



Accelerating the Global Adoption of ENERGY-EFFICIENT TRANSFORMERS

UN Environment - Global Environment Facility | United for Efficiency (U4E)



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[Angelo Baggini](#), Università degli Studi di Bergamo, U4E Expert Taskforce Chair

[Marcelo Padilla](#), Ministry of Energy - Chile, U4E Expert Taskforce Vice Chair

[Michael Scholand](#), UN Environment - Economy Division

[Mayur Karmarkar](#), International Copper Association (ICA)

[Kai Pollari](#), ABB

[Li Pengcheng](#), China National Institute of Standardization

[Liu Ren](#), China National Institute of Standardization

[Ibrahim Soumaila](#), ECOWAS - Centre for Renewable Energy and Energy Efficiency

[Victor Martins](#), Eskom

[Klaus Giefer](#), Hitachi Metals Europe GmbH

[Phil Hopkinson](#), HVOLT/NEMA Consultant

[Matt Malinowski](#), ICF International

[Joe Ritchie](#), International Energy Agency (IEA)

[Virginie Letschert](#), Lawrence Berkeley National Laboratory (LBNL)

[Dave Millure](#), Metglas/Hitachi Metals

[Paul Jarman](#), National Grid - United Kingdom (UK)

[Terry Brennan](#), Natural Resources Canada

[Ken Colburn](#), Regulatory Assistance Project

[Alison Chikova](#), Southern African Power Pool

[Richard Mariwa](#), Southern African Power Pool

[Paul Huggins](#), The Carbon Trust

[Adesh Singh](#), Eskom, South Africa

[Jacqueline Alvarez](#), UN Environment - Economy Division - Chemicals and Health

[Manuel Soriano](#), United Nations Development Programme (UNDP)

[Thomas Dressen](#), EPS Capital

[Steve Kukoda](#), ICA

[Philip Zheng](#), ICA

[Pierre Cazelles](#), ICA

[Sommai Phon-Amnuaisuk](#), International Institute for Energy Conservation

[Patrick Blake](#), UN Environment - Economy Division

[Giulia D'Angiolini](#), UN Environment - Economy Division

[Jonathan Duwyn](#), UN Environment - Economy Division

[Brian Holuj](#), UN Environment - Economy Division

[Mark Radka](#), UN Environment - Economy Division

[Eric Yang](#), UN Environment - Economy Division

[Sudhir Sharma](#), UN Environment - Asia Pacific Office

FOR MORE INFORMATION, CONTACT:

UN Environment, U4E
Economy Division
Energy & Climate Branch

1 Rue Miollis, Building VII
75015, Paris
FRANCE

Tel: +33 (0)1 44 37 14 50

Fax: +33 (0)1 44 37 14 74

E-mail: u4e@unenvironment.org
united4efficiency.org

FOREWORD

Improving energy efficiency is the fastest, cheapest and cleanest way to get reliable power to more people.

Well over half of the world's electricity is consumed by just four products: electric motor systems, lighting, room air conditioners, and residential refrigerators. These products, and the transformers that help get power to them, often waste significant amounts of electricity due to poor designs and improper use. As a result, consumers and business face higher electricity bills, utilities struggle to meet excessive demand for power, governments are burdened with additional economic development challenges, and the planet suffers from worse pollution and greenhouse gas (GHG) emissions.

Most developed countries are well underway in the transition to energy-efficient transformers.

However, many developing and emerging economies are just starting to explore such opportunities. A well-designed set of policies can help transform these markets by enabling them to leapfrog past out-dated technologies to superior, cost-effective alternatives.

United for Efficiency (U4E) is a global initiative launched in 2015 to accelerate such a transition and unlock lasting economic, health, environmental, and climate benefits. UN Environment leads U4E, with funding from the Global Environment Facility (GEF) and steadfast support from the UN Development Programme, CLASP, the International Copper Association, the Natural Resources Defense Council, and

an array of partners. Participating manufacturers include ABB, Arçelik, BSH Hausgeräte GmbH, Electrolux, MABE, MEGAMAN, Osram, Philips Lighting, and Whirlpool Corporation U4E works under the umbrella of the Sustainable Energy for All initiative, leading the "Energy Efficiency Accelerators" of Lighting, Appliances and Equipment.

This report guides policymakers on how to promote energy-efficient distribution transformers and large power transformers in their national markets. It is based on U4E's Integrated Policy Approach, which has been used around the world to bring about sustainable market transformations.



The content was developed based on expert insights from over 20 organisations ranging from manufacturers and industry associations to environmental groups, academia, and governments. This balanced cohort offers credible guidance to address common questions.

This report is part of a series of U4E guides, which cover lighting,

room air conditioners, residential refrigerators, electric motors, and transformers. An additional overarching “Policy Fundamentals Guide” provides general guidance on the establishment of a national programme for energy-efficient products. A wealth of additional resources and information on how to get involved in U4E is available at www.united4efficiency.org.

The content was developed based on expert insights from over 20 organisations, ranging from manufacturers and industry associations to environmental groups, academia, and governments.



THIS REPORT FOCUSES ON ENERGY-EFFICIENT TRANSFORMERS



OTHER GUIDES IN THIS SERIES INCLUDE:



AND AN OVERARCHING FUNDAMENTAL GUIDE:



Angelo Baggini,
Università degli
Studi di Bergamo,
U4E Expert
Taskforce Chair



EXECUTIVE SUMMARY

Many more transformers are needed to reliably meet the increasing demand for electricity around the world. The installed global stock is expected to increase by a compounded annual growth rate of 3.7 per cent, more than a doubling the number of transformers between 2015 and 2040. Africa has the highest projected annual growth rate over this period, 4.9 per cent, with the installed stock more than tripling.

The transformer's performance has major impacts on electricity use given the non-stop operation of the equipment over its 25-year service life. Better performance translates to reduced load on the electricity system, lower electricity bills, and greater reliability. Payback periods vary with the equipment and electricity costs and can be as short as one year or as long as six years or more.

Using more efficient transformers can save nearly 5 per cent of global electricity consumption. By 2040, annual electricity savings of over 750 TWh are possible (equivalent to the annual electricity generated by over 100 coal-fired power plants with a capacity of 1,000 MW), saving more than 450 million tonnes of greenhouse gas (GHG) emissions.

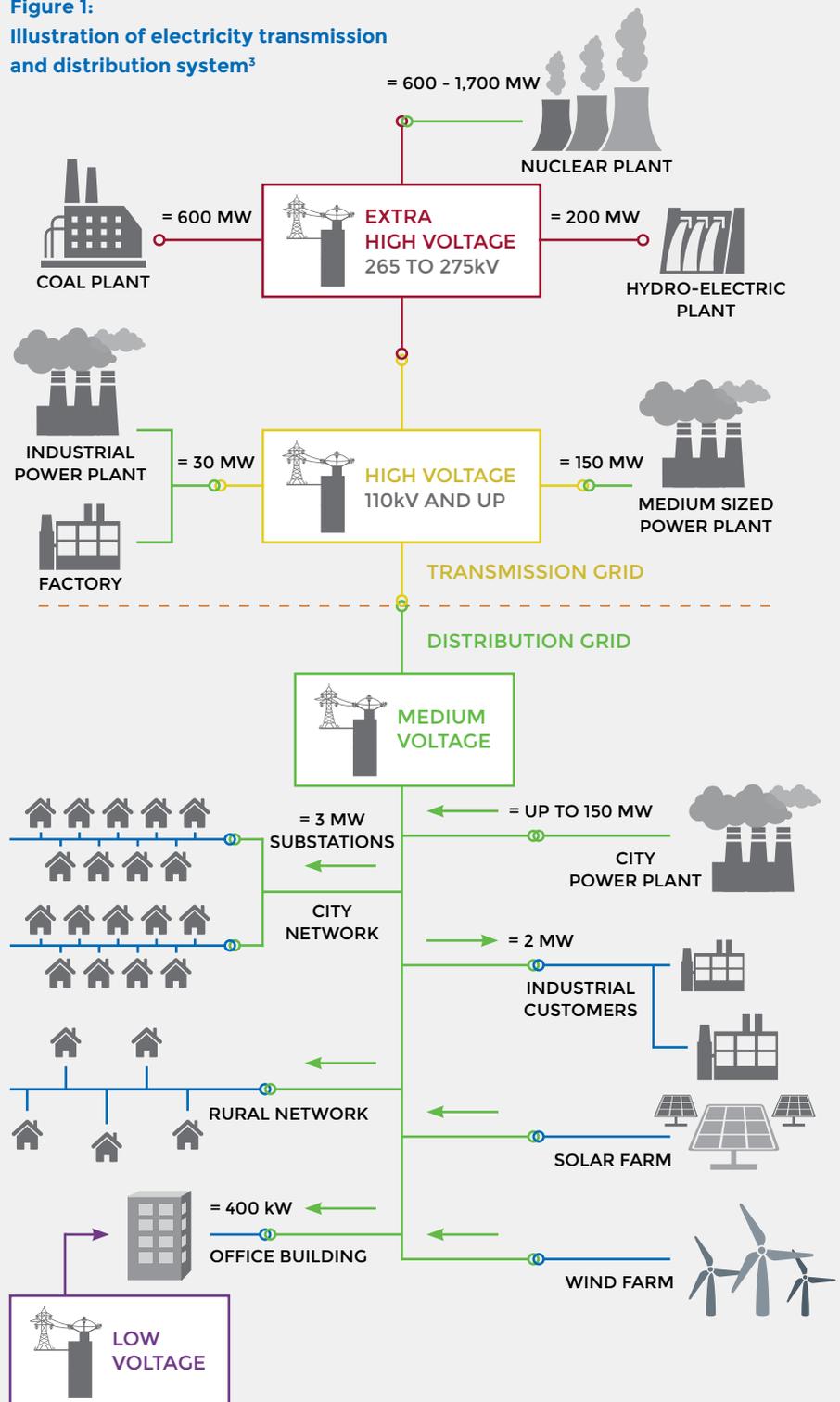
Although most transformers have efficiency levels greater than 98

per cent, a life-cycle assessment study conducted for the European Commission (EC) found that the energy consumed during a transformer's service life is the dominant factor contributing to the environmental impacts over its life cycle.¹ Therefore, it is important to consider cost-effective measures that could reduce losses in the transformer and alleviate these environmental impacts.

