is mentioned as another factor to consider when evaluating the necessity and effectiveness of increasing the efficiency of small transformers. Average efficiency of small transformers is estimated at 96 %[87]. The feedback provides some estimates of average efficiency for small transformers, which may not be as easily improved as medium or large transformers due to limitations in adding raw materials. Challenges related to materials are highlighted, including the need for higher grade e-steel, supply chain disruptions, and increased carbon emissions from materials. One stakeholder stated that the reliance on a limited number of suppliers outside the EU is noted to compromise supply chain resilience. Enhancing operational energy efficiency may inadvertently increase the carbon footprint from materials, posing environmental and social impacts. Challenges in the supply chain may lead to the use of the same e-steel grade instead of higher grades, decreasing material usage efficiency and increasing costs. Increasing material usage is seen as undermining the principles of a circular economy, which aims to minimise materials handled at the end of a transformer's life. The feedback references the effectiveness of the US DOE Regulation (See section 2.1.2.2) in covering various types of distribution transformers, implying that it could serve as a model for efficiency standards.

Some feedback suggests that small transformers could be excluded from the regulation due to the diverse nature of the market and the perceived complexity of setting performance requirements for such a wide range of products. It is argued that if energy efficiency is to be addressed, it should be done at the product level rather than regulating individual components like small transformers, which may have a relatively minor impact on overall energy wastage. It is mentioned that there may be no economic or environmental interest in regulating small transformers in this power range, and doing so may make them more complex to manufacture. Some feedback supports the idea that all transformers should be included in regulation and suggests examining the extension of tables for lower power ranges. It

[86] Stakeholder feedback

[87] Stakeholder feedback

is noted that very small transformers often reuse magnetic steel recovered from old transformers. ICF agrees that reuse of materials can have environmental benefits.

In conclusion, the feedback highlights the diverse nature and use-cases of small power transformers, which play a relatively smaller role in total power network losses compared to larger transformers. The feedback discusses challenges in setting a general efficiency level for small transformers and notes that they are often produced globally, embedded in other products, making it challenging to impose sanctions on manufacturers. ICF agrees to not consider regulating at the product level and establishing performance levels for classes of small transformers instead.

2.2.2.3 Effect of rising electricity prices

The feedback from a stakeholder acknowledges a lack of specific information, but it suggests that COVID-19 has likely brought about additional challenges and problems. Current high electricity costs are short-term due to gas shortages arising from sanctions on Russian gas, now replaced in the short-term by LPG, and is being increasingly substituted by renewables. So, the long-term trend for electricity's variable costs will be downward. The feedback notes that the costs of base materials have consistently increased in the last 2-3 years, which may affect the overall cost and efficiency of transformers. The capitalisation of losses over 25-40 years is highlighted, emphasising that it's not influenced by short-term price patterns. It also mentions the trend of falling energy costs within the kWh over the long term. When capitalising the stream of savings, a discount rate is used and in Tier 2 a real 4% social discount rate was advised for use by the EU to assess the societal benefits of long-term investment returns from energy efficiency. Such societal discount rates do not incorporate any project risk premiums, and these are to be incorporated in the cash flows directly before they are discounted. There is a shift towards larger transformer ratings to accommodate larger loads and higher peak loads, rather than restricting the use of renewables. Copper losses are reducing not only due to loss capitalisation but also because more copper improves voltage regulation at higher loads and the transformer's capability to handle peak loads. Tier 2 requirements have led to high levels of efficiency, but further increases in efficiency may be uneconomic due to disproportionately increased transformer costs High electricity prices have influenced manufacturing costs, potentially leading to higher transformer prices and financial compensation for already produced transformers. The feedback mentions that DSOs (Distribution System Operators) have used high electricity prices as a reason to halt investments, citing reduced benefits and profitability. Despite high electricity prices, the demand for transformers has increased due to the European energy transition program. On the DSO level, Tier 2 designs have limited margins in size and weight, reducing potential gains in energy efficiency. Capitalisation is considered the best way to control the loss level of large transformers. However, there are challenges related to formula flexibility and local decision-making. Scarcity of transformer supply and extended delivery times for both small and large transformers are mentioned as challenges in the current market by a stakeholder rather than electricity prices. A stakeholder mentions that higher electricity prices can result in higher efficiency for larger transformers, but material price increases work in the opposite direction. A stakeholder mentions that in line with the goals set by EU climate law to reach net-zero emissions by 2050 and the resulting increase in renewable energy generation it is important to analyse life cycle impact of transformers with different electricity levels and varying electricity mixes across Europe.

In conclusion, the feedback states that the consistent increase in the costs of base materials over the past few years, can impact the overall cost and efficiency of transformers. The feedback underscores the importance of capitalising losses over an extended period (25-40 years), emphasising that this approach is not influenced by short-term electricity price patterns. The interplay between higher electricity prices and transformer efficiency, as well as the counteracting effects of material price increases, are mentioned as important factors to consider.

2.2.3 Recommendations

2.2.3.1 Effectiveness of Tier 2, and implementation of Tier 3

A holistic approach is necessary to address the various challenges and opportunities presented by these requirements. It is important to continue to prioritise energy efficiency improvements but assess them from a TCO perspective rather than solely focusing on the initial transformer cost. This approach allows for a more comprehensive evaluation that considers energy losses over the operational life of the transformer. In the same way that GHG emissions at the generation level are factored into assessments of energy efficiency enhancements, the utilisation of materials at the generation level should also be acknowledged. The potential for material efficiency requirements should be explored, focusing on high-performance materials and rated power selection. This approach may offer efficiency gains without disproportionately increasing material consumption. Amorphous steel is not only denser but also more costly than regular steel, especially when operating at low saturation levels to mitigate excessive noise. This leads to the production of heavier and pricier transformers. Transformers are predominantly manufactured with Grain Oriented Stainless Steel. This suggests that the infrastructure and supply chains for manufacturing transformers with Amorphous Steel are still not well established. Hence it is recommended to adhere to the Tier 2 requirements and not consider the more aggressive Tier 3 requirements. Before prioritizing the minimization of Iron Losses, it is essential to conduct an analysis of future load factors. These factors determine the optimal balance between Iron and Copper losses, with a higher likelihood that the benefits of minimizing Copper losses will outweigh those of minimizing Iron losses.

For distribution transformers, it is recommended to encourage more compact designs that reduce material usage while maintaining or increasing efficiency standards after carefully evaluating the supply chain along with the design constraints. Transformers have a significant shelf life that the supply chains and associated manufacturing processes can evolve rapidly in that duration. This will offer material savings for the same energy efficiency or efficiency gains without disproportionately increasing material consumption. Thus, a comprehensive study evaluating detailed impact of TCO should be carried out before moving to higher energy efficiency requirements as some assumptions made during the initial cost benefit analysis such as expected cost of materials, level of CO_2 emissions and energy savings no longer seem relevant. It is recommended that this option be considered by the regulation in the future but is currently constrained by the supply chain.

Phase 2 contains the associated Base cases and TCO calculations supporting above arguments with updated data.

2.2.3.2 Energy efficiency metrics for small power transformers

It's important to recognise the diverse nature and varied applications of small transformers, making it challenging to set a one-size-fits-all efficiency standard. 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 group of standards (IEC 60076). As a result, there is currently no testing method present for small power transformers, since TC 14 only covers transformer > 1000 V. Therefore, it is not recommended to take this small power transformer metric forward because of the lack of a standard covering small power transformers. The study team is aware of TC 96 which covers small power transformers < 1000 V, however, these standards (IEC 61558) do not provide a testing methodology for the efficiency of small power transformers.

Additionally, it is necessary to explore the potential to include small transformers within broader product-level regulations as opposed to this regulation for appliances, since it may be more effective in addressing energy efficiency at the overall product level. Furthermore, it's vital to consider the environmental impact, including the carbon footprint of materials, especially given the limitations in improving the efficiency of small transformers due to constraints in adding raw materials and lack of industry test standards.

2.2.3.3 Effect of rising electricity prices

It is essential to monitor and adapt to the impact of external factors, including COVID-19 and the fluctuations in the costs of base materials, on the transformer industry. This entails developing strategies to mitigate cost increases by potentially seeking alternative materials or suppliers. While prioritising efficiency gains remains crucial, it is especially vital to consider the potential disproportionate increase in transformer costs associated with further efficiency improvements. Given the trend toward larger transformer ratings to accommodate the growing demand for renewables, there is a need to concentrate on optimising design and manufacturing processes while accounting for long term electricity price patterns which is a critical parameter to be considered during TCO analysis. This optimisation should aim to sustain cost competitiveness while upholding high efficiency standards over the transformer lifetime ensuring reliability and stability regarding pricing strategies.

2.3 Implementation of Ecodesign Requirements and Methodologies

b) the appropriateness of the concessions introduced for medium and large power transformers in cases where installation costs would have been disproportionate. In particular, the analysis should investigate concessions in concrete cases (e.g., manufacturers, electricity companies, market surveillance authorities) and determine their appropriateness;
c) the possibility of utilising the PEI calculation for losses alongside the losses in absolute values for medium power transformers;
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;
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).

2.3.1 Background

2.3.1.1 Disproportionate costs mechanism for large power transformers

At present the Commission Regulation (EU) 2019/1783 has concessions for derogation from Tier 2 to Tier 1 for one-to-one replacements of large power transformers, as well as new installations of large power transformers. Disproportionate costs need to be proven by the manufacturer, importer or authorised representative responsible for placing on the market or putting into service the transformer.

The Commission Regulation (EU) 2014/584 allowed certain large power transformer like-for-like replacements to be exempt from the Regulation as follows:

Figure 2.8 Extract from the Commission Regulation (EU) 2014/584 for large transformers like-for-life replacements

> — large power transformers which are like for like replacements in the same physical location/installation for existing large power transformers, where this replacement cannot be achieved without entailing disproportionate costs associated to their transportation and/or installation,

The Commission carried out a review study that analysed the specific aspects set out in Article 7 of Regulation (EU) 2014/548. For reference, Article 7 is as follows:

Figure 2.9 Article 7 of the Commission Regulation (EU) 2014/548

> *Article 7*
>
> **Review**
>
> No later than three years after the entry into force, the Commission shall review this Regulation in the light of technological progress and present the results of this review to the Consultation Forum. Specifically, the review will assess, at least, the following issues:
>
> — the possibility to set out minimum values of the Peak Efficiency Index for all medium power transformers, including those with a rated power below 3 150 kVA,
>
> — the possibility to separate the losses associated to the core transformer from those associated with other components performing voltage regulation functions, where this is the case,
>
> — the appropriateness of establishing minimum performance requirements for single-phase power transformers, as well as for small power transformers,
>
> — whether concessions made for pole-mounted transformers and for special combinations of winding voltages for medium power transformers are still appropriate,
>
> — the possibility of covering environmental impacts other than energy in the use phase.

Based on that study, the Regulation was amended in the Commission Regulation (EU) 2019/1783 to include further exemptions via the mechanism for new installations of large power transformers as follows:

Figure 2.10 Extract from the Commission Regulation (EU) 2019/1783 adding the installation new large power transformer transformers into the disproportionate costs mechanism

> An existing regulatory exemption for the replacement of large power transformers related to disproportionate costs associated with their transportation and/or installation should be complemented by an exemption for new installations, where such cost constraints are also applicable.

Definition and methodology of the disproportionate costs mechanism for large power transformers

The Commission Regulation (EU) 2019/1783 expanded upon the mechanism for large power transformers, defining the mechanism and stating what needs to be provided to qualify for it:

Figure 2.11 Extract from the Commission Regulation (EU) 2019/1783 defining the mechanism for large power transformers

> Minimum efficiency requirements for large power transformers are set out in Tables I.7, I.8 and I.9.There may be specific instances where the replacement of an existing transformer, or the installation of a new one, meeting the applicable minimum requirements set out in Tables I.7, I.8 and I.9 would result in disproportionate costs. As general rule, costs can be considered to be disproportionate when the extra transportation and/or installation costs of a Tier 2 or Tier 1, as applicable, compliant transformer would be higher than the net present value of the additional avoided electricity losses (tariffs, taxes and levies excluded) over its normally expected service life. This net present value shall be calculated based on capitalised loss values using widely accepted social discount rates (*).

Figure 2.12 Extract from the Commission Regulation (EU) 2019/1783 defining the mechanism for large power transformers (Continued)

> In those cases, the following fall-back provisions apply:
>
> As of the date of application of Tier 2 requirements (1 July 2021), when the one-to-one replacement of a large power transformers in an existing site entails disproportionate costs associated to its transportation and/or installation, or is technically infeasible, the replacement transformer is, exceptionally, only required to comply with Tier 1 requirements for the given rated power.
>
> Furthermore, if the cost of installing a replacement transformer complying with Tier 1 requirements are also disproportionate, or where no technically feasible solutions exist, no minimum requirements shall apply to the replacement transformer.
>
> As of the date of application of Tier 2 requirements (1 July 2021), when the installation of a new large power transformer in a new site entails disproportionate costs associated to their transportation and/or installation, or is technically infeasible, the new transformer is, exceptionally, only required to meet Tier 1 requirements for the given rated power.
>
> In these cases, the manufacturer, importer or authorised representative responsible for placing on the market or putting into service the transformer shall:
>
> include in the technical documentation of the new or replacement transformer the following information:
>
> — address and contact details of the commissioner of the transformer,
>
> — the specific location where the transformer is to be installed,
>
> — the technical and/or economic justification to install a new or replacement transformer that does not comply with Tier 2 or Tier 1 requirements. If the transformer(s) were commissioned by a tendering process, all the necessary information regarding the analysis of bids and the award decision, shall also be provided,
>
> — notify the competent national market surveillance authorities.

2.3.1.2 Disproportionate costs mechanism for medium power transformers

At present the Commission Regulation (EU) 2019/1783 has concessions for derogation from Tier 2 to Tier 1 for one-to-one replacements of medium power transformers. Disproportionate costs need to be proven by the manufacturer, importer or authorised representative responsible for placing on the market or putting into service the transformer.

The Commission Regulation (EU) 2014/584 did not include any concessions for medium power transformers via the disproportionate costs mechanism.

The Commission carried out a review study that analysed the specific aspects set out in Article 7 of Regulation (EU) 2014/548. For reference, Article 7 is as follows:

Figure 2.13 Article 7 of the Commission Regulation (EU) 2014/548

Article 7

Review

No later than three years after the entry into force, the Commission shall review this Regulation in the light of technological progress and present the results of this review to the Consultation Forum. Specifically, the review will assess, at least, the following issues:

— the possibility to set out minimum values of the Peak Efficiency Index for all medium power transformers, including those with a rated power below 3 150 kVA,

— the possibility to separate the losses associated to the core transformer from those associated with other components performing voltage regulation functions, where this is the case,

— the appropriateness of establishing minimum performance requirements for single-phase power transformers, as well as for small power transformers,

— whether concessions made for pole-mounted transformers and for special combinations of winding voltages for medium power transformers are still appropriate,

— the possibility of covering environmental impacts other than energy in the use phase.