Technical solutions to improve the energy efficiency of transformers are commercially available, and the market penetration of highly-efficient transformers has significant room for growth. Policy measures are being adopted in a few countries to encourage and ensure greater penetration of energy-efficient transformers, but the vast majority of markets remain untouched.

Transformers are static devices in electricity systems that transfer electrical power between circuits through electromagnetic induction. Their application enables significant energy savings by increasing the voltage and decreasing the current, since losses are proportional to the amount of current flowing through the wire.² Generally, electricity will pass through four or five transformers as it travels from the power plant to the customer.

Figure 1:
Illustration of electricity transmission and distribution system³



MW is an abbreviation for megawatt and kW is an abbreviation for kilowatt; both are measures of power, whereby 1,000 kW is equal to one MW. The abbreviation kV is kilovolt, meaning 1,000 volts; and transformers are depicted in the schematic as two interlocking rings.

The most common transformer is liquid-filled with windings that are insulated and cooled with a liquid. These transformers are most often used by electric utilities and can be found in all stages of the electricity network, from generation step up through transmission and distribution. They are usually filled with mineral oil, which is flammable and may be prohibited for use inside of buildings, but fire-resistant liquids are available.⁴



Liquid-filled transformers are housed in a sealed tank that facilitates circulation of fluid through the winding ducts and around wire coils. The heat removed from the core-coil assembly by the fluid is then transferred to the environment through the tank walls that have fins to enhance cooling effectiveness or through external radiators with passive or active fluid circulation (i.e. pumps) and cooling fans. Some countries have environmental protection laws requiring containment troughs

around the perimeter of liquid-filled transformers to guard against leaks.

A dry-type transformer is insulated and cooled by air circulating through the coils. These are found in certain distribution networks and are typically used by commercial and industrial customers, rather than electric utilities.

Liquid-filled transformers tend to be more efficient than dry-type transformers for the same rated power (kVA⁵). They also tend to have greater overload capability and longer service life.

The installation location can be a critical consideration. Liquid-filled transformers are physically smaller than dry-type for the same rated power, which can be important in space-constrained areas. Higher-capacity transformers used outdoors are almost always liquid-filled. Lower-capacity transformers used indoors are often dry-type since the fire-risk is lower than those that use mineral oil. Dry-type transformers typically are housed in enclosures, with the windings insulated through vacuum pressure impregnated varnish and epoxy resin. Dry-type insulation is typically designed to withstand operating temperatures up to 220°C.

Although there are no physical or design differences between transformers used in developed, developing, or emerging economies, there are important

market-related differences that need to be taken into consideration by policymakers. Capital-constrained electric utilities often procure less efficient transformers since the purchase price is lower or procure fewer units with higher loading to offset the high purchase price. Market protectionist policies such as tariffs or local content requirements can also prevent more energy-efficient transformers from entering the market, which is a particular problem if domestic manufacturers lack the competency to produce energy-efficient equipment.

In 2017, all electric power transformers in service globally are estimated to have 1,100 TWh of losses.⁶ This is roughly equivalent to the total annual electricity consumption of Japan. Over the next two decades, these losses are projected to rise as economies expand and additional electricity capacity is added.

Table 1 presents a projection of world electricity demand and the proportion of losses attributable to all electric power transformers around the world.⁷ It also shows the amount of energy and carbon dioxide (CO₂) savings that would result from all countries adopting new or updating existing minimum energy performance standards (MEPS) for transformers starting in 2020.

Table 1: Electricity and CO₂ savings potential of all electric power transformers globally^a

	DESCRIPTION	Units	2020	2025	2030	2035	2040
ELECTRICITY SAVINGS	World electricity consumption	TWh/yr	24,222	27,516	30,875	34,100	37,352
	Baseline electricity loss by transformers	TWh/yr	1,181	1,306	1,462	1,643	1,845
	% of world electricity use	%	4.88	4.75	4.73	4.82	4.94
	Annual savings from MEPS in 2020	TWh/yr	18	113	218	325	426
	Annual savings from BAT in 2020	TWh/yr	34	209	400	595	776
	Cumulative savings from MEPS in 2020	TWh	18	390	1,267	2,678	4,610
	Cumulative savings from BAT in 2020	TWh	34	718	2,331	4,918	8,444
CO ₂ SAVINGS	Baseline emissions from transformer electricity losses	MT/yr	732	817	923	1,046	1,183
	Annual savings from MEPS in 2020	MT/yr	10	66	127	190	250
	Annual savings from BAT in 2020	MT/yr	20	129	248	370	483
	Cumulative savings from MEPS in 2020	MT	10	226	737	1,562	2,693
	Cumulative savings from BAT in 2020	MT	20	441	1,438	3,045	5,240

Table 2 presents the list of countries with policies to promote more energy-efficient transformers based on International Electrotechnical Commission (IEC) and Institute for Electrical and Electronic Engineers (IEEE) standards. MEPS and high-efficiency performance specifications (HEPS) are listed. IEC 60076-20, published in January 2017, focuses on harmonisation (see section 3.2 of this report) to reduce trade barriers and expand markets for energy-efficient transformers.

Table 2: Countries with energy performance standards and specifications for transformers

COUNTRY	LIQUID-FILLED THREE-PHASE	LIQUID-FILLED SINGLE-PHASE	DRY-TYPE THREE-PHASE	DRY-TYPE SINGLE-PHASE	LARGE POWER TRANSFORMERS
AUSTRALIA	MEPS / HEPS	MEPS / HEPS	MEPS / HEPS	MEPS/HEPS	---
CANADA	---	---	MEPS	MEPS	---
CHINA	MEPS - Grade 1	JB/T (industrial)	MEPS - Grade 1	---	MEPS
EUROPE*	MEPS - Tier 1, 2	---	MEPS - Tier 1, 2	---	MEPS
INDIA	MEPS	MEPS	---	---	---
ISRAEL	MEPS / HEPS	---	MEPS / HEPS	---	---
JAPAN**	Top-runner	Top-runner	Top-runner	Top-runner	---
MEXICO	MEPS	MEPS	---	---	---
REPUBLIC OF KOREA	MEPS / HEPS	MEPS/HEPS	MEPS/HEPS	MEPS/HEPS	---
US	MEPS	MEPS	MEPS	MEPS	---
VIETNAM	MEPS	---	---	---	---

* The European regulations apply to all 28 member countries of the European Union (EU), as well as the European Free Trade Area (Iceland, Liechtenstein, and Norway) and Switzerland.

** Japan's Top Runner programme applies to medium voltage (3 and 6 kV) distribution transformers. It does not apply to the electric utility sector.¹⁰

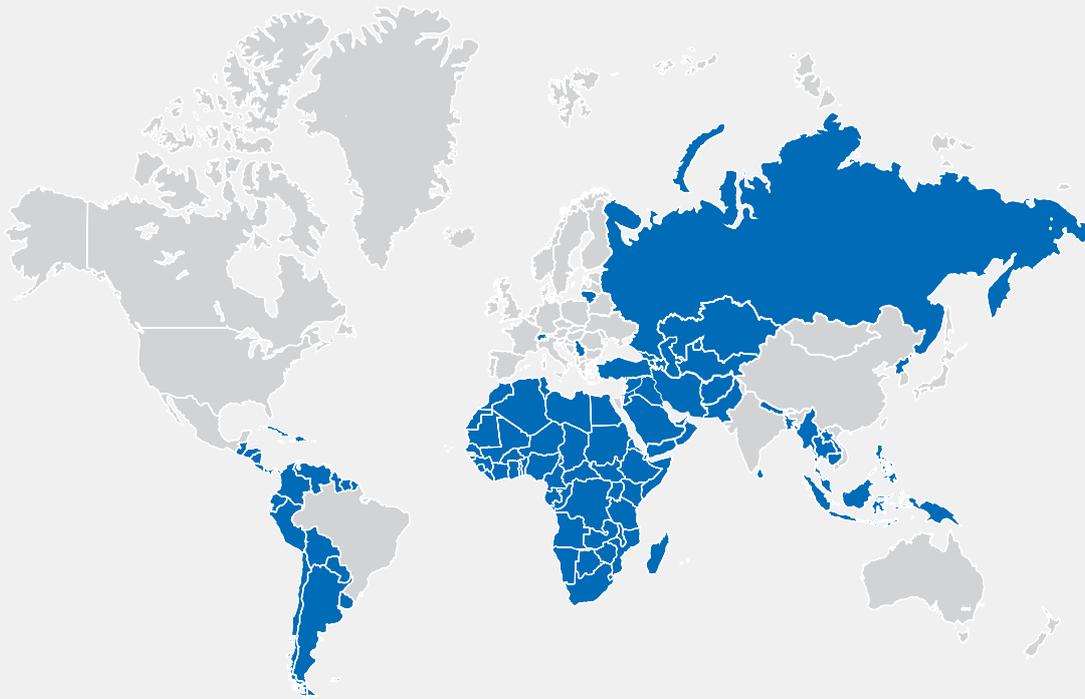


Figure 2:
Countries
without
efficiency
programmes
for distribution
transformers

The vast majority of countries have yet to take such action. At the time of this printing, the ten countries with the largest markets for transformers are (in descending order)¹¹: China, the United States (US), Russia, Japan, India, Brazil, Canada, Thailand, UK, and Saudi Arabia. Those that do not have policies to promote energy-efficient transformers are shown in blue in Figure 2.

Policymakers are encouraged to use this guide in concert with the “Policy Fundamentals Guide” and other resources available at www.united4efficiency.org to develop and implement a national efficient transformers strategy.

The guidance is meant to be flexible rather than prescriptive. Each country should consider and make decisions based on its specific priorities and circumstances. This process should involve all relevant authorities and stakeholders in jointly determining priorities and the most appropriate pathways

to achieve them. It can be applied to large power and distribution transformers in both utility networks as well as those used in commercial and industrial applications.

An Integrated Policy Approach to fully transform a market includes:

- **Standards and Regulations** that define which equipment is blocked from the market (those that do not meet minimum energy performance requirements (MEPS)), which equipment may be recognised for meeting performance and quality requirements, how to test the equipment, and other aspects. Standards and regulations are essential to the success of market transformation and therefore are the cornerstone of the U4E Integrated Policy Approach.
- **Supporting Policies** that ensure the smooth implementation of standards and regulations and achieve broad public acceptance. Supporting policies include labels that endorse the performance of the equipment or allow for easy comparison of performance between competing products. Consumer awareness campaigns are also used to help purchasers make more informed decisions about the total cost of ownership of the equipment and to modify behaviour (e.g. encouraging the timely repair of equipment by certified technicians).
- **Finance and Financial Delivery Mechanisms** that address the barrier of higher upfront costs of efficient equipment through incentives such as grants, rebates and tax-relief, or by extending credit lines, partial risk guarantees, loans, bulk procurement opportunities, and equipment leasing through financial intermediaries.
- **Monitoring, Verification and Enforcement (MVE)** to track which equipment is

sold in the market, to test the equipment to ensure that claims of performance are accurate, and to prompt corrections by those that fail to comply. Successful market transition depends on MVE. Unless effective and timely market surveillance systems are in place, substandard products risk entering markets in increasing numbers and reducing energy and financial savings. To enhance market enforcement capacities, the sharing of information and skills between countries and across regions offers an effective way through which to promote best practice. International and regional cooperation for enforcement through the sharing of laboratory and test capacities, programmes and test data, is highly recommended.

- **Environmentally Sound Management and Health** given that PCBs are a hazardous substance that is being removed from the installed stock of transformers around the world. Guidance developed by UN Environment and the Stockholm Convention Secretariat¹² detail global best practices for locating, handling and disposing of electrical equipment contaminated by PCBs and to thus avoid environmental or health impacts of PCBs. Special attention should be given to maintenance activities, to avoid spreading PCB contamination, and to the development of a legal framework around the end-of-life activities of recycling and recovery. Due to scrap metal value, transformers already enjoy a very high level of recycling of units taken out of service if cleaned from PCBs.

KEY RECOMMENDATIONS FOR POLICYMAKERS:

- Use this report, the “Policy Fundamentals Guide”, and other resources available at www.united4efficiency.org to develop and implement a national efficient transformers strategy.
- Adopt MEPS for transformers while making efforts to harmonise to standards with neighbouring countries and international test methods, such as IEC 60076.
- Energy labelling schemes should be implemented and/or HEPS levels defined to enable purchasers to easily identify top-performing transformers in the market.
- To account for losses in transformers, governments should implement purchasing practices that are based on the total cost of ownership, which includes the costs over a transformer’s entire lifetime (typically exceeding 25 years). A whole life costing model attributes a present value to the whole life costs of operating the transformer in a utility or end user’s electrical network.
- Countries should use extra caution for transformers containing PCBs to ensure properly handling and disposal according to the Stockholm Convention on Persistent Organic Pollutants.

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ACRONYMS AND ABBREVIATIONS

CAGR.....	Combined Annual Growth Rate	MEPS.....	Minimum Energy Performance Standards
CDM.....	Clean Development Mechanism	MVA.....	megavolt-ampere (10 ⁶ amperes)
CO ₂	Carbon dioxide	MT.....	megatonnes (10 ⁶ tonnes)
DFID.....	Department for International Development (UK)	MVE.....	Monitoring, verification and enforcement
DSM.....	Demand Side Management	MW.....	megawatt
EESL.....	Energy Efficiency Services Limited	NGO.....	Non-governmental organisation
EPA..	Environmental Protection Agency (US)	OECD.....	Organisation for Economic Co-operation and Development
EPR.....	Extended producer responsibility	PCB.....	Polychlorinated biphenyls
EPT.....	Energy performance test	PEI.....	Peak Efficiency Index
ESCO.....	Energy service company	PFI.....	Private Finance Initiative
EU.....	European Union	PPP.....	Public Private Partnership
FAQ.....	Frequently Asked Questions	PTT.....	Power transformer tests
GEF.....	Global Environment Facility	R&D.....	Research and development
GHG.....	Greenhouse gas	SEAD.....	Super-efficient Equipment and Appliance Deployment
GVA.....	gigavolt-ampere (giga = 10 ⁹)	SEforAll.....	Sustainable Energy for All initiative
HEPS.....	High Efficiency Performance Specification	TCO.....	Total Cost of Ownership
Hz.....	Hertz	TWh.....	Terawatt-hour
ICA.....	International Copper Association	U4E.....	United for Efficiency
IEC.....	International Electrotechnical Commission	US.....	United States of America
IEEE.....	Institute for Electrical and Electronics Engineers	UNDP.....	United Nations Development Programme
IECEE.....	IEC Conformity Assessment for Electrotechnical Equipment and Components	UNEP.....	UN Environment
kV.....	kilovolt	\$.....	United States Dollars
kVA.....	kilovolt-ampere (kilo = 10 ³)	W.....	Watt
kW.....	kilowatt	yr.....	year
LCA.....	Life-Cycle Assessment		



1. INTRODUCTION

Transformers are electrical devices in electricity systems that transfer electrical power between circuits through electromagnetic induction. Their application enables significant energy savings by increasing the voltage and decreasing the current.¹³ Generally, electricity will usually pass through four or five transformers as it travels from the power plant to the customer.

Transformers with the highest voltage above 230kV and self-cooled power ratings that exceed 60 MVA are generally referred to as large power transformers. These transformers can be found at generating stations and electrical substations converting electrical power to high voltages for transmission. Medium power transformers generally have voltage ratings between 36 kV and 230 kV and are three-phase units with power ratings between 2.5 MVA and 60 MVA. These are most often used to transfer power to a subtransmission circuit.

The voltage is further reduced by medium voltage distribution transformers into circuits where the electricity is distributed to residential, commercial, and industrial customers (see Figure 3). Transformers can be liquid-filled (cooled with mineral oil or other insulating liquid) or dry-type (cooled with air) (see Table 3). In some markets, there are a special subgroup of low-voltage distribution transformers having a primary voltage less than or equal to 1 kV.

Low-voltage dry-type distribution transformers are often found inside buildings or industrial facilities as part of the electrical infrastructure of those facilities, and work to reduce losses within the electrical distribution system or industrial installation. As a more efficient alternative to low-voltage dry-type transformers, some liquid-filled units are also used if they comply with local building codes by incorporating low-flammability cooling liquids (e.g. ester oil with a high flash (fire) point i.e. >300°C).