Based on that study, the Regulation was amended in the Commission Regulation (EU) 2019/1783 to include further exemptions via the mechanism for like-for-like replacements of medium power transformers.

Definition and methodology of the disproportionate costs mechanism for medium power transformers

For medium power transformers, the Regulation was amended in the Commission Regulation (EU) 2019/1783 to include exemptions for certain medium transformer like-for-like replacements via the disproportionate costs mechanism:

Figure 2.14 Extract from the Commission Regulation (EU) 2019/1783 adding medium power transformers into the disproportionate costs mechanism

The study analysed the economic viability of transformers compliant with minimum requirements set out in Tier 2 applicable as of July 2021 and found that lifecycle costs for compliant medium and large power transformers are always lower than Tier 1 compliant models, when these are being put into service in new installation sites. However, in specific situations where medium power transformers are being installed in existing urban substation locations, there can be space and weight constraints that affect the maximum size and weight of the replacement transformer to be used. Therefore, when the replacement of an existing transformer is technically infeasible or entails disproportionate costs, a regulatory relief should be justified.

The terms of this mechanism are expanded upon in the Commission Regulation (EU) 2019/1783 for medium power transformers, defining the mechanism and stating what needs to be provided to qualify for it:

Figure 2.15 Extract from the Commission Regulation (EU) 2019/1783 defining the mechanism for medium power transformers

> 'As of the date of application of Tier 2 requirements (1 July 2021), when the one-to-one replacement of an existing medium power transformer entails disproportionate costs associated with their installation, the replacement transformer is, exceptionally, only required to meet Tier 1 requirements for the given rated power.In this respect, installation costs are disproportionate if the costs of the replacement of the complete substation housing the transformer and/or the acquisition or rental of additional floor space are higher than the net present value of the additional avoided electricity losses (tariffs, taxes and levies excluded) of a Tier 2 compliant replacement transformer over its normally expected service life. The net present value shall be calculated based on capitalised loss values using widely accepted social discount rates (*).
>
> In this case, the manufacturer, importer, or authorised representative shall include in the technical documentation of the replacement transformer the following information:
>
> — Address and contact details of the commissioner of the replacement transformer
>
> — The station where the replacement transformer is to be installed. This shall be unequivocally identified by either a specific location or a specific installation type (e.g., station or cabin model)
>
> — The technical and/or economic justification of the disproportionate cost to install a transformer that is only Tier 1 compliant instead of a Tier 2 compliant one. If the transformers(s) were commissioned by a tendering process, all the necessary information regarding the analysis of bids and the award decision shall be provided.
>
> In the above cases, the manufacturer, importer or authorised representative shall notify the competent national market surveillance authorities.

From the above extracts, the definition of disproportionate costs for medium transformers is defined in the Regulation. However, identically to the mechanism for large power transformers, there is a practicality concern for the MSAs to verify this as an economic calculation needs to be done to justify these costs, and it is a difficult mechanism to survey. Furthermore, although stakeholders support the derogation for when costs are disproportionate and/or it is physically infeasible, some stakeholders have criticised its lack of clarity.

2.3.1.3 PEI usage for medium transformers

Peak Efficiency Index (PEI) is obtained when no-load loss equals load, but it does not require a specific loading point. Instead, the PEI finds the point where the no-load loss equals the load loss and calculates the value.

Commission Regulation (EU) 548/2014 which was updated in 2019, defines the formula to be used for Pead Efficiency Index is shown in Figure 2.11.

Figure 2.16 Extract from Commission Regulation (EU) 548/2014 updated in 2019

The formula to be used for the Peak Efficiency Index calculation is:

$$PEI = 1 - \frac{2(P_0 + P_{co} + P_{ck}(k_{PEI}))}{S_r\sqrt{\frac{P_0 + P_{co} + P_{ck}(k_{PEI})}{P_k}}} = 1 - \frac{2}{S_r}\sqrt{(P_0 + P_{co} + P_{ck}(k_{PEI}))P_k}\ (\%)$$

Where:

P_0	is the no load losses measured at rated voltage and rated frequency on the rated tap
P_{co}	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_{co} is always zero)
P_{ck} (k_{PEI})	is the electrical power required by the cooling system in addition to P_{co} 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';

The PEI 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.

- The 2014 regulation defines 'Medium Power transformer' as a power transformer with a highest voltage for equipment higher than *1,1 kV, but not exceeding 36 kV and a rated power equal to or higher than 5 kVA but lower than 40 MVA.*
- *The energy efficiency requirements in 2014 regulation for "Medium Power transformer' was divided into 2 components:*
  - 1. Absolute values of maximum load losses & maximum no load losses with rated power <= 3150 kVA
  - 2. Peak efficiency index (PEI) with rated power > 3150 kVA
- The 2019 regulation defines 'Medium Power transformer' as a power transformer with all windings having *rated power lower than or equal to 3150 kVA, and highest voltage for equipment greater than 1,1 kV and lower than or equal to 36 kV;*
  - 1. Absolute values of maximum load losses & maximum no load losses with rated power <= 3150 kVA with slight changes
  - Peak efficiency index (PEI) with rated power > 3150 kVA is removed since the definition has changed.

The changes are as shown in Table 2.9.

Table 2.9 Small, medium and large transformer definitions

	Ecodesign Regulation 548/2014	**Ecodesign regulation 2019/1783**	**Proposed change in the latest draft of IEC60076-1 standard**
Small transformers	*Highest voltage for equipment not exceeding 1.1 kV*	*Highest voltage for equipment not exceeding 1.1 kV*	Highest voltage for consumer circuit (or equipment) of 1.1 kV, highest rated power of the highest rated winding <= 3150 kVA three phase, or <= 1050 kVA single phase
Medium transformers	*highest voltage for equipment higher than 1,1 kV, but not exceeding 36 kV*	*highest voltage for equipment greater than 1,1 kV and lower than or equal to 36 kV*	
	*and a rated power equal to or higher than 5 kVA but lower than **40 MVA***	*and rated power lower than or equal to **3150 kVA***	*highest rated power of the highest rated winding > 3150 kVA but <= 31.5 MVA three phase* *or*

	Ecodesign Regulation 548/2014	Ecodesign regulation 2019/1783	Proposed change in the latest draft of IEC60076-1 standard
			>1050 kVA but less than 10.5 MVA single phase
	medium power transformers with rated power ≤ 3150 kVA *Table I.1: Maximum load and no-load losses (in W) for three-phase liquid-immersed medium power transformers with one winding with Um ≤ 24 kV and the other one with Um ≤ 1,1 kV*	***medium power transformers with rated power ≤ 3150 kVA*** *Table I.1: 'Maximum load and no-load losses (in W) for three-phase liquid-immersed medium power transformers with one winding with Um ≤ 24kV and the other with Um ≤ 3,6 kV*	
	medium power transformers with rated power ≤ 3150 kVA *Table I.2: Maximum load and no-load losses (in W) for three –phase dry-type medium power transformers with one winding with Um ≤ 24 kV and the other one with Um ≤ 1,1 kV.*	**medium power transformers with rated power ≤ 3150 kVA** *Table I.2:* *Maximum load and no-load losses (in W) for three-phase dry-type medium power transformers with one winding with Um ≤ 24kV and the other with Um ≤ 3,6 kV*	
	medium power transformers with rated power > 3150 kVA <=40000 kVA *Table I.4: Minimum Peak Efficiency Index (PEI) values for liquid immersed medium power transformers*	*NA*	
	medium power transformers with rated power > 3150 kVA <=40000 kVA Table I.5: Minimum Peak Efficiency Index (PEI) values for dry type	*NA*	

	Ecodesign Regulation 548/2014	Ecodesign regulation 2019/1783	Proposed change in the latest draft of IEC60076-1 standard
	medium power transformers		
Large 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.*	*Highest rated power of the highest rated winding > 3150 kVA or a highest voltage for equipment greater than 36 kV*	*Highest rated power of the highest rated winding > 31.5 MVA three phase or >10.5 MVA single phase*

2.3.1.4 A review of the technoeconomic aspects of Ecodesign

Whilst considering regulation under Ecodesign, aspects such as the energy efficiency, the consumer purchase price, the materials included in the manufacture, the costs of installations, repair, and the end-of-life considerations. There are multiple potential methodologies to determine this, which will be considered here.

2.3.1.5 Requirements for reverse flow power transformers

Transformers will need to cope with the increasing expansion of sustainable and renewable generation within the grid system in consideration of consumers and the bidirectional flows of energy within the transformer. Traditionally, power transformers would feed power unidirectional into the grid. However, with the increasing number of renewables on the grid at varying sizes and locations this has meant transformers are having to put power back into the grid, which has increasingly become a problem due to the increase of consumers The unpredictable nature of renewable energy sources means that in some circumstances the instantaneous power demand and supply do not always match, thus, there is insufficient energy storage capacity at the renewable source which leads to a reverse in the power flow towards the grid.

2.3.2 Feedback/ Research results

2.3.2.1 Review the usage and methodology under the disproportionate costs methodology for large power transformers

Feedback from MSAs and Stakeholders

Feedback from 8 EU countries' MSAs has been that no disproportionate costs mechanism clause has been requested to use in their respective countries for Tier 2 power transformers.

One of the MSAs stated that they do not believe the clause to be effective, as it is too easy to replace the product without relevant authorities being aware, as surveillance of already installed products is difficult. Furthermore, it poses a loophole risk to allow Tier 1 transformers to be installed if they are sufficiently cheaper than the Tier 2 alternative. It is noted that the regulation should not allow for this as it requires application on a case-by-case basis. However, there is little evidence that this process is being followed.

Feedback from stakeholders has been predominantly that the disproportionate costs mechanism and the procedure to apply to MSAs for concessions is not sufficiently clear, particularly from the customer and institutional bodies' points of view. The lack of clarity in the process also makes the administrative costs of the procedure higher. Albeit defined in the regulation, it is for the manufacturers to make the administrative request for exemption. Yet, it is the utilities who are best placed to make this submission, as the case for disproportionate cost is around installation and transportation, which are operations conducted generally by the utilities.

The lack of evidence that it has been used, as well as its lack of clarity, has driven some stakeholders to question the need for it.

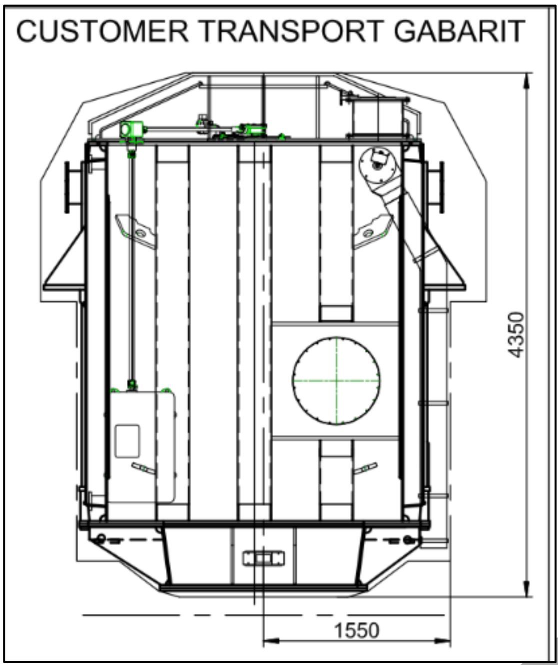
Stakeholder feedback in support of the mechanism

RTE, the transmission network association and operator of large transformers, has 9 standardised models that are currently installed in France. They do not use this derogation in order to keep the standardised models, which make it possible to build up a shared national stock of spare parts for transformers, which avoids the need to have a spare transformer per substation. The greater material impact is largely offset by not needing spare transformers in the national stock. This ensures that if there is a fault, the system can be repaired quickly. Furthermore, standardisation makes it possible to optimise the qualification phase, saving time and work on qualifying a transformer for each specific site.

However, speaking on behalf of the ENTSO-E, they are in favour of maintaining the disproportionate cost mechanism. The main concerns here are around transportation, where the stakeholder mentioned anecdotal evidence of the mechanism being used for remote locations. The alternative to the disproportionate cost mechanism could sometimes be overcome by building the transformer and factory on the site. Building them on site is approximately twice as expensive, thus not resolving the need for a spare transformer or the transportation problem.

The transport of these large transformers, weighing up to 210 tonnes, presents several constraints, expanded upon in Phase 2, Section 4.2.3. It can cost up to €1 million per transformer to transport it to its substation. Furthermore, the size of these large transformers makes them physically infeasible to fit in width on railways and many roads, and too heavy to pass over certain bridges. The size of a 170 MVA transformer is compared to the size of a standard French railway gauge below in Figure 2.17.

Figure 2.17 Comparison between railway gauge and the actual size of a 170 MVA transformer[88]



The Tier 2 requirements have more than doubled the transport costs for their transformers, and beyond Tier 2, transport becomes expensive and physically infeasible. They may be too heavy to pass over bridges, or too large to fit the gauge of a train or railroad.

If there was no derogation, a solution to transportation and on-site building issues is to install two smaller transformers that are able to be transported to the site. However, the higher the unit power of the transformer is, the more efficient it is in terms of losses and materials. The smaller transformers may be individually efficient and comply with the regulation, but together produce more losses and use more raw materials than a single, larger three-phase power transformer. Therefore, without the derogation, the transmission networks can find alternatives with regards to transport by using smaller transformers, but these are less efficient.

2.3.2.2 Review the usage and methodology under the disproportionate costs methodology for medium power transformers

Feedback from MSAs and stakeholders

Identically to the large power transformer mechanism, feedback from 8 EU countries' MSAs has been that no disproportionate costs mechanism clause for medium power transformers has been requested to use in their respective countries for Tier 2 medium power transformers.

One of the MSAs stated that they do not believe the clause to be effective, as it is too easy to replace the product without relevant authorities being aware as the market surveillance of already installed products is very difficult. Furthermore, it poses a loophole risk to allow Tier 1 transformers to be installed if they are sufficiently cheaper than the Tier 2 alternative. It is noted that the market size for

[88] Source: RTE feedback

medium transformers is significantly larger than large power transformers, making this mechanism even more difficult to implement and regulate.

Feedback from stakeholders has been predominantly that the disproportionate costs mechanism and the procedure to apply to MSAs for concessions is not sufficiently clear, particularly from the customer and institutional bodies' points of view.

As with the large transformer derogation, the lack of clarity in the process also makes the administrative costs of the procedure higher. Albeit defined in the regulation, it is for the manufacturers to make the administrative request for exemption. Yet, it is the utilities who are best placed to make this submission, as the case for disproportionate cost is around installation and transportation, which are operations conducted generally by the utilities.

Managing spares was also an issue because of the requirement for specific location. The 'cabin model' may be defined as where a transformer is placed inside an enclosure of Glass Reinforced Plastic (GRP)/ brick enclosure/ or any other enclosure type commonly used. Cabin models pose a challenge as it is placed inside an enclosure and has space constraints. Therefore, replacing a transformer in the cabin may pose a challenge in terms of efficiency, as requiring a higher tier performance may result in a larger and heavier device which doesn't fit within the enclosure.

A summary of stakeholder concerns for the feasibility of the mechanism is as follows:

- There are no clear guidelines to justify or present disproportionate costs. There can be any interpretation at any level.
- Many stakeholders also submitted that they are not aware of the number of cases where a concession for disproportionate costs was applied, which may imply it hasn't been used.
- Also, the responsibilities of the manufacturer versus the utility must be clearly defined.

It is noted that guidelines for justifying and presenting disproportionate costs are provided in the Regulation, and that it states that it is the manufacturer's responsibility. Stakeholder feedback suggests that this needs to be more clearly and accessibly written out for all stakeholders to implement them.

Stakeholder feedback in support of the mechanism

One stakeholder, in support of the mechanism, provided quantitative information on additional installation costs involved in one-to-one replacements. According to them, these costs generally significantly outweigh the value arising from loss savings from a more efficient transformer.

In the previous preparatory study on Tier 2 levels for a 400 kVA medium power transformer, the more efficient transformer saved €1,100 in losses over a 40-year period. Therefore, for costs to not be disproportionate, the installation costs associated with the one-to-one replacement should not be more than €1,100. It is noted that this amount saved is expected to be larger due to the price of electricity having risen since the study took place.

If the larger, more efficient transformer can no longer fit through the steel door of some substations, or into underground vaults, the costs of installation would be very high. This is due to:

- The need to switch out the substations.
- Necessary civil works to enlarge the size of the door opening.
- Designing and purchasing a new bespoke door to fit the new transformer.

Stakeholder feedback estimated these costs in the realm of €5,000. For other cases where the substation would not fit through the existing opening into an underground vault, the costs could rise to €15,000 per substation if a vault ceiling/floor needs to be redesigned. This is due to the high safety considerations, and thus rigorous technical engineering design and civil works would be necessary. Costs could rise to over €25,000 if the transformer is too large to be retrofitted in an existing packaged substation due to the need to remove the existing substation and installing a new one. The previous substation would need to be scrapped due to its short lifetime, particularly after being physically relocated.

The installation cost could therefore be up to 25 times the value of the losses saved. The disproportionate costs derogation would be justifiable in this case, if it could be enforced properly.

2.3.2.3 PEI usage for medium transformers

At present, PEI is currently only used for large transformers.

PEI provides more flexibility in the regulation as the efficiency is determined wherever the peak occurs. PEI simply sets a peak efficiency, wherever the peak may be. This would be irrelevant of whether investment is made to reduce core losses or winding losses. There are different incentives for manufacturers and utility with regards to efficiency and PEI.

PEI favours the utility who know about the desired usage. Separate core and winding losses favour the manufacturer who can predict material needs more accurately, with the production of a standardised product.

Manufacturers can buy the materials in advance and the utility is likely to tell the manufacturer to quote a price. With fixed losses the manufacturers can standardise their products, which leads to streamline their manufacturing process and also in standardising the material purchasing.

The PEI is set by the regulation but in case where the utility specifies the peak and the PEI value, then this should result in the most efficient product spec for its usage. However, it would be more difficult for the manufacturer to meet this requirement as materials standardisation would not be feasible.

From a regulatory perspective, the PEI approach could result in a situation where there is a mismatch between where the transformer is eventually applied or used, the average load may not match where the efficiency peak is set.

Medium power transformers have the highest usage (highest sales figure)[89] in the EU and the rationale behind not using PEI for medium transformers is:

<u>Case: If PEI is used at the *only* metric for efficiency</u>

- 1. For a given PEI several combinations of no-load loss (P0) and load loss (Pk) with different optimum equivalent load factor (kPEI) are possible.

[89] PREPARATORY STUDY FOR THE REVIEW OF COMMISSION REGULATION 548/2014 ON ECODESIGN REQUIREMENTS FOR SMALL, MEDIUM AND LARGE POWER TRANSFORMERS- 2017

- 2. However, if we look at these several combinations of P0 & Pk only one might be compliant with losses in *absolute numbers as set out in regulation*.
- 3.Therefore, PEI, metric would result in many other combinations which are non-compliant for their utilisation level but meet the PEI criteria.
- 4.A loophole which would emerge from only requiring a minimum PEI to be specified is that the lowest CAPEX design could be specified simply by choosing a very low load factor at PEI (kPEI) within a tender process, This could occur by underspecifying the optimum load factor in the tender compared to the expected equivalent load factor in use, e.g. specifying kPEI=0.1 while keq=0.3 means that a 400 kVA (P0=430W, Pk=4600W) will run at real efficiency 98.83% instead of its optimum 99.30% but can result in a low cost design. Designing for a low optimum load factor (kPEI) means that one does not need to invest in conductor material (e.g., less copper) and this will therefore lower the transformer CAPEX.
- The idea behind not using PEI for all medium transformers was that most of them are used in distribution network and are manufactured in large numbers whereas large transformers is a niche market. (Sales figure of Distribution transformer for 2020 in EU was 173,891)[90]
- The PEI formula is flexible given that a minimum load factor must be specified with PEI.
- In the absence of minimum load factor, PEI can be manipulated as to achieve the minimum required PEI at less efficiency.
- It can be tested for gameability by devising a methodology where a minimum load factor can be calculated where the required PEI is met with maximum efficiency.

Stakeholder feedback summary:

- Majority of the stakeholders are of the opinion that PEI for medium power transformers is not the best option, as these operate over a wide range of load. If PEI is introduced then overall energy efficiency would be lower, losses higher.
- Also, the fixed losses lead to standardisation of the market. Introducing PEI will lead to de-standardisation of the market.

- While some of the stakeholders are in favour of combination of PEI and losses for Medium Power transformers as it would help to optimise the design of transformers.
- Some other stakeholders are of the opinion that using only PEI without absolute values is a good option as it gives more flexibility and possibility to optimise the design. Also, it would help to design the transformer as per the application.

2.3.2.4 Techno economic methodologies to review Ecodesign considerations for transformers

The Ecodesign methodology is designed to account for the energy consumption of a device, the material components during the manufacturing process, the packaging, the end-of-life of the device, and the total cost to the end user.

[90] PREPARATORY STUDY FOR THE REVIEW OF COMMISSION REGULATION 548/2014 ON ECODESIGN REQUIREMENTS FOR SMALL, MEDIUM AND LARGE POWER TRANSFORMERS -2017

Stakeholders suggested that the study looked into the use of the measures:

- Total Cost of Ownership (TCO)
- Alignment with the UN sustainability goals
- An LCA analysis
- Environmental Conscious Design considerations
- Digital Product Passports

Furthermore, the EN standard 50708-1-1 has recently been amended to include new ratings with regards to sustainability, including not only energy performance but also material efficiency concerns. A standardized quantitative parameter or rating to bring these together is under study.

Following the Ecodesign Methodology and the Ecoreport tool, some of these considerations are already included. The methodology determines a Base case for an average transformer product, which will represent the average material composition, energy efficiency, utilisation rates and end of life practices. This will then also be represented against the cost to the consumer, allowing for a TCO analysis to be completed. Different impacts are calculated for aspects such as greenhouse gas emissions, but also toxicity and water usage, which accounts for some of the UN sustainability goals, and LCA considerations. Further LCA concerns are difficult to evaluate as this analysis is done for the base case product and not for each product placed on the market.
Digital Product Passports (DPP) are currently not in scope of Ecodesign. However, the implementation may be covered under the powers of the upcoming Ecodesign Sustainable Products Regulation, and hence may become a useful mechanism for future Ecodesign regulation.

2.3.2.5 Are there requirements when using reversed power flows transformers due to increase of imbedded generation?

The increase in embedded generation (e.g., renewables at the distribution network level of the grid) is leading to increasing scenarios of reverse power flow (RPF) across electrical networks, which historically were designed for single direction flow, from large generators at transmission level, through step-down transformers to distribution networks and local circuits.

RPF scenarios could impact transformers throughout the network, e.g.:

- Domestic rooftop solar exports, reversing flow on 10 kV / 0.4 kV transformers within the distribution network.
- An excess of distributed wind and solar power to a distribution network, leading to reverse flow across 110 kV / 10 kV transformers into the transmission network.

RPF across transformers can lead to changes in the flux leakage pattern, core loss, the temperature of the core, metal parts and windings. These changes can lead to reductions in transformer life, as well as increases in losses from the transformer[91,92].

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[91] On the Effects of Solar Panels on Distribution Transformers | IEEE Journals & Magazine | IEEE Xplore

[92] https://www.mdpi.com/1996-1073/15/23/9238#:~:text=Results%20revealed%20that%20significant%20reversed%20power%20flow%20can,transformer%20results%20in%20an%20increase%20in%20winding%20losses

Reverse power flow can cause additional winding loses thus affecting the transformers insulation[93]. Consequently, the increased losses and thermal cycling that occurs because of bidirectional power flows reduces the life expectancy of transformers. This is caused by increases in the excitation voltage above the limits of a transformer leading to significant magnetising current increases and harmonics which ultimately causes significant core losses[94]. The life expectancy of transformers has been observed to reduce due to the impact of reverse power flows, in particular older transformers are more vulnerable to failure. This poses a more significant threat to aging transformer fleet in the EU, however it is considered that for a new transformer designed appropriately to match the system requirements these losses can be avoided[94].

As discussed, the stresses caused by a reversed power flow prematurely decrease the life expectancy of a transformer therefore, manufacturers have explored ways to withstand these stresses. One technique is to increase the steps for on-load tap changers, full-load voltages regulators, or reduced flux densities to compensate the over-voltage saturation of the core[95]. The harmonic stresses on a transformer can be reduced by integrated inductors and increased k-factor designs[94]. One of the major problems experienced in the electrical network is that often reverse power flows are not communicated across the network. Therefore, smart transformers which automatically monitor for example the voltages a transformer receives can help provide a better prediction of potential transformer failures[94].

Stakeholder feedback summary:

Many stakeholders are of the opinion that “reverse power flow” must be defined and its condition clearly set. Also, the RPF will impact the lifetime of the transformer. Reversed power flows may lead to increased loading and potential overheating of transformers. It might also require redesigning protection and control system to ensure safe and reliable operation. A transformer can handle both flows if properly designed and specified.

Also, for reverse power flow the transformers would need an on-load tap changer which might increase the cost of the transformers.

2.3.3 Recommendations

2.3.3.1 Concessions for disproportionate costs for large transformers

Certain insights from stakeholders suggest that this mechanism is needed. Building transformers on site is approximately twice as expensive, and transporting large transformers to the sites of installation is infeasible in many cases due to road and railway limitations.

However, the mechanism needs to be clarified and improved. Although the method of applying seems relatively straightforward in the regulation, surrounding information needs to be provided in a simplified, clear format such as an FAQ sheet.

Furthermore, the lack of evidence that it has ever been used, applied for, or exploited as a loophole suggest that either it is not being used at all, or it is not being enforced. Although numbers provided by stakeholders suggest that it is required, it

93 https://link.springer.com/article/10.1007/s40998-019-00300-9

94 der_reverse_power_flow_impacts.pdf (energycentral.com)

95 https://www.daaam.info/Downloads/Pdfs/proceedings/proceedings_2012/134.pdf

is recommended that it is removed as a derogation until it is improved or until evidence that it is being used is provided.

Provide solutions to simplify usage of mechanism for large power transformers

The disproportionate costs mechanism needs further clarification via an accessible and clearly defined FAQ sheet. This would essentially repeat the regulation, but in simpler terms. The Commission Regulation (EU) 2019/1783 does define what costs are defined as disproportionate, but it needs greater clarity particularly with regards to how to apply to MSAs. Utilities should be allowed to apply for the derogation too, as the case for disproportionate cost is around installation and transportation, which are operations conducted generally by the utilities. Furthermore, the FAQ should include a list of contacts to contact the respective countries' MSAs for applying.

Furthermore, based on MSA feedback, it needs to be clearer how to enforce the mechanism. It is difficult for MSAs to enforce a ruling for products once they are already on the market. Comprehensive, exhaustive guidelines need to be provided that state exactly what is required in the application for this derogation, as well as how to apply to MSAs. Essentially, this section in the Regulation needs to be expanded upon in the form of the aforementioned FAQ:

Figure 2.18 Extract of the Commission Regulation (EU) 2019/1783 listing the requirements to apply for the mechanism

> In these cases, the manufacturer, importer or authorised representative responsible for placing on the market or putting into service the transformer shall:
>
> include in the technical documentation of the new or replacement transformer the following information:
>
> — address and contact details of the commissioner of the transformer,
>
> — the specific location where the transformer is to be installed,
>
> — the technical and/or economic justification to install a new or replacement transformer that does not comply with Tier 2 or Tier 1 requirements. If the transformer(s) were commissioned by a tendering process, all the necessary information regarding the analysis of bids and the award decision, shall also be provided,
>
> — notify the competent national market surveillance authorities.

Additionally, a labelling system on exempt transformers would be useful to provide transparency and clarity regarding the reasons for exemption, particularly concerning Tier 2 requirements. Currently, the requirement is only for the paperwork to be filled and kept by the MSAs, which is insufficient.

2.3.3.2 Concessions for disproportionate costs for medium transformers

Based on stakeholder feedback, it is likely that installation costs associated with like-for-like replacements are significantly larger than the monetary amount saved by a more efficient transformer. Therefore, this mechanism seems necessary.

However, likewise with large transformers, the mechanism needs to be improved if it is to be a viable, enforceable derogation. The lack of evidence that it has ever been used, applied for, or exploited as a loophole suggests that either it is not being used at all, or it is not being enforced.

Numbers provided by stakeholders suggest that it is required. However, due to the lack of evidence of it being used, (which due to the widespread use of medium power transformers, should result in a high number of applications), it is recommended that it is removed as a derogation until it is improved or evidence is provided. This is especially important for medium transformers due to their significantly larger market size compared to large transformers, and thus a higher administrative workforce is required by MSAs to deliver this. A third party may be required to process the volume of applications if it were to be used in future.

Provide solutions to simplify usage of mechanism

Similarly to this mechanism for large power transformers, the disproportionate costs mechanism for medium transformers needs further clarification. The Commission Regulation (EU) 2019/1783 does define what costs are defined as disproportionate, but it needs greater clarity particularly with regards to how to apply to MSAs. An adequate FAQ needs to be provided with MSA contact information, and if the MSAs cannot process the volume of applications, then the contact of a relevant third party.