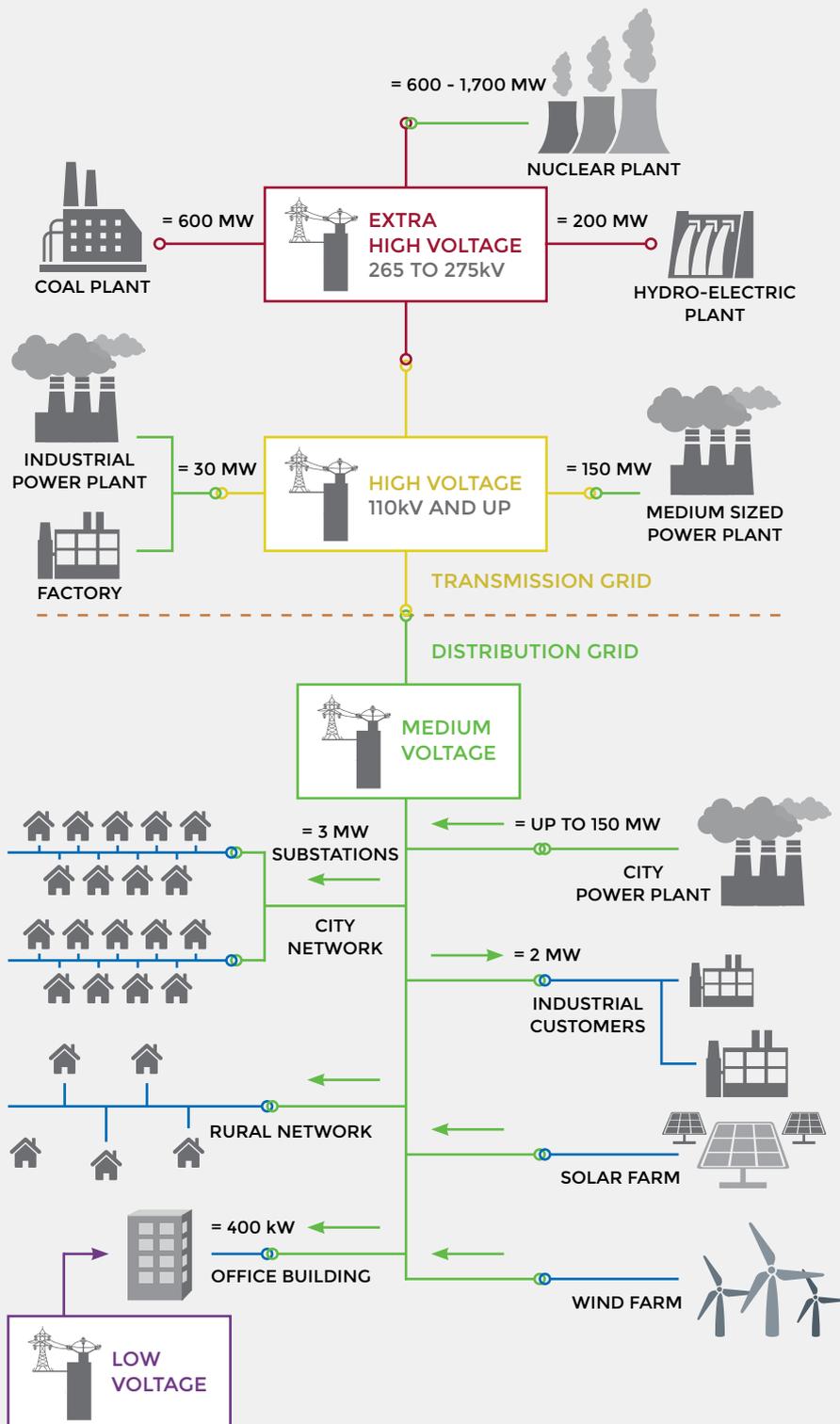


Figure 3:
Illustration
of electricity
transmission
and distribution
system¹⁴

MW is an abbreviation for megawatt and kW is an abbreviation for kilowatt; both are measures of power, whereby 1,000 kW is equal to one MW. The abbreviation kV is kilovolt, meaning 1,000 volts; and transformers are depicted in the schematic as two interlocking rings.

DISTRIBUTION TRANSFORMER



POWER TRANSFORMER



DRY-TYPE TRANSFORMER



Table 3:
General
overview of the
main types of
electrical power
transformers

TRANSFORMER GROUP	VOLTAGE (KV)	PHASES	TYPICAL INSULATION	COMMON USE
LARGE POWER	>245 (High voltage)	Single and Three	Liquid-filled	Stepping up to or down from higher voltages for transmission of electricity over long distances; substation transformers
MEDIUM POWER	>36 & ≤230 (Medium voltage)	Single and Three	Liquid-filled or dry-type	Stepping voltages down from a sub-transmission system to a primary distribution system
MEDIUM VOLTAGE DISTRIBUTION	≤36 (Medium voltage)	Single and Three	Liquid-filled or dry-type	Stepping voltages down within a distribution circuit from a primary to a secondary distribution voltage
LOW VOLTAGE DISTRIBUTION	≤1 (Low voltage)	Single and Three	Dry-type	Stepping voltages down within a distribution circuit of a building or to supply power to equipment

Transformers operate nonstop and often have very long service lifetimes, typically exceeding 25 years. Although most transformers have efficiency levels greater than 98 per cent, a study conducted for the EC found that energy consumed during a transformer's service life is still the dominant factor contributing to environmental impacts over its lifecycle.¹⁵ Therefore, it is critically important to consider cost-effective measures that could reduce losses in the transformer and alleviate these environmental impacts.

Technical solutions to improve the energy efficiency of transformers are commercially available. The market penetration of highly efficient transformers still has significant room for growth. Policy measures are being adopted in a few countries to encourage and ensure greater penetration of energy-efficient transformers, but the vast majority of markets remain untouched.

1.1 WHY LEAPFROG TO ENERGY-EFFICIENT TRANSFORMERS?

Transformers lose approximately 1,100 TWh of electricity worldwide.¹⁶ This is roughly equivalent to the total national electricity consumption of Japan. Over the next two decades, such losses are projected to rise as economies expand and additional capacity is added. Table 4 presents a projection of world electricity consumption and the proportion of losses attributable to power and distribution transformers.¹⁷ The table also shows the energy and CO₂ savings that would result from all countries adopting or updating minimum energy performance standards (MEPS) for transformers starting in 2020 or the best available technologies (BAT) starting in 2020.

Table 4:
Electricity and CO₂ savings potential of all electric power transformers globally¹⁸

	DESCRIPTION	Units	2020	2025	2030	2035	2040
ELECTRICITY SAVINGS	World electricity consumption	TWh/yr	24,222	27,516	30,875	34,100	37,352
	Baseline electricity loss by transformers	TWh/yr	1,181	1,306	1,462	1,643	1,845
	% of world electricity use	%	4.88	4.75	4.73	4.82	4.94
	Annual savings from MEPS in 2020	TWh/yr	18	113	218	325	426
	Annual savings from BAT in 2020	TWh/yr	34	209	400	595	776
	Cumulative savings from MEPS in 2020	TWh	18	390	1,267	2,678	4,610
	Cumulative savings from BAT in 2020	TWh	34	718	2,331	4,918	8,444
CO ₂ SAVINGS	Baseline emissions from transformer electricity losses	MT/yr	732	817	923	1,046	1,183
	Annual savings from MEPS in 2020	MT/yr	10	66	127	190	250
	Annual savings from BAT in 2020	MT/yr	20	129	248	370	483
	Cumulative savings from MEPS in 2020	MT	10	226	737	1,562	2,693
	Cumulative savings from BAT in 2020	MT	20	441	1,438	3,045	5,240

Policy measures are urgently needed to accelerate adoption of energy-efficient transformers. The fact that 13 of the largest economies in the world already regulate these products is a sign that transformers present a compelling opportunity for saving energy and money.

On a life-cycle cost basis, an energy-efficient transformer is very appealing given its non-top operation and 25-year service life. These savings translate into reductions in peak loading, lower electricity bills and greater reliable of supply. Payback periods vary with the equipment and electricity costs and can be as short as one year or as long as six years or more, depending on how ambitious the government wishes to be with the regulation.

For transformers, a six -year payback on a product that typically lasts more than 25 years is still very attractive.

1.2 BARRIERS TO MARKET TRANSFORMATION

Barriers (see Table 5) to the adoption of energy-efficient transformers must be addressed at the policy design phase to ensure a successful market transformation.

Table 5:
Barriers to
the adoption
of energy-
efficient
transformers

BARRIER	DESCRIPTION	EXAMPLES
FINANCIAL	Magnitude of the first cost relative to less efficient technologies	<ul style="list-style-type: none"> Higher relative cost of energy-efficient transformers, poses an initial investment hurdle, despite favourable payback periods (which vary by economy and cost of generation) Lack of sustainable financing schemes Lack of ability of institution to earn return on investment
MARKET	Market structures and constraints that prevent efficient transformer investments	<ul style="list-style-type: none"> Limited availability of energy-efficient transformers High import costs or tariffs Split incentive—utilities lack incentive to invest in efficiency because losses are simply passed along as a cost of business to end-use customers High number of refurbished transformers offered on the market
INFORMATION AND AWARENESS	Lack of information provided on efficient transformers and their energy savings benefits	<ul style="list-style-type: none"> Lack of knowledge among policymakers, T&D system designers, suppliers, operations and maintenance facility managers Poor promotion of efficient transformer products Business as usual approach / risk aversion
REGULATORY AND INSTITUTIONAL	Structural characteristics of the political and legal system that make it difficult to promote efficient transformers	<ul style="list-style-type: none"> Lack of policies and practical experience with energy-efficient transformers Lack of policies encouraging energy-efficient transformers—including regulatory, monitoring/verification, and enforcement Lack of warranties to ensure product quality
TECHNICAL	Lack of resources and infrastructure for promoting efficient transformers	<ul style="list-style-type: none"> Lack of adequate or accredited testing facilities Limited resources to monitor, verify and enforce regulations Accessibility of poor-quality refurbished transformers through unorganised units disrupts consumer choices Access to new materials and technologies
ENVIRONMENTAL AND HEALTH RISK PERCEPTION	Concerns over health or safety relating to PCBs and other technologies	<ul style="list-style-type: none"> Lack of collection and recycling schemes for recovery and treatment at end of life Addressing safety issues such as PCB recovery and destruction, electrical safety Lack of knowledge amongst different stakeholders (including customs departments/border control in developing countries where end-of-life material (transformer scrap) is imported and used for making new transformers).