Furthermore, based on MSA feedback, it needs to be clearer how to enforce the mechanism. It is difficult for MSAs to enforce a ruling for products once they are already on the market. Thus, guidelines need to be developed on this to not risk a loophole forming that allows Tier 1 transformers to be installed without sufficient justification. A requirement for the site of installation to be engraved onto the transformer itself would be a potential solution for this, hence not allowing for the mechanism to be abused as a loophole.

Comprehensive, exhaustive guidelines need to be provided that states exactly what is required in the application for this derogation, as well as how to apply to MSAs. Essentially, this section in the Regulation needs to be expanded upon:

Figure 2.19 Extract of the Commission Regulation (EU) 2019/1783 listing the requirements to apply for the mechanism

In these cases, the manufacturer, importer or authorised representative responsible for placing on the market or putting into service the transformer shall:

include in the technical documentation of the new or replacement transformer the following information:

— address and contact details of the commissioner of the transformer,

— the specific location where the transformer is to be installed,

— the technical and/or economic justification to install a new or replacement transformer that does not comply with Tier 2 or Tier 1 requirements. If the transformer(s) were commissioned by a tendering process, all the necessary information regarding the analysis of bids and the award decision, shall also be provided,

— notify the competent national market surveillance authorities.

2.3.3.3 PEI usage for medium transformers

The medium transformers have one of the largest number of installations in the EU and they affect the grid losses to a significant extent.

The absolute value of losses for medium transformers is recommended since using only PEI may give several combinations of no-load loss (P0) and load loss (Pk) with different optimum equivalent load factor (kPEI). However, if we look at these several combinations of P0 & Pk only one might be compliant with losses in absolute numbers as set out in regulation.

Also, absolute values of losses are important for market standardization.

Therefore, it is recommended to keep only absolute values of losses for medium transformers without PEI.

2.3.3.4 Techno economic methodologies to review Ecodesign considerations for transformers

The study will progress under the analysis scope of the Ecodesign methodology. However, Phase 2 sensitivity analysis will be done to determine the TCO of the base cases and the suggested changes to the regulation, this will include the changes to material content, but also the effects of increased lifetime through recycling.

2.3.3.5 Are there requirements when using reversed power flows transformers due to increase of imbedded generation?

As the grid would eventually keep getting greener (i.e., more renewable sources being connected to the grid) there would be growing need for reversed power flows transformers.

It is recommended that Reverse Power Flow (RPF) be defined to ensure manufacturers can accommodate appropriate protection and control systems, minimising the effects of RPF. This would help in safe and reliant operation. 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.

2.4 Regulation definitions and scope

d) the possibility to adopt a technology-neutral approach to the minimum requirements set out for liquid-immersed, dry-type and, possibly, electronic transformers;
f) the appropriateness of the exemptions for transformers in offshore applications;
g) the appropriateness of the concessions for pole-mounted transformers and for special combinations of winding voltages for medium power transformers;
p) functional categorisation of power transformers (including conventional transformers, overload transformers and fire performant transformers and any others that the contractor may suggest).

2.4.1 Background

2.4.1.1 Offshore exemption

The Ecodesign regulation 2019/1783 on small, medium and large power transformers sets out requirements for power transformers in the EU with a minimum power rating of 1 kVA used in 50 Hz electricity transmission and distribution networks or for industrial applications. "*Transformers specifically designed to be installed on fixed or floating offshore platforms, offshore wind turbines or on-board ships and all kinds of vessels*" are specifically exempt from the regulation.

2.4.1.2 Pole-mounted transformer exemptions

The regulation defines "*medium power pole-mounted transformer*" as *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.* These medium power pole-mounted transformers are subject to a concession, for one-to-one replacements of existing medium power pole-mounted transformers with a power rating between 25 – 400 kVA. Maximum allowable losses for these transformers follows those set in Table 2.10, where those not explicitly mentioned are obtained by linear interpolation or extrapolation.

Table 2.10 Maximum load and no-load losses (in W) 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)

The Regulation states that '*for one-to-one replacement of existing medium power pole-mounted transformers, the manufacturer, importer or authorised representative shall include in the technical documentation of the transformer the following:*

- *the address and contact details of the commissioner of the replacement transformer;*
- *the station where the replacement transformer is to be installed. This shall be unequivocally identified either by a specific location or an specific installation type (e.g. technical description of the pole).*

In the above cases, the manufacturer, importer or authorised representative shall notify the competent national market surveillance authorities.'

New pole-mounted transformers being installed are not included in this exemption.

2.4.1.3 Concessions to medium transformers with special combinations of winding voltages

The regulation sets out concessions for medium transformers with special combinations of winding voltages. 'Dual voltage transformer' is defined as a 'transformer with one or more windings with two voltages available in order to be able to operate and supply rated power at either of two different voltage values'. The concessions for these transformers are defined below in Table 2.11.

Table 2.11 Correction factors applied to the load and no load losses for medium power transformers with special combinations of winding voltages

Special combination of voltages in one winding		Load losses (P_k)	No load losses (P_o)
For both liquid immersed and dry type			
Primary highest voltage for equipment Um ≤ 24kV	Primary highest voltage for equipment Um ≤ 24kV	No correction	No correction
For liquid immersed			
Primary highest voltage for equipment Um = 36kV	Secondary highest voltage for equipment Um ≤ 3,6 kV	10 %	15 %
Primary highest voltage for equipment Um = 36kV	Secondary highest voltage for equipment Um > 3,6 kV	10 %	15 %
For dry type			
Primary highest voltage for equipment Um = 36kV	Secondary highest voltage for equipment Um ≤ 3,6 kV	10%	15%
Primary highest voltage for equipment Um = 36kV	Secondary highest voltage for equipment Um > 3,6 kV	15%	20%

2.4.1.4 A technology neutral approach

Liquid-immersed and dry-type transformers currently have minimum requirements which are different, but not hugely so, across different kVA ratings in various programmes globally. Comparison of MEPS for liquid-immersed and dry-type transformers of different kVA ratings for different global programmes is covered in section 2.1.2.2.

2.4.1.5 Functional categorisation

Transformers are categorised in the Ecodesign regulation according to their size: small, medium and large. These are split according to their voltage and power ratings. Functional categorisation is not yet something implemented in the regulation, apart from some specific exemptions.

2.4.2 Feedback/ Research results

2.4.2.1 Appropriateness of the exemptions for transformers in offshore applications

Transformers in offshore applications are used in a wide range of processes, from the distribution of electricity to platforms used for the extraction of crude oil from oil fields, or as collector step-up transformers on fixed or floating offshore platforms, to being used on ships and wind-turbines. Such transformers are often exposed to harsh, marine environments.

Within the nacelle

These are typically step-up transformers for each wind turbine, ranging from 3 MVA to 20 MVA. They are usually dry type, 3-phase, and designed to be smaller, lighter and more salt resistant.

The turbine nacelle within a traditional wind power generation system is heavy, especially in offshore applications due to the large mass of the power frequency step-up transformer. The weight and volume of a 0.69/33 kV 2.6 MVA transformer are typically in the range of 6-8 tonnes and 5-9 m^3 respectively. A 10 MW direct drive permanent magnet generator weighs about 300 tonnes. The transformer is usually installed inside the nacelle together with other equipment, such as the generator and power converter, at a height of about 80 m[96].

The costs of the tower construction, turbine installation and maintenance of the turbine are significantly increased by the heavy and large size transformer. It greatly increases the weight and volume of the nacelle as well as the mechanical stress of the tower. 26% of the total component cost of the turbine is comprised by the tower, and on average 20% of the capital costs are associated with installation. 54% of the cost is therefore the blades and the interior electronics (transformer and generator).

The cost of installation and regular maintenance is high, with offshore wind farms requiring about 20% higher operating and maintenance cost compared with an onshore wind farm[23]. This is due to sea waves and very high winds damaging turbines, as well as them being difficult to access compared to onshore wind turbines.

The marketshare of offshore wind transformers is estimated to be 5-7% of the total annual European transformers market volume[97]. The market share is likely to remain significant, with much more capacity expected to be installed over the coming decades. Onshore wind farms have larger market share than offshore wind farms. This is due to onshore windfarms being more economical, with offshore

[96] https://ro.uow.edu.au/cgi/viewcontent.cgi?referer=&httpsredir=1&article=2081&context=eispapers1

[97] Stakeholder qualitative questionnaire feedback

windfarms having higher maintenance and installation costs due to the sea being a more hostile environment and less accessible. The market share in 2019 for both onshore and offshore wind turbines is presented in Table 2.12 below:

Table 2.12 Market data of offshore and onshore wind turbines in 2019[98]

Type of Wind Turbine	New Installations (MW)	Total Capacity (MW)	Average Size of New Installed Turbines (MW)
Onshore	9,552	178,162	3.1
Offshore	3,627	22,069	7.2

Offshore turbines are larger on average than onshore turbines, as onshore turbines are limited by obstructions such as buildings and trees.

On platforms, on-board ships and all kinds of vessels

Offshore transformers on platforms are typically for the distribution of electricity to machinery involved in the extraction of crude oil from oil fields. Large offshore collection transformers, usually varying from 200 – 500 MVA, are also supported by large platforms. These are for bringing together the power from multiple offshore wind turbines, then stepping-up the voltage and sending it to the onshore grid over connecting cables.

The exemptions for these stem primarily from the need to meet compact dimensions and weight requirements for offshore platforms. For each additional tonne a transformer weights, an additional 1.5 to 2 tonnes of material is needed in the platform to support the transformer. The installation and maintenance of them is also complex, hazardous and expensive due to the hostility and inaccessibility of the sea.

The exemptions for transformers on-board ships and all kinds of vessels stem from similar reasons for transformers on platforms. These need to meet compact design dimensions and weight requirements of the ship or vessel.

2.4.2.2 Review of the exemptions for each offshore technology type

Stakeholder feedback has implied that MSAs have little oversight on what happens offshore. This may happen if the transformer is shipped directly from a foreign manufacturer and not via an EU port, and thus may not meet all EU regulatory requirements.

Within the nacelle

One stakeholder stated that removing the exemption for these transformers would support the coming need to replace equipment in place for existing wind turbines. Furthermore, it would facilitate the increasing demand of OEMs in higher rated equipment.

Another stakeholder shared this opinion, adding that the transformers used within the nacelle, 3-20 MVA, have the same space and weight constraints within the nacelle as onshore wind turbines of comparable capacity, which are not exempt.

[98] https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2019.pdf [extracted 15/04/2024]

However, offshore wind turbines are much larger than average onshore wind turbines. As shown previously in Table 2.12, the average power rating of new onshore wind turbines in the EU was 3.1 MW in 2019. The average power rating of new offshore turbines was 7.2 MW, more than double the capacity of an average onshore wind turbine[99]. This is an increase from 2010 averages, where the average onshore and offshore wind turbines had capacities of 2.5 MW and 3.6 MW respectively[100]. The larger capacity of offshore wind turbines would justify the need for heavier and larger transformers, which are more difficult to fit within the nacelle. This adds further difficulties to the inaccessibility of offshore turbines compared to onshore turbines. Therefore, doing like-for-like comparisons between onshore and offshore wind turbines does not justify releasing exemptions.

A stakeholder in favour of these exemptions stated that offshore wind farms require about 20% higher operating and maintenance cost compared with onshore wind farms. This is due to them needing to be resilient to harsh environmental conditions including saltwater, corrosion and strong winds, as well as the inaccessibility of them.

On platforms, on-board ships and all kinds of vessels

Stakeholders have stated that it is difficult to justify including these into the regulation due to the expense of the platforms. The cost of space on an offshore platform is far higher than even that of a dense, urban area[101]. 1 tonne of transformer needs 1.5 to 2 tonnes of platform, hence a larger, more efficient transformer would result in significant platform expansion costs.

To illustrate this further, relations between power, weight and volume for power transformers with two windings have been approximated for designing offshore transformers on sea platforms[102]:

- 'Weight / power' is about 0.5 t/MVA
- 'Weight / volume' is about 2.38 t/m^3
- 'Power / weight' is about 2 MVA/t
- 'Power / volume' is about 5.8 MVA/m^3

Using these approximations, a 200 MVA transformer would weigh about 100 tonnes. The amount of platform required to support this larger transformer would be approximately 150 – 200 tonnes. This is assumed to be significant in terms of costs, but also material impact for the steel required to build the offshore structure.

Transformers on platforms need to be compact due to limited space available, light weight, and also need to be resilient to the harsh conditions out at sea. Therefore, stakeholders feel that the exemption is necessary, as the aforementioned points make installing a larger platform these platforms/transformers very expensive.

With regards to environmental impacts, additional materials would also increase the carbon footprint of the platform. Furthermore, increasing regulatory pressure on offshore transformers may be seen as a barrier to develop offshore wind resources, inhibiting renewable energy policies.

[99] https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2019.pdf

[100] https://www.brunel.net/en/blog/renewable-energy/onshore-offshore-wind

[101] 2024 stakeholder feedback

[102] https://publica-rest.fraunhofer.de/server/api/core/bitstreams/86ba12ed-0ab6-4a11-a83a-bc8d5c5c4dd3/content

With regards to transformers on-board ships and all kinds of vessels, no stakeholders have provided feedback on this. It is assumed that these exemptions are valid, due to needing to meet compact designs and weights to fit on these ships and vessels. Furthermore, it may incentivise ships not registering in the EU to avoid regulations.

2.4.2.3 Appropriateness of clause for pole-mounted transformers in regulations

Concessions are made for pole-mounted medium power transformers, as there is a concern that increased efficiency requirements would mean the transformers would be much heavier. This additional weight might be able to be taken by the existing pole, might require the transformer to need either a 2-pole + tray installation in a “H” formation, or to be replaced by a ground-mounted transformer facility, which has a cost of €25-30k against €4-9k for pole-mounted.[103] The ground-mounted facility would also have safety concerns. The concessions were made to ensure that pole-mounted transformers can be replaced like for like on a single pole.

When erecting pole-mounted transformers, the following estimated requirements apply depending on the weight and size of them[104]:

- A single transformer with a maximum weight of 400 kg, usually corresponding to a 1-phase 50 kVA capacity, can be mounted on a single bolt fixing.
- Transformers with a maximum weight of 1000 kg and up to 100 kVA can be mounted on a single pole platform.
- For transformers weighing up to 1400 kg, an ‘H’ pole platform or a single pole with an additional pole (lazy/stub leg) for support is needed.
- Transformers weighing from 1400 – 2000 kg (usually older and the new tier 2 315 kVA pole-mounted transformers are in this range), an ‘H’ pole platform is necessary, or with an additional supporting pole supported by gusset plates.

These are technical limits, but there may be local regulations for different countries that differ from these.

Market and geographical usage of pole-mounted transformers

Data from 2021 show that around 47% of distribution transformers in European utilities are pole-mounted, 53% are ground-mounted, of which 8% are either indoors or underground (and therefore have additional space restrictions)[105]. Many DSOs in Europe have large fleets of pole-mounted transformers, with 290,000 existing in France. The term distribution transformers here is assumed to refer to medium sized transformers. Considering the size of the pole-mounted distribution transformer market, the savings of shifting the savings would be non-negligible. There may be a case to review if the market can be encouraged to shift towards ground-mounted transformers.