1.3 THE INTEGRATED POLICY APPROACH

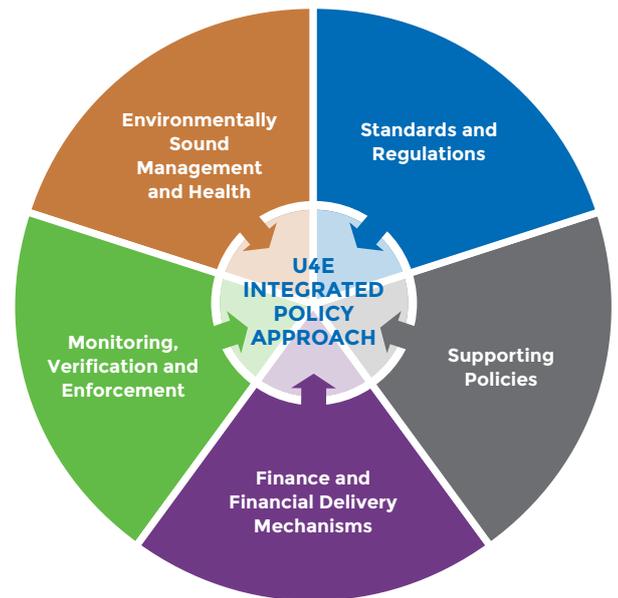
Policymakers are encouraged to use this guide in concert with the “Policy Fundamentals Guide” and other resources available at www.united4efficiency.org to develop and implement a national efficient transformers strategy.

The guidance is meant to be flexible, rather than prescriptive. Each country should consider and make decisions based on its specific priorities and circumstances. This process should involve all relevant authorities and stakeholders in jointly determining priorities and the most appropriate pathways to achieve them. It can be applied to large power and distribution transformers in both utility networks as well as those used in commercial and industrial applications.

Figure 4: U4E Integrated Policy Approach for a rapid transition to efficient transformers

An Integrated Policy Approach to fully transform a market includes:

- **Standards and Regulations** that define which equipment is blocked from the market (those that do not meet mandatory MEPS), which equipment may be recognized for meeting performance and quality requirements, how to test the equipment, implementation periods, and other aspects. Standards and regulations are essential to the success of market transformation and therefore are the cornerstone of the U4E Integrated Policy Approach. Regulations should always be cost-effective.
- **Supporting Policies** that ensure the smooth implementation of standards and regulations and achieve broad public acceptance. Supporting policies include labels that endorse the performance of the equipment or allow for easy comparison of performance between competing products. Consumer awareness campaigns are also used to help purchasers make more informed decisions about the total cost of ownership of the equipment and to modify behaviour (e.g. encouraging the timely repair of equipment by certified technicians).
- **Finance and Financial Delivery Mechanisms** that address the barrier of higher upfront costs of efficient equipment through incentives such as grants, rebates and tax-relief, or by extending credit lines, partial risk guarantees, loans, bulk procurement opportunities, and equipment leasing through financial intermediaries.
- **Monitoring, Verification and Enforcement (MVE)** to track which equipment is sold in the market, to test the equipment to ensure that claims of performance are accurate, and to prompt corrections



by those that fail to comply. Successful market transition depends on MVE. Unless effective and timely market surveillance systems are in place, substandard products risk entering markets in increasing numbers and reducing energy and financial savings. To enhance market enforcement capacities, the sharing of information and skills between countries and across regions offers an effective way through which to promote best practice. International and regional cooperation for enforcement through the sharing of laboratory and test capacities, programmes and test data, is highly recommended.

- **Environmentally Sound Management and Health** given that polychlorinated biphenyls (PCBs) are a hazardous substance that is being removed from the installed stock of transformers around the world. Standards should be established in line with global best practice to minimize any environmental or health impact of PCBs or other harmful material. Special attention should be given to the development of a legal framework around end-of-life activities, recycling and recovery. Due to scrap metal value, transformers already enjoy a very high level of recycling of units taken out of service.

1.4 REPORT OVERVIEW

This report offers an overview of key elements needed for transforming a national transformer market with unique insights in the following chapters:

Chapter 2

Transformer Markets and Technology—gives an overview of technology—provides a description of some of the recent innovations that are now promoting energy performance in the market. It provides an overview of the market (end-use sectors) and technology trends. Finally, this chapter offers an overview of the U4E Integrated Policy Approach which is the approach for promoting energy performance in transformer markets.

Chapter 3

Standards and Regulations—provides an overview of the test methods and metrics used to measure the performance and quality of transformers, and which are used in product regulations. It also provides a summary of requirements, functionality-related requirements and product information obligations.

Chapter 4

Supporting Policies—offers a synopsis of the two main areas of supporting policies, product labelling and communication and education. The labelling summary explores the different types of labels, including comparative and endorsement labels. The communications and education section focuses on the critical aspect of empowering transformer owners with information, enabling them to understand how they can benefit from least life-cycle cost.

Chapter 5

Financing and Financial Delivery Mechanisms—addresses the critical issue of overcoming first-cost barriers to market adoption, including topics such as financing sources, approaches and stakeholders. Areas covered include energy service companies, lender finance, multilateral development institutions and other mechanisms.

Chapter 6

Market Monitoring, Verification and Enforcement (MVE)—discusses the importance of MVE, from both a manufacturer's and consumer's perspective. Discusses the critical role of government in establishing and maintaining a robust market surveillance programme.

Chapter 7

Environmental Sustainability and Health—provides a summary of the importance and benefits of recycling of used transformer metals and coolant, and possible financing mechanisms for these schemes. This chapter has a specific focus on PCBs.

Chapter 8

Conclusions and Recommendations—offers an overview of the main value and benefits associated with efficient transformers. Touches on the critical aspects of standards and regulations (MEPS), supporting policies, finance, MVE and environmental sustainability, offering a sustainable approach overall.

Chapter 9

Implementation—provides a summary of the process governments may choose to follow to implement a policy-driven market transformation in their respective national markets.

Chapter 10

Resources—presents an overview of reports and resources and energy-efficient transformer programmes and initiatives from around the world, including a high-level summary, web links and additional information.

Finally, the report offers a glossary (Annex A) of commonly used terms found in this report.



2. TRANSFORMER MARKETS AND TECHNOLOGY

WHAT?	Provides an overview of transformer markets and technology.
WHY?	Sets the context on transformer technology and markets that will affect all the subsequent discussion and decisions.
NEXT?	<p>Some key questions to keep in mind:</p> <ul style="list-style-type: none"> • When should my country shift its markets to energy-efficient transformers? • What are the market barriers to more efficient transformers in my country, and how can these be overcome? • Who are the stakeholders in our national supply chain with whom we should be engaged with to promote energy-efficient transformers? • If we are buying refurbished units, can they still be efficient?

2.1 TRANSFORMER TECHNOLOGY

Transformer losses occur in an energised transformer that is ready to convert voltage (i.e. in a no-load condition), and when it is energised and actively converting the voltage (i.e. in a load condition). The losses

are manifested in the transformer as excess heat, which occur in the transformer core and/or windings. The following sections discuss how losses occur and what can be done to minimise them.

2.1.1 TRANSFORMER LOSSES

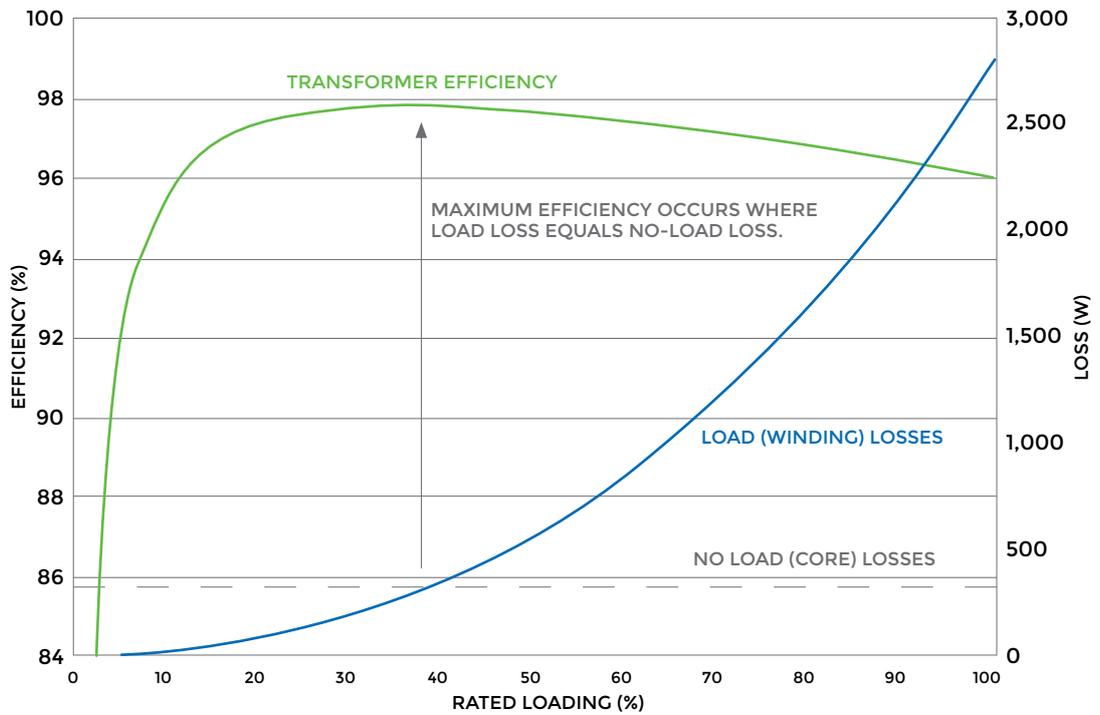
Losses in the core of a transformer are often called “no-load losses” or “iron losses” because they are present whenever the transformer is energised, even when the transformer is not actively supplying a load. No-load losses are independent of the loading on the transformer, meaning they do not change as the loading on the transformer varies. No-load losses come from two sources – hysteresis and eddy currents. Hysteresis losses are created by the magnetic lag or reluctance of the molecules in the core material to reorient themselves at the operating frequency of the transformer (i.e. 50 or 60 Hz). Eddy currents occur in the core due to the induction of the alternating magnetic field—the same way that field induces current in the secondary winding. These circulating electrical currents do not leave the core; they simply circulate within the material and become waste heat.