The market of pole-mounted transformers is expected to grow due to the rising demand for electricity in both urban and rural areas, as well as the expansion of the infrastructure supporting the power grid. The derogation, however, only applies for like-for-like replacements, and thus new ones installed are out of scope with regards to this derogation.

[103] Stakeholder Qualitative questionnaire feedback

[104] https://www.nationalgrid.co.uk/downloads-view-reciteme/615348

[105] Microsoft Word - Ester Oil Penetration in Europe’s Transformer Market.docx (ptr.inc)

Pole-mounted transformers are particularly used for remote rural connections. In Ireland, they are used for small villages where there is only one 50kVA, 3-phase transformer. This is enough as the grid is designed to accommodate 1.5kW per household. However, with the transition to electric vehicles and heat pumps, 6-7kW per household may soon be required. For this reason, stakeholders indicate that rural transformer capacity is typically being shifted from 50kVA to 300kVA.[106] Pole-mounted transformers make up the majority of Ireland's fleet, with the 2017 market data being as follows[107]:

- Urban Areas: 20,000 Ground Mounted Three Phase
- Rural Areas: 20,000 Pole-mounted Three Phase, 210,000 Pole-mounted Single Phase (90% being 15 kVA and 10% being 33 kVA).
- Total amount of transformers: 250,000

Arguments for and against the concession

Feedback from stakeholders in support of maintaining these exemptions for one-to-one replacements is due to the impact of weight and dimensions. Replacing existing pole-mounted transformers with larger, more efficient ones would result in them not being feasible to fit with the current installation. Tier 1 increased the mass of transformers by 20-40% depending on the range[108]. Without these exemptions, DSOs would have to either change the pole structures, construct more stations with smaller capacity units, or evolve to ground-based substations capable of supporting the increasing weight of transformers. Overhead lines would also have to be moved or renewed.

Another stakeholder stated that these concessions are essential for dealing with the replacement of transformers in existing substations (3,500 transformers per year out of an installed base of 290,000 in France). Along with the cost of replacement, the environmental consequences of installing emergency power supply while replacing the pole need to be considered. The industrial consequences such as restoration time and intervention resources are also important factors.

In view of the volume of investments required to be made by DSOs to face the challenges brought by the energy transition, it is considered essential by them to maintain the exemptions to guarantee the continued use of the overhead lines and prevent the generation of additional costs in like-for-like replacements.

Feedback in support of removing concessions for pole-mounted transformers is that they have a significant market share of distribution transformers in Europe, and therefore should be regulated. Furthermore, stakeholders have said that there is a risk that having lower efficiency requirements for pole-mounted transformers would create a trend that DNOs have more of them in their fleet in order to have more transformers with lower efficiency requirements. However, as this exemption only applies to like-for-like replacements and not for new installations, this risk is not considered significant.

One stakeholder claimed that existing pole-mounted transformers with aluminium windings could be replaced by transformers with copper windings, which would result in a similar or lower weight, and smaller volume, while providing better energy

[106] Stakeholder meeting feedback

[107] Lot 2: Preparatory study for the review of commission Regulation 548/2014 on Ecodesign Requirements for small, medium and large power transformers, VITO, BIO, 2017

[108] 2024 stakeholder feedback

performance[109]. However, it is yet to be confirmed whether or not this would be sufficient for removing the need for an 'H' pole formation for a more efficient pole-mounted transformer.

There are regional differences, as although the Ecodesign regulation allows for concessions for pole-mounted transformers to up to 315kVA, France has a limit of pole-mounted transformers at 160kVA and of maximum weight of 560kg. Stakeholder feedback indicates that there are no Tier 2 compliant (without concession) transformers that would meet this pole-mounted weight criteria. However, conflicting feedback also states that utilities (notably in Spain) already require Tier 2 pole-mounted transformers without the concession, implying that either Spain uses a stronger pole type, or that these more efficient and light transformers can be manufactured.

Some stakeholders stated that the concession limit of 400kVA is too high as the current like for like replacements are typically of 50 to 200 kVA. Consideration could therefore be given to reducing the concession limit to 100 or 200kVA as higher loads (typically for >250kVA) are being moved to ground based setups.[110]

Cost differences among formations

One stakeholder provided quantitative information on this matter, stating that pole-mounted transformers cost between €2,000 - €6,000, and have smaller ratings, thus there is less scope for any loss savings[111]. A new 'H' formation two-pole platform may be necessary to support a larger transformer. New permission from the landowner would also be needed for the platform to be erected, the old pole and transformer to be scrapped, and the new one transformer reconnected using new wiring to the new action. They claim this would cost €4,000 at a minimum merely for the new platform and extension of wiring, which would not justify the requirement for extra loss saving that would be possible for a transformer with a rating that small.

The 2017 preparatory study compared the LCC of a 160 kVA single-pole-mounted transformer (which is compliant with the Tier 2 concessions for pole mounted transformers), with the equivalent value for a Tier 2 compliant H-pole-mounted liquid transformer. Table 2.13 contains an estimated prices for these based on that study's Tier 1&2 400 kVA BC 1 extrapolation. 'BC pole' is the single-pole-mounted transformer, and 'BC 2pole' is the H-pole-mounted transformer. For the H-pole-mounted transformer, the second pole costed €500, which was assumed to be the price for a street lighting pole.

[109] 2024 stakeholder feedback

[110] Tier 2 Fixed loss levels on distribution and power transformers implementation, Eurelectric proposals, Oct 2017 , tier_2_fixed_loss_levels_on_distribution_and_power_transformers_implementation-2017-030-0687-01-e-h-C7672AA6.pdf (eurelectric.org)

[111] 2024 stakeholder feedback

Table 2.13 LCC calculation comparison[112]

Base Case		BC pole liquid Tier2	BC 2pole liquid Tier2
transformer rating (Sr)	kVA	160	160
No load losses (P0)	W	270	189
no load class		C0-10%	Ao-10%
Load losses (Pk)	W	3102	1750
load class		Ck+32%	Ak
Auxiliary losses (Paux)	W	0	0
PEI	%	98,856%	99,281%
Load Factor (k) (=Pavg/S)	ratio	0,15	0,15
Load form factor (Kf)(=Prms/Pavg)	ratio	1,073	1,073
availability factor (AF)	ratio	1	1
Power factor (PF)	ratio	0,9	0,9
Equivalent load factor (keq)	ratio	0,18	0,18
load factor@PEI (kPEI)	ratio	0,295	0,329
no load and aux. losses per year	kWh/y	2365,2	1655,6
load losses per transformer per year	kWh/y	869,0	490,3
losses per year	kWh/y	3234,2	2145,9
transformer life time	y	25,00	25,00
kWh price no load and aux. Losses	€	0,15	0,15
kWh price load losses	€	0,15	0,15
CAPEX - transformer	€	**3 129,64**	**4 091,00**
losses per year	kWh/y	3234,2	2145,9
discount rate	%	**2%**	**2%**
electricity escalation rate	%	**0%**	**0%**
PWF	ratio	19,52	19,52
No load loss capitalization factor (A)	€/W	25,65	25,65
Load loss capitalization factor (B)	€/W	0,82	0,82
TCO A/B ratio	ratio	0,03	0,03
OPEX electricity	€/y	485,14	321,89
LCC electricity	€ /life	9 471,55	6 284,35
LCC total (excl. scrap@EOL)	€ /life	**12 601,19**	**10 375,35**

€2,226 is saved in the LCC total when using a more efficient, Tier 2 compliant H-pole-mounted transformer. This is based on the electricity price being €0.15 per kWh at that time. This saving would be higher in current times, due to the EU average price in the first half of 2023 for electricity by household consumers being €0.2890 per kWh, which is the weighted average using the most recent (2022) data for electricity by household consumers.[113] Scaling up the LCC electricity savings with the ratio difference between the electricity price in 2017 to the current electricity price, the total LCC saved today would be approximately €5179.

However, for like-for-like replacements, other costs will arise if a second pole needs to be installed (such as rewiring, gaining planning permission, etc.). It may also not be possible to identify a suitable position for a second pole to be placed beside the existing one, so that the existing pole would also need to be relocated, along with all the attachments. This can become very expensive. These may result in requiring it be relocated to a site further away, with greater losses on the associated circuits due to them being made longer.

Comparing this to the stakeholder estimations; a €2,226 LCC saving, as shown in Table 2.13, would not justify the costs of everything involved in the replacement, with a new platform and extension of wiring estimating to cost €4,000 at a minimum if required. This makes it likely that that the costs involved in the replacement would exceed what is saved in LCC by the more efficient transformer, even with the

[112] Lot 2: Preparatory study for the review of commission Regulation 548/2014 on Ecodesign Requirements for small, medium and large power transformers, VITO, BIO, 2017

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

[113] 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]

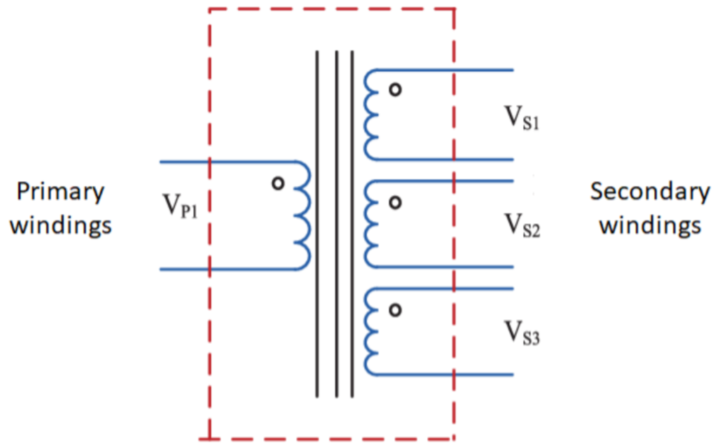
current electricity price being higher than what it was in 2017. Hence, in principle, there is no technical rationale to maintain this concession. It is rather a lock-in effect into existing procedures and installations for which this exemption is necessary to maintain.

2.4.2.4 Concessions to medium transformers with special combinations of winding voltages

Technology background

Multi-winding transformers are commonly used in applications that require multiple voltage levels, such as in power distribution networks, industrial machinery, and complex electronic systems. The primary advantage of multiple winding transformers is their ability to provide various output voltages from a single core, which enhances efficiency and reduces the need for multiple separate transformers. This technology enables better voltage regulation, improved load management, and enhanced flexibility in power distribution. Additionally, it supports galvanic isolation between different circuits, enhancing safety and reliability. The design considerations for multiple winding transformers include managing the magnetic flux distribution, minimizing core losses, and ensuring thermal stability, which are crucial for maintaining performance and longevity.

Figure 2.20 Primary and secondary windings in a multi-winding transformer[114]



Market data for dual windings transformers

It is expected that the multi-winding transformers market will grow at a CAGR of 11.8%.[115] The growing renewable energy sector and increasing demand for electricity are key factors driving this market growth. They are seen as essential for the efficient integration of renewable energy sources into the existing power grid. They are particularly useful for renewable energy due to it often being an intermittent power source, such as the output of solar energy differing between night and day. Smart grid technologies require advanced transformers for effective power management, and they are crucial in the power industry for transmitting and

[114] How Multi-Winding Transformers Are Used in Power Converters (cadence.com)

[115] https://github.com/RoccoManning/Market-Research-Report-List-1/blob/main/double-winding-transformers-market.md

distributing electricity in electric trains and trams to convert high voltage energy to lower voltage for traction motors.

Stakeholder feedback

Most stakeholders strongly advocate for the retention of correction factors, emphasising their crucial role in accommodating the unique characteristics of transformers with special voltage combinations. They stress that correction factors are indispensable for specific applications, where dual-winding transformers are vital for voltage conversion, such as transitioning between 10kV and 20kV networks, or shifting from 230V to 400V using dual secondary windings. Allowing for these higher voltage operations delivers efficiency savings on the grid level, and allows for the gradual change in an electricity grid to a higher voltage level without all customers having to change their voltage at once. These stakeholders contend that while it is technically possible to design transformers without concessions, doing so would result in larger and heavier units.

The example of Belgium is provided, whereby two secondary voltages 230V and 400V are connected to appropriate loads in parallel. New networks will only be at 400V, but it will take decades to switch all 230V customers to 400V. The change of network is done gradually, and the footprint of the substations is often kept fixed, meaning more efficient (and usually larger) transformers need to be fitted into the same spaces. Thus, stakeholders have indicated that without the correction factor to avoid costs of transformer efficiency and footprint concerns, new transformer installation costs would increase by 10-20%.[116]

In the case of Ireland, virtually every transformer has been produced with dual 20/10 kV windings since 1995[117]. This comprises around 50% of the 60,000 km of MV network currently converted to 20kV. It is stated that the shift from 10kV to 20kV saves 75% of all copper losses on the circuits leading from the transformers, which dual windings transformers enable the possibility of doing so[118]. Maintaining concessions for these transformers helps to ensure that the conversion to 20 kV remains economic. These transformers allow for the replacement of existing transformers with dual ratio units on the same pole and with the same connections. This accelerates the voltage uprating and minimises costs.

Certain stakeholders advocate for the elimination of special voltage combinations transformer exemptions, citing declining demand and the potential advantages of long-term voltage standardisation. They assert that transformers with special voltage combinations can attain equivalent efficiency levels as standard two-winding transformers from a technical perspective, therefore the regulation should not provide the concession, even if it results in higher prices due to winding complexity. It should also be noted that similar markets such as the US, do not have concessions in place for special voltage combination transformers.

Stakeholders have also indicated that there is limited presence of transformers with special voltage combinations, underscoring that applying correction factors to these transformers has minimal effects on overall loss levels. However, this may soon change as most grids are transitioning to higher voltages in order to increase system

[116] Stakeholder qualitative questionnaire feedback

[117] Stakeholder qualitative questionnaire feedback

[118] Stakeholder qualitative questionnaire feedback

efficiency. There may therefore be more special combination windings transformers installed to accommodate for these voltage shifts.

One stakeholder states that for MV combinations, the concession could be removed considering that the losses rule to be applied is strictly clear in the regulation. Regarding dual LV, based on the constraint on the design, they recommend keeping the concession as it is.

Similarly to pole-mounted transformers, one stakeholder states that for dual windings transformers, characterised by low ratings, the potential for incremental loss savings is small whereas the cost for any additional work necessary to replace existing transformers would be of a disproportionate magnitude, validated by Tier 1 and Tier 2 studies.