Losses in the windings of a transformer are often called “winding losses” or “copper losses.” They are associated with the current flowing through the windings. Load losses are primarily caused by the electrical resistance of the windings. The magnitude

of these losses varies with the square of the current being carried. There are also stray eddy losses in the conductor that are caused by the magnetic flux. The resistive losses in the windings mean that as the loading on the transformer increases, the losses increase as well, by approximately the square of the load. This impact is visible in Figure 5 that shows the no-load losses and load losses described over loading points from 0 to 100 per cent of rated capacity transformer loading. Peak efficiency of the transformer occurs at the point where no-load losses are equal to load losses, and this is always less than the rated nameplate capacity of the transformer.

In addition to the losses in the core and the winding of a transformer, certain transformers could have other sources if they incorporate active cooling systems engaged while the transformer is operating. Active cooling systems include pumps and/or fans that operate when the transformer gets above a certain temperature. The energy used by these cooling systems is considered an operating loss of the transformer.

Figure 5:
Example of the
relationship
between
transformer
losses and
efficiency



2.1.2 IMPROVING ENERGY PERFORMANCE

A transformer can be made more energy-efficient by improving the materials of construction (e.g. better-quality core steel or winding material) and by modifying the geometric configuration of the core and winding assemblies. Making a transformer more energy efficient (i.e. reducing electrical losses) is often a trade off between more expensive, lower-loss materials and designs, and the value a customer attaches to those

losses. For a given efficiency level, the no-load and load losses are generally inversely related: reducing one usually increases the other, as shown in Table 6. The table also shows are five approaches to reducing no-load losses. One of these is a material-substitution option and four are transformer-design options. For a discussion on each of these options, please see Annex E.

Table 6: Loss-reduction interventions for transformers

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

2.1.3 REFURBISHED TRANSFORMERS

In some capital-constrained markets, businesses or utilities may opt to install refurbished transformers to help control installation costs. These tend to be less reliable and have already lost some of their useful life. They can experience higher losses than new units either because of the old,

inefficient materials they were built with and/or the work that was done to repair them. Refurbished transformers do not offer the same durability and reliability as new units, yet still incur the same installation and commissioning costs and have higher operating costs.

CASE STUDY: ESKOM's Policy for Refurbished Distribution Transformers, South Africa

In South Africa, the national electric utility, ESKOM, decided to no longer purchase and install refurbished distribution transformers. They conducted research in one region of the grid with approximately 100 transformers and identified various problems with refurbished units. The suppliers were not accredited or subject to the same quality control and quality assurance inspections as those offering new transformers.

The costs of transformer refurbishment, the lack of a technical specification for repair and the inadequacy of repair quality management processes led to Eskom's decision. Eskom concluded that all faulty transformers that are outside of warranty should be scrapped according to commercial scrappage and recycling procedures unless the transformer has very minor defects (e.g. replacing a bushing) that can be addressed by Eskom's maintenance teams.

2.2 MARKET DEVELOPMENTS

In general, transformer manufacturers are supportive of energy efficiency requirements because they enable them to earn more revenue through the construction of superior equipment. Indicative of this, in the regulatory processes to establish MEPS in Canada, the EU, and the US, transformer manufacturers were supportive of the processes, providing data, technical assistance, and information to policymakers.

With the expansion of trade and sourcing of distribution transformers from around the world, a few companies are emerging as global and regional sales leaders. The global market shares of the manufacturers from 2014 are given in Table 7.

Table 7: Global market share of leading transformer manufacturers in 2014¹⁹

COMPANIES	MARKET SHARE IN 2014 (%)	COMPANIES	MARKET SHARE IN 2014 (%)
ABB	11.5	SCHNEIDER	2.9
SIEMENS	8.8	XD GROUP	2.7
GENERAL ELECTRIC	7.9	HOWARD INDUSTRIES	2.3
TOSHIBA	4.9	TWBB - BAODING	2.2
TBEA	4.0	JHSP	2.1
CG GROUP	3.7	HYUNDAI	1.8
mitsubishi	3.4	MEIDENSHA	1.7
HITACHI	3.0	SPX WAUKESHA	1.7

As shown in Table 8, world demand for electricity is rising quickly and thus more transformers will need to be installed to reliably service the increasing demand. Losses from the installed stock of transformers are increasing in absolute terms, even though some economies have energy efficiency policies in place. Losses as a percentage of consumption have declined.

Some regions are experiencing load growth faster than other; for example, both Africa and Asia have over 3 per cent average annual load growth.

Table 8: Electricity demand growth projection by region, annual consumption (TWh)²⁰

REGION/ COUNTRY	2015	2020	2025	2030	2035	2040	CAGR (%)*
AFRICA	669	805	967	1,158	1,385	1,642	3.7
AMERICA	5,836	6,357	6,847	7,348	7,851	8,430	1.5
ASIA	9,590	11,802	14,039	16,321	18,426	20,475	3.1
EUROPE	4,343	4,591	4,932	5,255	5,586	5,905	1.2
EURASIA	329	360	401	444	486	522	1.9
OCEANIA	300	330	356	379	400	417	1.3
TOTAL	21,066	24,245	27,542	30,906	34,135	37,391	2.3

Table 9 provides estimates of the installed stock of transformers that are servicing the global growth in electricity consumption, transmitting and distributing power from the generating stations to homes, offices and industry around the world.

Table 9: Projection of installed stock of transformers by region, capacity (GVA)²¹

The units in this table are gigavolt-amperes, or one million kilovolt-amperes.

REGION	2015	2020	2025	2030	2035	2040	CAGR (2015-40)
	(GVA)	(GVA)	(GVA)	(GVA)	(GVA)	(GVA)	(%)
AFRICA	564	764	994	1,256	1,550	1,878	4.9
AMERICA	2,771	3,307	3,856	4,394	4,889	5,342	2.7
ASIA	12,415	15,899	20,046	24,671	29,478	34,252	4.1
EUROPE	2,566	2,847	3,122	3,405	3,679	3,937	1.7
EURASIA	285	330	379	431	484	535	2.6
OCEANIA	250	286	325	364	399	428	2.2
TOTAL	18,850	23,433	28,722	34,521	40,478	46,372	3.7
OECD	6,184	7,298	8,405	9,447	10,345	11,097	2.4
NON-OECD	12,666	16,134	20,317	25,074	30,134	35,276	4.2

The region with the highest projected growth rate in installed stock of transformers is Africa, with a 4.9 per cent combined annual growth rate from 2015 to 2040. Over that time period, Africa's installed stock of transformers are expected to more than triple. Globally, the installed stock increases by a CAGR of 3.7 per cent, equating to slightly more than a doubling of transformer stock between 2015 and 2040.

The rate of growth in the non-OECD countries is nearly double the rate in the OECD.

With this growth, the electrical losses across the global stock of transformers is increasing. Table 10 provides an estimate of the losses in all the distribution and power transformers in the installed global stock, broken down by region.

Table 10: Projection of transformer losses by region, annual electricity consumption (TWh)²²

REGION	2015	2020	2025	2030	2035	2040	CAGR (2015-40)
	(TWh/yr)						
AFRICA	36	48	61	77	95	114	4.8%
AMERICA	141	148	158	169	183	197	1.4%
ASIA	730	813	920	1,051	1,202	1,366	2.5%
EUROPE	141	138	129	122	118	118	-0.7%
EUROPE & ASIA	18	20	23	26	29	31	2.2%
OCEANIA	13	14	15	16	17	18	1.3%
TOTAL	1,079	1,181	1,306	1,462	1,643	1,845	2.2%
OECD	326	329	328	330	334	341	0.2%
NON-OECD	753	852	978	1,132	1,309	1,504	2.8%

This is a business as usual scenario that assumes no new policy measures are adopted.

It is projected that the European market will experience a slight reduction in losses over this time period owing to a regulatory measure adopted in 2014. This absolute reduction in losses demonstrates the effectiveness of this policy instrument, as it occurs concurrently with a growth of 1.7 per cent per annum in electricity consumption in Europe.

Overall, the OECD countries are projected to only experience a very slight increase (0.2 per cent) in transformer losses in absolute terms between 2015 and 2040, due in large part to the regulatory measures that have already been adopted in these economies.

3. STANDARDS AND REGULATIONS

<p>WHAT?</p>	<p>A discussion on regulations and standards as policy tools for transforming markets; an overview of the test standards and methods used to define and measure transformer performance; a summary of minimum energy performance standards (MEPS) as a regulatory tool to transform markets; an outline of a systematic approach to developing MEPS; and the benefits of harmonisation regionally and with trading partners.</p> <p>Of all the policy instruments, minimum energy performance standards (MEPS) are one of the most powerful tools, as they require that entire markets shift to higher levels of efficiency. When combined with supporting policies including financial incentives and communications programmes, as well as with monitoring, verification and enforcement activities to ensure regulatory compliance, MEPS will change markets and ensure the realisation of national benefits from cost-effective energy savings. This chapter starts with a discussion of the metrics that can be used for measuring the efficiency of transformers and then focuses on MEPS as a policy instrument. The chapter finishes by providing an overview of the International Electrotechnical Commission (IEC) recommended levels.</p>
<p>WHY?</p>	<p>Provides information on minimum energy performance standards, or MEPS, the first part of the U4E Integrated Policy Approach which is the cornerstone of market transformation.</p>
<p>NEXT?</p>	<p>Some key questions to keep in mind:</p> <ul style="list-style-type: none"> • What is the status of technical standards in the different markets? Are we affiliated with the IEC? • Do we have all the information needed to provide a complete picture? • What is the proportion of demand met by domestic manufacturing? How concentrated or fragmented is the industry? Who are the key players? How current is their level of technology? • Do we have accredited testing facilities for transformer testing? • What level of ambition would be appropriate; should we adopt the technically achievable, economically justifiable efficiency level in one go or in multiple steps?

3.1 MINIMUM ENERGY PERFORMANCE STANDARDS

MEPS establish the minimum energy performance levels that all transformers would have to meet in a market. Utilities and other customers are still able to purchase at energy performance levels higher than the MEPS level; however, they would not be allowed to purchase units with an energy performance below this level.

Many countries around the world have established MEPS for transformers to help ensure that efficiency requirements are guaranteed. Due to the fact that there

are differences in how electrical systems are designed and operated around the world, there are barriers that make it difficult to compare the performance requirements of transformers around the world. Annex B provides a discussion on how a comparison can be made, taking into account differences in the definition of the transformer rating, the reference temperatures for loss measurement, and the operating frequency.

3.1.1 TESTING AND ENERGY PERFORMANCE METRICS

The purpose of a test standard is to reliably and accurately measure the performance of a product. Officials can then use the results to determine whether the product meets MEPS. Testing standards are complex and detailed documents developed over many years with the input of hundreds of experts from around the world. Test standards, like those published the IEC, are updated regularly and strive to meet the following objectives:

- **Coverage:** the testing standard scope must cover that of the regulated product
- **Metric:** the testing standard must can determine energy consumption, efficiency or other metric that constitutes the basis of the regulation
- **Accurate:** is designed to minimise random or systemic errors, establishes maximum margins of error and avoids the use of optional approaches
- **Representative:** provides robust measurement of energy consumption reflective of in-situ energy use under conditions where the product is used
- **Repeatable:** gives the same result each time a product is tested in the same laboratory
- **Reproducible:** gives the same result each time a product is tested in different laboratories
- **Low cost:** is not overly expensive or time consuming to conduct, and balances the robustness of the test and cost of testing and
- **Portable (optional):** if necessary, should be designed to be applied onsite with separate energy source generation (e.g. large distribution transformers can be difficult to transport to laboratories).

When selecting the energy performance metric for regulating transformers, policymakers have a few options. Policymakers need to decide which approach is best given the conditions of their market. To assist with that choice, four common approaches are described below:

- **Maximum losses at no load and maximum losses at full load**—this metric places two constraints on each design and is closest to that specified in the common test standards. It involves ensuring that a design does not exceed the maximum values of no-load losses and full load losses in watts, when specified separately. This approach is used in China and the EU (for distribution and medium-power transformers).
- **Maximum combined losses at a specified loading point**—this metric places a single constraint on the design, measured in watts, which is the sum of the no-load losses and the load losses at the specified loading point. This approach is used in India and Japan.
- **Minimum efficiency at a defined loading point**—this metric is the ratio of the active power in watts delivered by the transformer over the load relative to the active power in watts drawn by it from the source. Percent efficiency varies with load and consequently must be declared at a specified loading point. This approach is used in Australia and US (See Annex B for slightly different methods for calculating percent efficiency between the IEC and IEEE)
- **Minimum efficiency using peak efficiency index (PEI)**—this is an index that was developed by a technical working group supporting the EC’s analysis of regulations for large power transformers. The equation for peak efficiency determines the appropriate highest efficiency value of any transformer design at an optimal loading point. This approach was included in the European Ecodesign regulation for transformers.²³

3.1.2 MEPS FOR LIQUID-FILLED TRANSFORMERS

Table 11 offers a summary of liquid-filled distribution transformer efficiency programmes around the world. This table identifies the country/economy, the scope of transformers covered, the requirements, whether it is mandatory or not, and the standard or regulation referenced.

In addition to these regulations on distribution transformers, two economies, China and the EU, also have regulations on large power transformers. In China, the regulations on large power transformers were adopted in 2009 (GB 24790-2009:

Minimum allowable values of energy efficiency and the energy efficiency grades for power transformers). The Chinese National Institute of Standardisation is currently reviewing this regulation along with their Distribution Transformer regulation released in 2013 and will be updating both and combining them into one regulation. In Europe, the regulation adopted in 2014 applies to both distribution transformers and large-power transformers and is under review by the EC.

Table 11: Summary of coverage of liquid-filled distribution transformer programmes²⁴

COUNTRY / ECONOMY	TRANSFORMERS COVERED	INDICATIVE REQUIREMENTS	MANDATORY?	STANDARD / REGULATION
AUSTRALIA/ NEW ZEALAND	1 phase: 10-50 kVA 3 phase: 25-2500 kVA Voltage: 11 and 22 kV	Efficiency at 50% load	Yes, adopted 2004	AS2374.1.2-2003
BRAZIL	1 phase: 5 to 100 kVA 3 phase: 15 to 300 kVA Voltage: 15, 24.2 & 36.2kV	Max watts core and coil losses at 100% load	Yes, adopted 2010	ABNT NBR 5356; ABNT NBR 5440
CANADA	1 phase: 10-833 kVA 3 phase: 15-3000 kVA	Efficiency at 50% load	No, voluntary since 2000	CSA C802.1
CHINA	1 phase: 5-160 kVA 3 phase: 30-1600 kVA	Maximum core and coil losses at 100% load	Yes, adopted 2013	JB/T 10317-02 GB 20052-2013
EUROPE*	3 phase: 25-40,000 kVA; Voltage: 24 and 36kV	Maximum core and coil losses at 100% load	Yes, adopted 2014	EN50588-1:2014; EU No 548/2014
INDIA	1 phase: 5 - 25 kVA 3 phase: 16-2500 kVA	Maximum W losses at 50% and 100% loading	Yes, adopted 2014	IS 1180:2014 & Gol Gazette 2968
ISRAEL	100-2500 kVA Voltage: 22kV or 33kV	Maximum W losses 100% load	Yes, adopted 2011	IS 5484
JAPAN	1 phase: 5-500 kVA 3 phase: 10-2000 kVA both 50 and 60 Hz Voltage: 3 and 6 kV	≤500 kVA: 40% load >500 kVA: 50% load	Yes, adopted 2008, updated 2013	Top Runner
MEXICO	1 phase: 5-167 kVA 3 phase: 15-500 kVA Voltage: 15, 25 and 34.5 kV	Efficiency at 50% load	Yes, adopted 1999	NOM-002-SEDE-1997
REPUBLIC OF KOREA	1 phase 10-100 kVA; 1 and 3 phase; 3.3-6.6kV, 100-3000 kVA 1 and 3 phase; 22.9kV, 100-3000 kVA & 10-3000 kVA	Efficiency at 50% load	Yes, adopted 2012	KS C4306; C4316 and C4317
US	1 phase: 10-833 kVA 3 phase: 15-2500	Efficiency at 50% load	Yes, adopted 2010, updated 2016	10 CFR 431
VIETNAM	25-2500 kVA, 0.4-35kV	Efficiency	Yes, adopted 2013	TCVN 8525:2010

* The European regulations apply to all 28 member countries of the EU, as well as the European Free Trade Area (Norway, Iceland and Liechtenstein) and Switzerland.

Figure 6 presents a comparison of the various programmes for liquid-filled three-phase distribution transformers. These data have been normalised to all show 50 per cent loading, 50 Hz operation and using the IEC definition of rated power (kVA). For the US, the transformers have also had their load losses corrected to 75°C, making them consistent with the IEC reference temperature. This figure consists of mandatory, minimum level performance requirements (i.e. MEPS) from the countries listed in the table above. Thus, programmes like the high-efficiency performance levels from Australia, Israel, and the Republic of Korea are not included in this graph.

For the countries shown, the highest efficiency curve for the smaller power ratings (up to about 50 kVA) is the US DOE MEPS level that took effect in January 2016. Above that size, the European Tier 2 requirements that take effect in 2021 are the most ambitious. The two low efficiency curves in the graph are the MEPS in the Republic of Korea and Brazil.

As clearly visible in the Figure 6, the very small power ratings (i.e. below 30 kVA) of the EC's Tier 1 MEPS that took effect in 2015 are the lowest, and continue off the scale of the graph for sizes between 5 and 25 kVA. Due to the fact that the IEC adopted the European curves, this same issue with very low ambition on small power ratings is also prevalent in IEC 60076-20. Policymakers may wish to review and make adjustments to these requirements, given that these small power ratings are popular in small and emerging distribution networks.