Additionally, the benefits arising from the use of such windings would also need to be taken into consideration, including the 75% saving in MV lines losses achieved with dual winding 20/10kV transformers, as well as more specialised transformers used to accommodate increased electrification in older LV urban networks. A stakeholder provided quantitative savings calculations arising from the conversion from 10kV to 20kV: at 20kV losses are reduced to a quarter (i.e., 75% savings in line losses) of what they would be at 10 kV. When moving from 10kV and 55A, to 20kV and 27.5 A, losses are reduced from 55^2R to 27.5^2R. Dual winding transformers allow for this change to be done gradually without the entire grid having to increase their voltage at once, which would delay benefits that arise from this change in voltage. This showcases the usefulness of these transformers.

2.4.2.5 A technology neutral approach

Currently, liquid and dry-type transformers have separate efficiency requirements. With the Regulation setting out the efficiency requirements for liquid and dry-type power transformers in terms of its energy performance only. At the time of writing this review the IEC 60076-1 standard is currently under review. Within the draft version of this standard, it can be seen that the IEC TC14 has adopted a technology neutral approach when defining a power transformer. It has been communicated with the study team that although this standard is currently in draft form and not yet published, a technology neutral approach is the direction in which the TC14 wishes to move the standard forward.

The concept for technology neutral approach is more relevant if specifying what the transformers are being used for i.e., their functionality.

- The current regulation specifies different MEPS for ‘liquid-immersed transformer’ and ‘dry-type transformer’. This approach was taken to avoid excessively high cost where specific performance levels- such as fire-safe behaviour and leak-proof design were required. Dry-type technology was probably the only technology available for achieving the required fire behaviour at the time when the regulatory process started[119].
- New technologies are emerging or are expected to emerge, providing the same performance that had been exclusive to one particular technology until recently. Examples include electronic power transformers and ester-insulating liquids. Excluding these emerging technologies from the scope of the Regulation could introduce unfair competition for the existing types of transformers on the market. Since electronic power transformers are providing the same function as power

[119] https://hrcak.srce.hr/file/443567

transformers however, they would not fit within the scope of the Regulation. Therefore, electronic transformers would not be required to meet the regulatory performance requirements. For example, if the Regulation introduced stricter MEPS this would further hinder the Regulation's eligible transformers market.

- Drawing comparisons between maximum-load losses and no-load losses are provided in the below tables. It is the ratio of maximum-load losses (Table 2.14and no-load losses (Table 2.15) allowed for dry-type transformer under Tier 1 of regulation (EU) No. 2019/1783, and those allowed for liquid-filled transformer.

Table 2.14 Ratio of Maximum load losses for dry-type transformer to liquid-filled transformer under Tier 1 of regulation (EU)No. 2019/1783

Rated Power(kVA)	Load losses (Liquid filled)	Load losses (Dry type)	% variation of load losses for dry type to liquid-filled
50	1100	1700	155%
100	1750	2050	117%
250	3250	3800	117%
400	4600	5500	120%
630	6500	7600	117%
800	8400	8000	95%
1000	10500	9000	86%
1250	11000	11000	100%
1600	14000	13000	93%
2000	18000	16000	89%
2500	22000	19000	86%
3150	27500	22000	80%

Table 2.15 Ratio of Maximum No- load losses for dry-type transformer to liquid-filled transformer under Tier 1 of regulation (EU)No. 2019/1783

Rated Power(kVA)	No-Load losses (Liquid filled)	No-Load losses (Dry type)	% variation of No-load losses for dry type to liquid-filled
50	90	200	222%
100	145	280	193%
250	300	520	173%
400	430	750	174%
630	600	1100	183%
800	650	1300	200%
1000	770	1550	201%
1250	950	1800	189%
1600	1200	2200	183%
2000	1450	2600	179%
2500	1750	3100	177%
3150	2200	3800	173%

ISO/IEC standards formulated the performance principle: ‘whenever possible, requirements shall be expressed in terms of performance rather than design or descriptive characteristics like a technology’.

In general, this technology-neutral approach should be used to balance Ecodesign requirements with other performance factors. It should be taken into account when evaluating the adequacy of all upcoming regulatory documents and technical standards. The choice of performance factors to be included would first require rigorous investigation and diligent deliberation and might include but not necessarily – fire-safe behaviour, internal arc safety, leak-proof design, and noise restriction, maintainability, material efficiency, recyclability, among others. A technology neutral way of defining a ‘fire-safe transformer’ could be done in a way that allows technical standards to set maximum levels of flammability, emission of toxic substances and opaque smoke covering for example. This way the fire requirements do not favour certain types of transformers, but rather ensure all types of transformers are considered.

A technology-neutral approach and harmonised test procedures facilitate technological innovation along with fair trade conditions. Well-designed regulations and standards encourage trade, the execution of conformity assessments, performance level comparisons, technology transfer, and the adoption of best practices. Governments, as much as manufacturers, stand to gain from neutral, harmonised, consistent, and stable standards.

Benefits to governments include:

- The ability to incorporate innovative technical solutions;
- Reducing the number of exceptions in regulations;
- The ability to adopt a common set of upper thresholds that can be used for market pull programmes, such as labelling and incentive schemes; and
- Faster and less costly testing – for compliance and other purposes — since harmonised testing leads to a wider range of laboratories able to conduct product testing.

For manufacturers, having one harmonised test method with specified measurement uncertainties used by markets around the world will reduce testing costs associated with demonstrating regulatory or product labelling compliance. In an ideal world, every manufacturer would always conduct exactly the same tests in exactly the same way, and the results would be universally accepted as being accurate and representative of the performance of their product. A harmonised test method also means they can look forward to long-term rewards for innovative product designs.

There are few possible technology neutral scheme[120] as shown in Table 2.16.

Table 2.16 Possible technology neutral scheme

Requisite	MEPS	Applicable technologies
No particular requirement	Level 1	Liquid-filled, dry-type, and other emerging technologies
Fire performance without the presence of people	Level 2	Dry-type and other emerging technologies

[120] https://hrcak.srce.hr/file/443567

Requisite	MEPS	Applicable technologies
Fire performance/explosion proof (involving the presence of people)	Level 3	Dry-type, other emerging technologies
No environmental damage in case of leakage	Level 4	Ester-filled, dry-type, and other emerging technologies
Low noise	Level 5	Oil-filled, ester-filled, dry-type, and other emerging technologies
…	…	…

A technology neutral approach can also allow a suitable reference temperature to be determined when testing power transformers using the IEC 60076 standard. Currently, the Regulation states that the reference used during testing must correspond to the reference temperature mentioned in the IEC standard. However, the existing standard provides two ways of determining the reference temperature value. At present the standard provides two entry standards for oil immersed transformers allowing the manufacturer to choose the lowest reference temperature. Therefore, allowing the test to underestimate the losses of these types of transformers. A stakeholder explained that using a reference temperature of 75 °C instead of 85 °C can lead to a reduction of 4% in load losses. As a result, a bias can be created when comparing large power transformers since this is not based on comparable elements but rather the manufacturers choice of reference temperature during testing. Thus, the losses that are reported using different technologies can vary, impacting the transformers perceived efficiency.

Overall, the existing standards use of a choice of reference temperature is favouring one technology and therefore, effecting the market because oil-immersed transformers appear to be the greener technologies in terms of losses. However, oil-immersed technologies are not the greener technology and pose significantly more environmental impact than dry-type transformers.

To ensure that this aspect of the IEC standards testing methodology do not continue to favour oil-immersed transformers, the IEC standards adoption of a technology neutral approach has meant updates to the reference temperature are expected. The thermal capability of each part of the transformer's insulation system is indicated by the assigned thermal class of that part.

At present, the temperature rise limits given in IEC 60076-1:2011 are valid for transformers with solid insulation designated with a thermal class of 105 °C and applies to transformers immersed in mineral oil or synthetic liquid with a fire point not above 300 °C[121]. The limits refer to steady state conditions under continuous rated power, and 20 °C average yearly temperature of the external cooling medium. If not otherwise agreed between manufacturer and purchaser, the temperature rise limits given in IEC 60076-1:2011 shall be provided[122].

In contrast, the draft IEC 60076-1:2023 standard provides an additional thermal class of 120 °C. This new thermal class is to be assigned if a higher thermal class of material such as thermally upgraded kraft paper are used at all the parts of the winding where the temperatures for thermal class 105 °C are exceeded and the transformer sealing is such that moisture and oxygen in the insulating liquid are

[121] IEC 60076-1:2011

[122] IEC 60076-1:2011

expected to be retained at a low level over the lifetime of the transformer. Additionally, the manufacturer must make it clear to the user any maintenance requirements needed to maintain the conditions required to allow a thermal class of 120. A transformer may be assigned a lower thermal class (105 °C) than would be indicated by the insulation system used if the temperature rise and corresponding rated power for the lower thermal class are also assigned to that transformer.

Stakeholder feedback summary:

Some of the stakeholders are of the opinion that technology neutral approach won't be appropriate as these are different technologies and have different standards for each technology and also applications. Requiring dry type transformers to have same energy efficiency requirement as liquid immersed would result in increase in weight, cost and volume.

Also, fire resistance characteristic is also critical when selecting a transformer and its application. Different technologies have different applications, and each has its own advantages and disadvantages.

Some of the stakeholders submitted that the technology neutral approach is appropriate, and transformer should be selected based on functionality rather than technology as certain functionality can be provided by different technologies.

Regarding electronic transformers, some stakeholders submitted that the technology of electronic transformers is not mature enough at this point.

2.4.2.6 Functional categorisation

Current categorisation of transformers in the Ecodesign regulation is done for the size of the transformer (load rating and voltage), dry-type versus oil-immersed, and single versus 3-phase systems.

Nearly all of the stakeholders consulted agree with this approach, as these are based on physical characteristics of the transformers and additional categorisation may lead to confusion within the regulation. There are concerns that adding new categories might lead to a long list of exemptions, potentially undermining the main scope of the regulation. Some stakeholders advocate to look at technology-neutral requirements rather than introducing additional functional categories. Therefore, the recommendation would be for the Ecodesign regulation not to make functional categories, beyond those existing and those covered under the IEC 60076 standard.

Some stakeholders did suggest potential transformer categorisation based on function or applicability. These are listed here:

- **Overload Transformers**: designed for applications where they may be subjected to overload conditions, such as temporary high loads. This would allow for specific requirements tailored to transformers used in overload scenarios, optimising performance and safety. Overload capabilities are already defined under IEC 60076-7.
- **Ultrahigh Voltage Transformers:** designed for extremely high voltage applications, typically exceeding 800 kV, which are relatively rare but may have distinct requirements. This can accommodate for ultrahigh voltage transformers used in specialised applications. UHV transformers allow the efficient transmission of large amounts of electricity over long distances. The higher voltage levels enable a lower transmission loss over longer distances[123]. It is

[123] http://www.chinatoday.com.cn/ctenglish/2018/ln/202102/t20210226_800237464.html

especially useful for transmitting renewable electricity to large cities situated far from the source (such as a hydroelectric dam or solar farm). However, it is noted that these are covered under the PEI rules from the large transformers in Ecodesign, which are straightforward to meet at such voltages. There therefore is no need for this categorisation.

- **Fire Performant Transformers:** designed with enhanced fire safety features, particularly applicable to dry-type transformers. Fire performant transformers are defined by standard EN 60076-11 and are dedicated to dry type transformers, because other transformers cannot reach the required level of fire safety. Therefore, although there is a legitimate case to distinguish fire performant transformers, it seems these are already covered under the IEC standards and Ecodesign.
- **Transformers for Renewable Energy Applications:** specifically designed for use in renewable energy systems, such as wind turbines and photovoltaic plants. These could address the unique characteristics and requirements of transformers in renewable energy applications, promoting efficiency and reliability. However, providing special criteria to this category would prove difficult to differentiate with other generator capabilities, and hence difficult to monitor their end use is as intended.
- **Transformers for Rectifier Applications:** designed for use with rectifiers to provide a DC power supply. This category seems difficult to define as the distinction for them is their pairing with a rectifier, which is outside of the scope of Ecodesign.
- **Generators Excitation Transformers:** designed for excitation systems for large rotating machines, to help them meet appropriate performance standards. A definition for this type of transformer could not be identified, making their categorisation difficult.
- **Bank of Single-Phase Transformers:** configured as a bank of single-phase units, as opposed to traditional three-phase transformers. This could be for two or three, single-phase transformers are interconnected via a Delta or Star connection. This configuration can be useful instead of using a three-phase transformer, where there are size or weight constraints, allowing for three separate transformers to be transported independently rather than one large three-phase transformer.
- **Auxiliaries' Transformers for Nuclear Safety Applications:** used as auxiliaries in nuclear safety systems, requiring specific safety and performance criteria.
- **Fault Current Limiting Transformers:** designed for the purpose of limiting fault currents in electrical systems, which are typically used to improve safety and reliability of power distribution. It should be noted that transformers are often used for this application, it would therefore be difficult to identify designs specifically for this usage only.
- **Step-up Power Transformers for Electricity Production/Generation:** specifically used for stepping up voltage in electricity production or generation applications, often found in power plants to enhance efficiency of electricity transmission. As this is one of the typical transformer applications, this functional categorisation seems redundant. There are already concessions set for transformers with special windings configurations.

- **Transformers for Railway Feeding Systems:** designed for use in railway power supply systems.
- **Earthing or Grounding Transformers**: designed for earthing or grounding applications, often used to ensure electrical safety.
- **Transformers Specifically Designed for Explosion-Proof and Underground Mining Applications:** designed for use in hazardous or underground mining environments. These could warrant review but under the needs for safety, which would require additional protections to the transformer system. However, stakeholders would need to specify why this additional protection would change the internal mechanism of inside transformers.
- **Transformers Specifically Designed for Deep-Water (Submerged) Applications:** used in submerged or underwater applications. These may warrant review but under the needs for safety and isolation from the water. However, stakeholders would need to specify why this additional protection would change the internal mechanism of inside transformers.
- **Medium Voltage (MV) to Medium Voltage (MV) Interface Transformers up to 5 MVA:** designed for medium voltage interface applications with a capacity of up to 5 MVA. As the Ecodesign regulation currently has an allowance for special combination windings of up to 3.1MVA, this is categorization suggestion would need to review if this allowance should be brought up to higher rated power transformers.

2.4.3 Recommendations

2.4.3.1 Offshore exemption

For offshore transformers within the nacelle of offshore wind turbines, it is important to note that they have more than double the capacity on average than onshore wind turbines. If exemptions were removed and they needed to meet the current Ecodesign requirements, they would struggle to fit into the nacelle, and therefore result in the nacelle and overall turbine needing to be bigger. A like-for-like comparison with onshore wind turbines is not deemed appropriate due to onshore turbines being smaller on average, more accessible, and cheaper to maintain and install. It is recommended that the exemptions are kept, however they are worth reviewing in future, as it is a significant market share that is continuing to grow.

For offshore transformers on platforms, it is recommended that these exemptions are kept. The increased structural material that is required for larger transformers makes costs very high, as well as increasing the environmental impact when considering the additional steel. Furthermore, increasing regulatory pressure on offshore transformers may be seen as a barrier to develop offshore wind resources, inhibiting renewable energy policies.

2.4.3.2 Pole-mounted transformer concessions

It is recommended to keep the concession as is for like-for-life replacements, as the cost for replacements are estimated to be significantly more than what would be saved from a more efficient pole-mounted transformer. Consideration could be given to reducing the concession limit to 100 or 200kVA as higher loads (typically for >250kVA) are being moved to ground based setups.

However, these concessions need to be reviewed and enforced by MSAs. There has been no evidence from MSAs that this concession has been used. Thus, documentation for applying for this concession needs to either be kept or provided to another body, instead of being sent to MSAs due to a lack of bandwidth. A mark on a transformer indicating that it is specifically for a like-for-like replacement would be good to implement, avoiding confusion and the risk of loopholes forming. It is also recommended that an FAQ document is created to state the conditions when this concession can be used and the process for applying for it.

2.4.3.3 Concessions to medium transformers with special combinations of winding voltages

Stakeholder insights have strongly suggested that these concessions are necessary. They are crucial for the growing renewable energy sector, due to their effectiveness at handling intermittent sources of power. The 75% saving in MV lines losses achieved with dual winding 20/10kV transformers, which reduces losses from 55^2R to 27.5^2R, emphasises the usefulness of these transformers and the significant positive impact they have. While it has been stated that it is technically possible to design these transformers without concessions, doing so would result in larger and heavier units that usually cannot 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, which could take a long time if all customers had to increase their voltage at the same time.

It is therefore recommended to keep these concessions as is. Similarly to the pole-mounted transformer concession, it is also recommended that an FAQ document is created to state the conditions when this concession can be used and the process for applying for it.

2.4.3.4 A technology neutral approach

A completely homogeneous approach to transformer regulation may be problematic as there is a need to differentiate technologies such as dry type and liquid immersed, in order to allow properties such as fire safe and leak-proof devices to be on the market. However, these properties should not be defined by the regulation to products of a particular type, but rather those who can meet the final property. Therefore, requirements for fire safe transformers could be set in a technology neutral fashion, whilst the fire safety property is preserved. An example of how fire safe transformers could be set in a technology neutral fashion has been provided in Section 2.4.2.5.

As the Regulation currently aligns its definitions with those adopted from EN/ISO 60076-1:2011, which are harmonised with IEC 60076-1:2011. It is likely that the updated definition will impact the one adopted for power transformers by the Regulation. However, the standard is due to be published after this study finishes therefore, a technology neutral approach will not be adopted until the next review of this Regulation. 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.

2.4.3.5 Functional categorisation

As there is little appetite from stakeholders, no technical reason and no definition in the IEC 60076 standard to introduce new functional categories of transformers, it is recommended not to investigate this concern further. The issue should be reviewed if, and when, IEC 60076 introduce new categorisations.

2.5 Material Efficiency

i) material efficiency aspects;

m) strengthening potential of the existing MEPS and the potential of introducing material efficiency requirements (MMPS).

2.5.1 Background

Material efficiency goals are broadly set in measures to minimise our usage of materials in products. This can be done with various methods, such as by increasing product lifetime, tracking materials of particular environmental concerns, improving recuperation and reuse of devices/parts, increasing recycling of materials. Reducing the usage of materials has beneficial effects to reduce the emissions, energy consumption, biodiversity loss and pollution that may be associated with their manufacture.

The transformers Ecodesign regulation 548/2014, only had one mention of material efficiency, which was for product information to be provided regarding the weight of all the main components of a power transformer (including at least the conductor, the nature of the conductor and the core material).

The Ecodesign regulation 2019/1783 also included a mention with regards to repair of transformers, included Article 1.3 stating:

Medium and large power transformers, regardless of when they were first placed on the market or put into service, shall be reassessed for conformity and comply with this Regulation, if they are subject to all of the following operations:

(a) replacement of the core or part thereof;

(b) replacement of one or more of the complete windings.

This is without prejudice to the legal obligations under other Union's harmonisation legislation that these products could be subject to.

However, this statement is not intended to ensure improved material efficiency, but rather to close a loophole such that repaired transformers will still meet the Ecodesign regulation.

With other technologies, the Ecodesign framework directive has been used to boost circular economy and recent Ecodesign regulations, published (e.g., smart phones) or in development. Notably measures adopted have been the requirement for providing spare parts, information provision on material content and disassembly requirements. We shall investigate these options below.

2.5.2 Feedback/ Research results

2.5.2.1 Increasing product lifetime

Before discussing how to increase the product lifetime, it is good to understand current transformer lifetime. These are currently estimated at 180,000 hours when operating at rated temperature, mean full load and yearly average temperature. This is equivalent to approximately 20 years. These transformers are on average operating at 30 to 60% load range, so their lifetime should be higher.[124] This results in the typical life expectancy of medium transformers to be 40 years, 30 years for

[124] Stakeholder feedback

large transformers and 10 to 20 for small transformers.[125] Life expectancies for transformers can even reach up to 60 or 80 years if adequate maintenance is in place.[126] Extending life expectancies beyond 60 years can be difficult as spare parts become harder to find. A more comprehensive review of average product lifetime has been included in .

The most common reason for replacement of a transformer is not due to product failure, but rather due to its capacity no longer meeting the required load and being replaced with a larger unit. Utilities may not deem the remaining estimated lifetime as being worth reusing on another site.

Technical failures which reduce the lifetime of a transformer are typically linked to damages to the materials in the windings, core or insulation. These damages are generally brought on by poor use parameters (such as temperature) and poor maintenance with introduction of humidity. Damage, or stress, can be caused through mechanical, temperature or electrical nature. Most of the component failures are on bushing, tap changer, and leakages. The following are the factors which may negatively affect the life expectancy of transformers:

- **Overloading** the transformer, making it operate at load levels above its rated capacity, leading to excessive heat generation and insulation deterioration.
- **Environmental factors** such as high humidity, extreme temperatures, or corrosive substances which will deteriorate materials, like the core, windings and insulation (paper or oil).
- **Electrical disturbances** such as voltage surges, load cycling, partial discharges, short circuits, transients, and electrical faults, which can deteriorate materials (notably insulation), cause mechanical stress on the transformers and damage to windings and core.
- **Oil maintenance** through contaminated oil can be more susceptible to breakdown or insufficient oil levels which would result in inadequate cooling.
- **Inadequate cooling systems** can lead to overheating and the deterioration of materials.

To increase the lifetime of transformers, the following can be considered:

- Preventative maintenance operations such as cleaning, and oil analysis should be carried periodically.
- Improving cooling systems to ensure electrical losses are evacuated and do not strain the materials.
- Increasing the efficiency of transformers will mean that more electrical energy is transferred, and hence not converted to heat or mechanical stress within the device. This should however not be done at the detriment of the cooling systems to evacuate losses.
- Improved insulation systems can be used which can withstand stress better. These include high-performance liquids (such as esters), thermally upgraded paper. Some of these improvements can only be done when the windings are completely replaced.

[125] Lot 2 preparatory study: distribution and power transformers, 2011.

[126] Stakeholder feedback

- Improving the assembly of the coils, for them to be supported with appropriate wood cheeks (rather than simply using strapping) and for appropriate wedges to be used between the coils. These measures will ensure the integrity of the coils to withstand electrical shocks and mechanical resistance during transport.
- Increasing the rate of retrofitting and repairs can expand the average lifespan. This can be done by recuperating key components such as the tanks and magnetic core and regenerating the transformer oil. Stakeholders indicate that up to 90% of a medium liquid immersed transformer can be recuperated (tank, magnetic ore and regenerating the oil).
- Designing transformers to operate at lower temperatures will increase their life expectancy.
- Digital monitoring solutions are proposed to control temperature hotspots, allowing for better modelling and control of the insulation lifetime. This would improve maintenance activities to happen before any damage occurs to the transformer.

2.5.2.2 Improved repair

If a transformer fails, it is likely to be a concern with improper sealing. For a repair on windings (which are more likely than for the core), rewinding may result in improper matching, which would mean an inefficient running transformer.

Some suggestions to improve the repair rate are to have measures to:

- Ensure that repair staff have access to technical documentation which would include instructions how to appropriately seal the transformer, disassemble the transformers and provide a winding plan.
- Design transformers such that they can be disassembled without destruction.
- Ensure that the disassembly can be done be professional repairers with standard repair tools.

Stakeholders have indicated that there are no associated standards to date on transformer assembly, disassembly and protection. These are practices which are included as part of repair industry knowledge. Dismantling instructions are currently not provided by manufacturers.

Another suggestion was to ensure that transformer manufacturers would have spare parts available for repairs. However, as transformers have lifespans of 20 to 40 years, with some even reaching 60 years, having spare parts available for manufacturers can be difficult as it would require foresight for decades. This is inaccurate as one will not need to have all the spare parts during the initial manufacturing process, but rather require for spare parts to be made (or made available), when needed. Hence this can be manufactured later in the product lifecycle than during inception. For large power transformers, spare parts can be made for older designs, however the timelines to source these, and the need to ensure service is always deliver, may mean that faster, and less cost-effective options are prioritised.

It is noted that a typical repair would replace approximately 10% of transformer material in the process.

2.5.2.3 Repair requirements under article 1.3

A key concern raised by stakeholders is the article 1.3 of the Ecodesign regulation 2019/1783, which states:

Medium and large power transformers, regardless of when they were first placed on the market or put into service, shall be reassessed for conformity and comply with this Regulation, if they are subject to all of the following operations:

(c) replacement of the core or part thereof;

(d) replacement of one or more of the complete windings.

This is without prejudice to the legal obligations under other Union's harmonisation legislation that these products could be subject to.

This article is in place to ensure that there is no loophole for transformers under the right performance standard which enter the EU market via a "repair" route. The article conditions of needing to meet the new Ecodesign regulation is only a requirement if both windings and core are replaced, which would be beyond the scope of a normal repair operation and could be interpreted as the building of a new transformer.

There is a concern that it is unclear who the responsibility of making these reassessments would fall to. This reassessment would need to be for whomever endeavours both the core and winding repair, which could be the utilities or a third-party repairer. It is also important to ensure that product information is maintained such that records are available regarding who was the original equipment manufacturer, and who was the repairer, along with the performance records for each.

As a parallel, in the US, the transformer needs to be upgraded to the latest efficiency requirements if it re-enters the market. With that in mind, if a utility is able to repair a transformer themselves, then the repaired transformer is not required to meet a performance standard. However, if the transformer ownership changes hands (such as to a repair firm), then, after repair, the product would re-enter the market and would need to meet the regulation efficiency standards.

Furthermore, an upgrade in energy efficiency is tied to the core and the windings, therefore a repair operation could only increase the efficiency if those components are being replaced.

European repairer stakeholders have also shown concern that their status is unclear if they are considered as "producers" of transformers once they repair. The article stated above is very specific on which repair operations require reassessment of conformity. This ensures that there isn't a market distortion between the repairs done in house by stakeholders and those taken out by independent repairers.

2.5.2.4 Materials with environmental impacts

The materials of concern for transformers, with regards to their potential impacts on the environment are the insulation materials and specific oils .

The first and most prevalent is with regards to the insulating oil. These are mainly mineral oils which can contaminate the local environment if there is a leak. These require to be bunded around the transformer to ensure any leaks do not go into the environment. This mineral oil can be cleaned and regenerated to be reused in the transformer. IEC 60296 catalogues recycled oils as equivalent to virgin oils.

Certain oils, such as PCBs (Polychlorinated Biphenyls), pose a health risk due to their toxic and bio-accumulative properties. PCBs were used as a dielectric filler liquid in transformers but have been very heavily regulated in Europe since 1985.[127] In 1996, the disposal of these products was regulated under Directive 96/59/EC.[128] These have now been included within the Persistent Organic Pollutants (POPs) regulation of 2019. These are relevant, as although these chemicals have not been used in manufacture for a long time, the high lifespan of transformers means that there are still some products is use with them inside.

Other non-mineral oils are suggested which are less flammable, such as silicone, synthetic ester or natural ester (FR3). Ester is a biodegradable oil, which is more expensive but which may have a lower environmental impacts due to their reduced risk if a leak were to occur.

Older transformers may also include asbestos in their old tap changers, and paints which are not lead free, which will require at the end of life of the product.

Most of these products of concern are regulated by the European Chemicals Agency (ECHA) through the REACH or RoHS directives. The SCIP provides a database with information on these substances of concern. France also has an example of Extended Producer Responsibility for mineral oils.

2.5.2.5 Recycling

Transformers are made of materials which are largely recyclable or reusable. The main components are the magnetic core, the windings, the enclosure and the insulation materials. The magnetic core is typically iron, amorphous metals or ferrite ceramics, which can be recovered, however the products now coming out of service have laminate thickness too large to meet the Ecodesign regulation needs. Hence this material may be sent to third countries where transformer performance requirements are less high or is typically not reused but downcycled, where the recycling process may remove the magnetic properties. The windings are either aluminium or copper, which are recovered and both highly recycled. The enclosure is typically made of iron or steel and is similarly recycled.

The insulating material is where there is difficulty, as for liquid immersed transformers, the oils can be recuperated and regenerated for reuse. However, solid insulator like epoxy resin, paper, wood and pressboard are not recycled. Windings covered in epoxy resin may also not be recycled due to the difficulty to separate the materials. Evidence provided by stakeholders shows how these insulation materials, notably epoxy resin, may be recovered for waste to heat processes. Separating the cast resin from the windings may be difficult, but there is now commercially viable process to separate the epoxy resin from the coils to allow for the metal recycling of the coils, a shown for GEAFOL cast-resin transformers[129]. Silicone rubber has also been indicated as a good insulator, which can be separated from winding conductors.

For liquid immersed transformers, the ratio of materials is typically in the range of 40-50% for the magnetic steel core, 12-18% structural steel, 12-22% aluminium or copper windings, 16-25% dielectric fluid.[130] The composition for dry type transformers is similar, only that the epoxy resin is lighter than the dielectric fluid and hence can be as little as 8% of the total mass.

[127] https://environment.ec.europa.eu/topics/waste-and-recycling/pcbspcts_en

[128] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31996L0059

[129] siemens-geafol-cast-resin-transformer.pdf

[130] Stakeholder feedback

The core which is made of steel is the most valuable aspect in large transformers. It is also difficult to reuse in other products, and hence is often downcycled. The copper/aluminium windings can easily be recovered and used elsewhere. Common practice is to recover the windings and send the core steel overseas.

Stakeholder feedback indicates that transformer parts are typically not recovered and reused for new transformers.

2.5.3 Recommendations

To improve material efficiency of transformers, we recommend first to discuss with CENELEC if a standard exists, or can be developed, to improve for transformers the insulation materials, assembly of the coils with wood cheeks and wedges for electrical and mechanical safety.

Furthermore, Ecodesign can include a requirement that transformers need to be disassemblable without destruction to allow for repair. This requirement would be set up such that an expert (class C, with specific training and/or experience relate to the product category), can perform the repair with tools of class C (commercially available tools). Some exemptions on disassemblability and separation may need to be provided with regards to epoxy which is difficult to separate. A recommendation can be made to enquire for the use of silicone rubber 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 products can be adequately repaired.

A review of article 1.3 and the reasons for its implementation show that it is not a concern for normal repair operations, but rather only for core and windings replacements. This is in place to ensure that there is no loophole to the ecodesign regulation, where product is remanufactured under the realm of "repair" and resold at lower performance metrics. As the article is only in effect when both core components are replaced, we recommend not making any further changes to it.

To improve sustainability of the mineral oil, the research team recommend reviewing if the recovery and regeneration of oil can be encouraged. The team can also recommend the usage of esters to increase the lifetime of assets, diminish environmental concerns in case of leaks, and improve fire safety considerations.

2.6 Environmental considerations

h) the possibility and appropriateness of covering environmental impacts other than energy in the use phase, such as noise and material efficiency.
k) technological, market and regulatory evolutions affecting environmental performance;

2.6.1 Background

The Ecodesign regulation 2019/1783 currently has no requirements with regards to environmental impacts such as noise.

The EU does have the Directive 2000/14/EC on 'noise emission in the environment by equipment for use outdoors', however transformers are out of scope.

2.6.2 Feedback/ Research results

2.6.2.1 Noise considerations

Transformers can create noise due to losses in the device which are converted to mechanical forces in the transformer. These mainly originate from the windings, which will be proportional to the load current.

With regards to noise, it is important to note that EN 50708-2-1 already lists maximum noise levels for medium power transformers.

Although Ecodesign does not directly have measures on the noise of transformers, there are indications that the efficiency requirements of Ecodesign have had a consequence of reducing noise levels. Indeed, as transformers become more efficient, the designs will minimise the magnetostriction within the core, which in turn minimises the vibrations of the core (and hence the noise). Furthermore, the reduced losses means that less resistive heat is emitted by the transformer. There will therefore be less of a need for cooling and ventilation systems. However, these considerations are changed when using amorphous steel core, as although they are more efficient, they are much louder than grain-oriented steel cores.

Another method to reduce noise levels is to include a sound barrier around the transformer itself to attenuate the sound propagation.

Stakeholders have pointed out that there are local regulations around noise, such as in Germany, France and Belgium. Some of these are national, but also some are applied within urban areas to reduce noise levels, defined by local authorities.

Stakeholders have also indicated that noise testing would provide an additional charge for testing at certified laboratories.

2.6.2.2 Oil considerations

A key environmental concern for transformers is to ensure that there are no oil leaks into the environment. For this reason, 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. This is done for all oil transformers, though it should be noted that the environmental risk is lower for biodegradable oils.

However this bunded system is not used for certain setups with a lack of space, such as pole mounted transformers. Non-toxic, biodegradable esters may be a better fitting for these products to limit environmental risks.

2.6.2.3 Temperature and climate considerations

With regards to temperature operation of transformers, IEC 60076-1 already states operating ranges for transformers. IEC 60076-2 also sets out the cooling measures, temperature rise limits and the corresponding verification 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.

The considerations of climate change mean that transformers will need to operate at more extreme temperatures, for sudden cold snaps, respond to heat waves and periodic overheating. For higher temperatures will cause a challenge to transformers as it will affect the capacity and life expectancy of devices.

In colder climates, climate change will heighten the risk of ice storms, resulting in adverse effects such as gasket damage, hastened aging of sealing systems, and complications for various insulating fluids. These issues are particularly concerning in instances where the insulating fluids have higher pour points, denoting the lowest temperature at which they remain in a liquid state. For instance, natural esters remain fluid at temperatures as low as -10°C, whereas synthetic esters can withstand temperatures as frigid as -45°C, and mineral oil maintains its liquid form down to -40°C. Furthermore, in dry-type transformers subjected to low temperatures, the potential for the development of cracks in the windings becomes a prominent concern, however there are tests set out in IEC 60076-11 to mitigate these concerns.

Mandating temperature operating ranges for transformers may be counterproductive as it may go against the exiting standards and would not allow utilities the flexibility to adapt to changing climate conditions. However, Ecodesign currently does not set any information requirement on temperature. Setting a requirement to provide information such as operating and storage temperature ranges for transformers, would allow for utilities to adequately track and plan their inventory of transformers in line with current and expected weather conditions.

2.6.3 Recommendations

With regard to noise, it seems that the increase in efficiency from Ecodesign is already having an effect on reducing the noise of transformers. Furthermore, there are separate standards and regulations from national and local governments which provide a maximum noise requirement. It is therefore recommended not to include this metric within Ecodesign.

With regards to climate adaptation, we recommend not making further requirements in the Ecodesign regulation, as the IEC and CENELEC standards already provide temperature requirements.

2.7 Other topics

s) other topics, as emerged from consultations with stakeholders.

2.7.1 Ecodesign Considerations for the use of SF6 in Gas-Insulated Transformers

2.7.1.1 Background

SF6 (Sulphur Hexafluoride) is a potent greenhouse gas, with a GWP_{100} of 23,500 (i.e., the release of 1 kg of SF6 has equivalent warming impact over 100 years to releasing 23,500 kg of CO_2). The reduction in emissions of SF6 from equipment either through venting or leaking is a key net-zero consideration for policy makers.

In electrical power equipment, SF6 has been widely used in high voltage switchgear, owing to its chemical stability, arc quenching properties and fire resistance. In transformers it is only applicable in gas-insulated transformers.

2.7.1.2 Feedback/ Research results

***Prevalence of SF6 Gas-Filled** Transformers*

Gas-Filled (or Gas Insulated) transformers are seldom in use within Europe:

- In the 2011 pre-study it was noted by the stakeholders ORGALIME there were less than 100 large gas-filled transformers across the EU [131].
- In responses to the qualitative questionnaire distributed in 2023, multiple stakeholders noted that gas-filled transformers are seldom used except in rare exceptions, with one noting they had never seen one, and that 'they do not exist in Europe', and that 'except Japan, nobody else uses SF6 transformers.
- It was also noted by a stakeholder in the 2023 questionnaire responses that liquid immersed and dry-type transformers can fulfil all existing technical requirements without the need for SF6.

Given the qualitative evidence provided by a range of stakeholders, which remains stable between the 2011 to 2023 period, it can be broadly concluded that the prevalence of SF6 gas-filled transformers is low and is likely to remain low.

Applicability of F-Gas Regulations

The F-Gas Regulations[132] (Regulation 517/2014) place controls on switchgear that utilise fluorinated greenhouse gases (F-Gasses, which includes SF6), depending on the amount of F-Gas such as:

- Prohibiting the intentional release (where not technically necessary)
- Requiring leak tests (unless tested to have a rate of <0.1%/year and has monitoring devices or less than 6kg of F-Gas).

[131] 2011 Transformers Preparatory Table p39

[132] REGULATION (EU) No 517/2014 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, of 16 April 2014, on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006

- Monitoring and record keeping, including the quantities of F-Gas installed, added and recovered through equipment life.
- Ensure F-Gases are recovered from equipment.
- Labelling of F-Gas containing equipment.

An update to the F-Gas regulation has been proposed[133,134], which will prohibit the placing on the market of switchgear containing gases with a GWP of 10 or more (from 2026 onwards, depending on the rated size) unless evidence is provided that no suitable alternative is available based on technical grounds within the lower GWP ranges referred to above.

Switchgear is defined under these regulations as:

'*electrical switchgear' means switching devices and their combination with associated control, measuring, protective and regulating equipment, and assemblies of such devices and equipment with associated interconnections, accessories, enclosures and supporting structures, intended for usage in connection with the generation, transmission, distribution and conversion of electric energy".*

Given power system transformers are not generally considered as switchgear, this definition suggests that transformers are not within the scope of the updated F-Gas Regulations, therefore the consideration under Ecodesign requirements would not be an overlap of regulation with respect to the specific prohibitions on placing on the market of equipment.

The F-Gas regulations do however put in place constraints on the overall quantity of Hydrofluorocarbons (HFCs) that can be placed on the EU Market, which by default would reduce the availability of SF6 containing transformers.

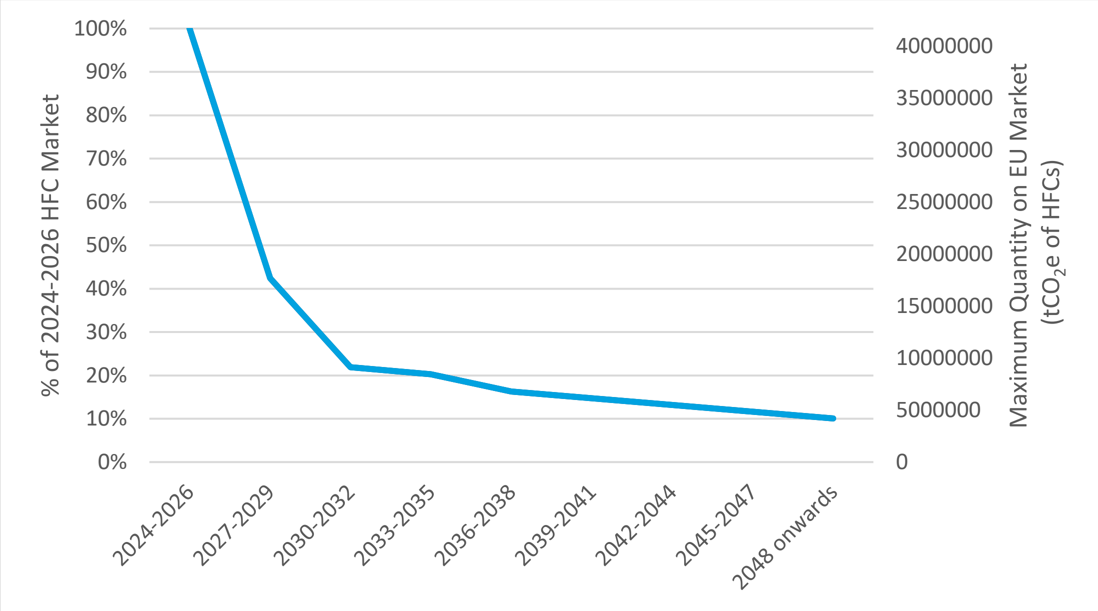
Figure 2.21 below replicates the limits on the complete HFC market in the EU (not product specific) defined in Annex VII of the proposed regulations, showing the maximum quantity of HFCs (in tonnes of CO2e equivalent) that can be placed on the EU Market across different time period on the right-hand axis, and the percentage reduction in market size relative to the first 2024-2026 period on the left-hand axis. The regulation requires that by 2030-2032 the maximum quantity on the market will be 20% of that in 2024-2026[135].

[133] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014

[134] ANNEXES to the Proposal for a Regulation of the European Parliament and of the Council on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014

[135] ANNEXES to the Proposal for a Regulation of the European Parliament and of the Council on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014

Figure 2.21 Curve of allowable KFCs on EU market till 2050 according to the proposal on fluorinated Greenhouse gases



2.7.1.3 Recommendations

Given the stakeholder feedback outlines that there is a very low prevalence of gas-filled transformers utilising SF6 in use or on the market within the EU, and that there is 'by default' a phasing out of the use of SF6 within the EU market, there would be limited benefit to regulating the use of SF6 specifically within the Ecodesign regulation.

2.7.2 Methodology concerns to determine kPEI under different cooling conditions

2.7.2.1 Background

A concern was raised to CENELEC with regards to the determination of the kPEI. The standard EN50708-1-1 sets out determining the kPEI as being for the "optimum value", which is where the efficiency curve would be highest. Unfortunately, this does not account for the cooling of the transformer, which would activate at different load values, requiring power and hence making the curve discontinuous. This results in multiple values of PEI depending on the load when there are different stages/modes of the cooling system being activated.

2.7.2.2 Feedback/ Research results

The study team has been in communication with CENELEC on this matter as this issue was being considered in the current review of EN 50708-3. CENELEC informed the study team that they have been able to tackle the concern of where the kPEI should be set at.

As mentioned the EN 50708-3 standard current methodology for PEI does not consider the products cooling capacity, allowing the kPEI to be set at approximately 0.5 load factor on the continuous curve. However, with active cooling this continuous function does not occur therefore, in order to ensure the energy consumption from cooling is considered CENELEC have updated their methodology. The updated methodology now includes P_{c0} and P_{ck} to be added to P_0. Thus, it now considers cooling when obtaining the PEI value. P_{ck} is considered here because the cooling system is switched on before $k_{PEI\text{- STEP 0}}$ and $k_{PEI\text{ STEP 1}}$. Within a non-continuous function, the absolute function will be at the extremes or inside intervals, the internal extremes have to be analysed to find the true PEI value.

In the example provided by CENELEC to the study team, as a result the calculated PEIs and k_{PEI}s are within the second interval (step 1). Therefore, it can be seen that the maximum for the transformer performance is not the relative maximum calculated in step 1 but it is the maximum value calculated in step 0 (corresponding to k = 0,4, (k_{PEI} in this case).

2.7.2.3 Recommendation

The methodology which as described is currently under review by CENELEC however, after communications with the TC the issue looks to have been resolved. Therefore, once the revised version of EN 50708-3 is published the Regulation should adopt the new version thus, adopting the method for determining the PEI of large power transformers.

2.7.3 "Sustainable Peak Load" as substitute to rated power

2.7.3.1 Background

Currently the rated power of a transformer is used to determine what is the maximum load that should be set through it. This power rating is measured for a given temperature (usually 65degrees C) which is set in the testing standards under the use of mineral oil and paper insulators.

2.7.3.2 Feedback/ Research results

Stakeholders have indicated that the rated power methodology of transformers may no longer be appropriate. This is because there are now new insulation materials that can operate at higher temperature than what is required in the testing standard. These will take the form of upgraded paper, or Nomex used in combination with ester fluid. With this in mind, some transformers are capable of operating at higher load ratings that their rated power (or in overload), without suffering thermal damages. For this reason, a new rated power metric decried as "sustainable peak load", may be developed to appropriate describe what can be used safely in the grid. This would be defined as the capacity where the transformer could be loaded continuously at this kVA rating without compromising reliability or cutting short the transformers expected lifetime. A formal definition from a standardisation body does not yet exist.

2.7.3.3 Recommendation

Although there is a need for such a new power rating to be developed, this metric is still in its infancy, with no standard in place. Therefore, it is recommended for the next review of the Ecodesign regulation on transformers to consider the implementation of sustainable peak load as a power rating tool, once the standard is in place. If "sustainable peak load" is adopted, then the regulation would need to realign energy efficiency criteria in line with the new capacity ratings.