Figure 6:
Efficiency at
50% load (IEC)
for three-phase
liquid-filled
transformers²⁵

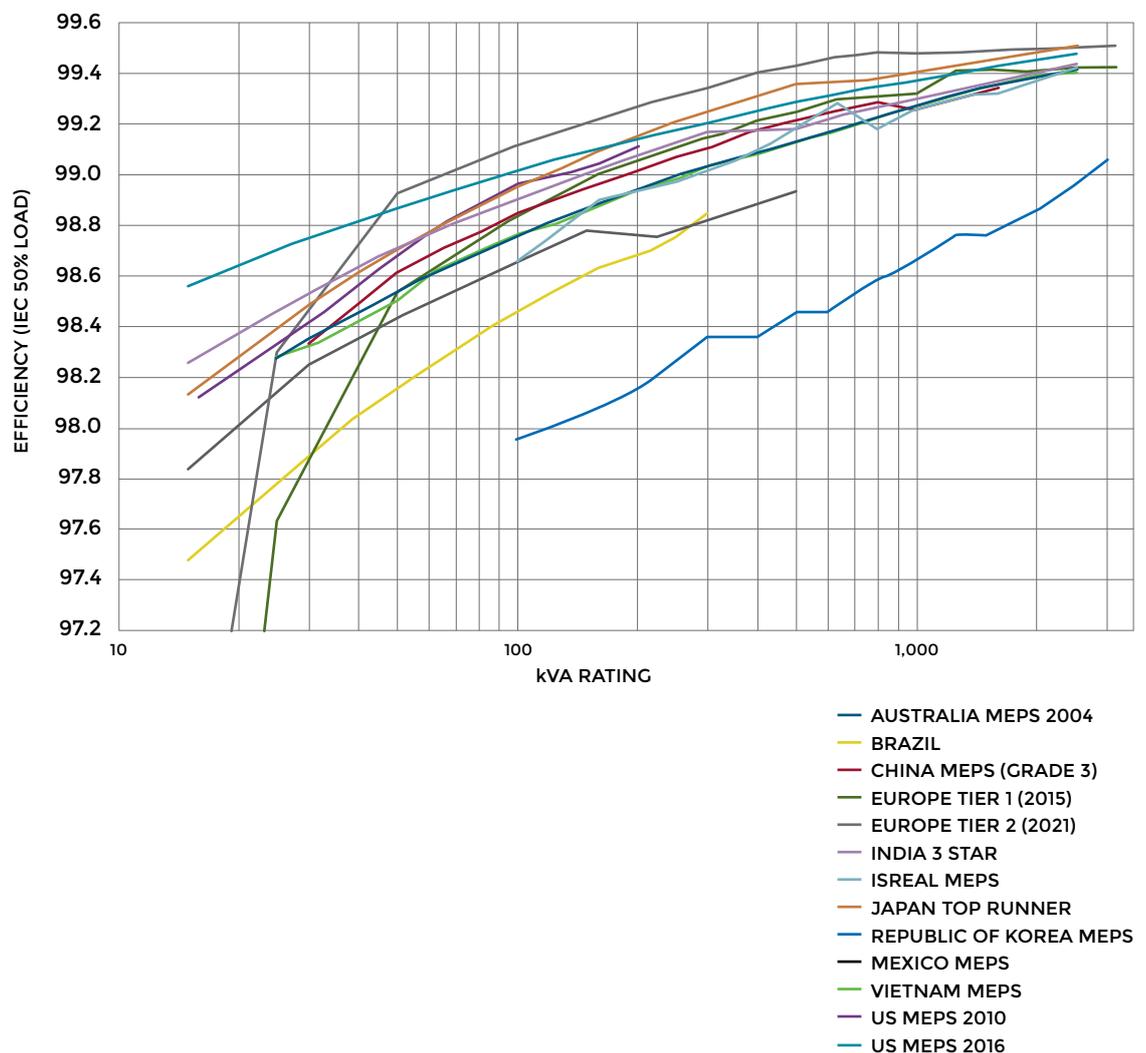


Figure 7 presents the comparison of single-phase liquid-filled transformers regulations (note: fewer governments regulate these transformers). The US DOE MEPS levels that take effect in January 2016 are the most ambitious of the MEPS programmes and are very much in line with Japan's Top Runner scheme. The requirements for Brazil, China's JB/T (industry) standard and the Republic of Korea's MEPS levels (which start at 100 kVA) are the lowest of those analysed. The curves generally show that all the countries are clustered between 1.0 to 1.5 per cent of each other on the efficiency scale at any given rated power.

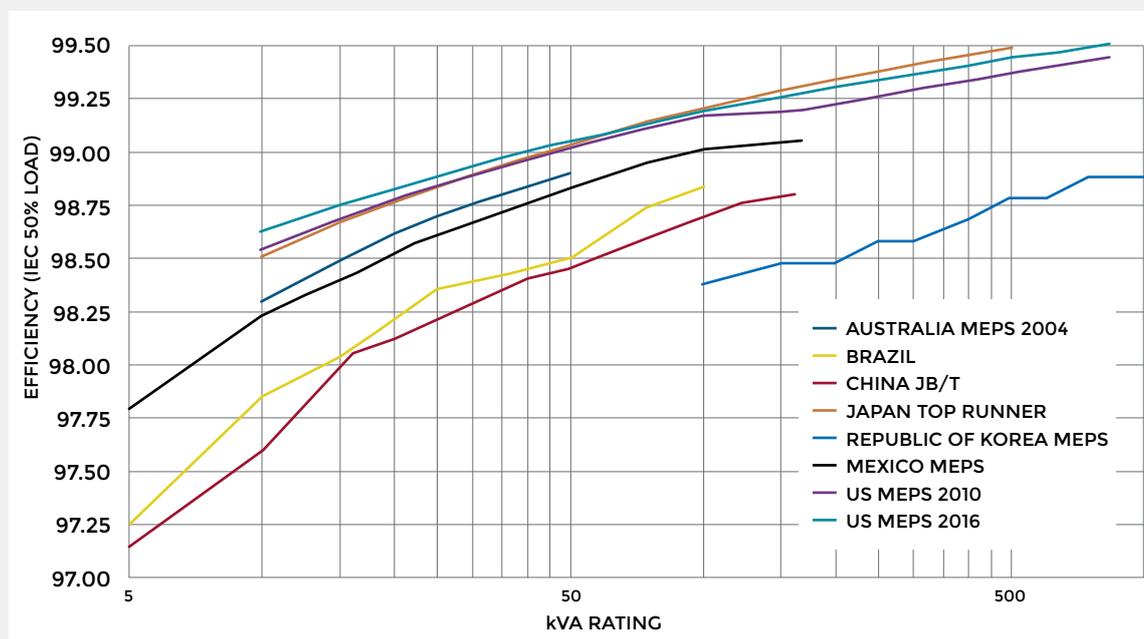


Figure 7: Efficiency at 50% load (IEC) for single-phase liquid-filled transformers²⁶

3.1.1 MEPS FOR DRY-TYPE DISTRIBUTION TRANSFORMER

Table 12 offers a summary of the dry-type distribution transformer efficiency programmes in place around the world. This table identifies the country/economy, the scope of transformers covered, the requirements, whether it is mandatory or not, and the standard or regulation referenced.

Table 12: Summary of coverage of dry-type distribution transformer programmes²⁷

COUNTRY/ ECONOMY	TRANSFORMERS COVERED	INDICATIVE REQUIREMENT	MANDATORY?	STANDARD / REGULATION
AUSTRALIA	1 phase: 10-50 kVA 3 phase: 25-2500 kVA; Voltage: 11 and 22kV	Efficiency at 50% load	Yes, April 2004	AS2374.1.2-2003
CANADA*	1 phase: 15-833 kVA 3 phase: 15-7500 kVA Voltages: 20-45, >45-95; >95-199kV BIL	35% loading for low voltage (1.2kV) and 50% for >1.2kV	Yes, April 2012	C802.2-12/ Canada Gazette Part II
CHINA	3 phase: 30-2500 kVA; Class B, F and H.	Maximum core and coil losses at 100% load	Yes, 2013	GB 20052-2013
EUROPE**	3 phase: 50-40000 kVA ≤12kV, 17.5 and 24kV, ≤36 kV	Maximum core and coil losses at 100% load	Yes, 2015	EN50588-1:2014
ISRAEL	100-2500 kVA Voltage: 22kV or 33kV	Maximum W losses 100%	Yes, 2011	IS 5484
JAPAN	1 phase: 5-500 kVA 3 phase: 10-2000 kVA both 50 and 60 Hz Voltage: 3 and 6kV	≤500 kVA: 40% load >500 kVA: 50% load	Yes, March 2008; updated 2013	Top Runner
REPUBLIC OF KOREA	1 and 3 phase; 3.3-6.6kV, 50-3000 kVA 1 and 3 phase; 22.9kV, 50-3000 kVA	Efficiency at 50% load	Yes, July 2012	KS C4311
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: 20-45kV, 46-95, >96kV BIL	35% loading for low voltage (LV) (<600V) and 50% for medium voltage (MV)	Yes, Jan 2010; revised Jan 2016	10 CFR 431

* Please note that Canada (Natural Resources Canada) is in the process of updating its MEPS for dry type transformers. The update is part of Amendment 14 to the Energy Efficiency Regulations. <http://www.nrcan.gc.ca/energy/regulations-codes-standards/18468>

**The European regulations apply to all 28 member countries of the EU, as well as the European Free Trade Area (Iceland, Liechtenstein, and Norway) and Switzerland.

Figure 8 offers a comparison of the energy efficiency programmes reviewed for medium-voltage, three-phase dry-type distribution transformers. The data has been normalised to show 50 per cent loading, 50Hz operation and using the IEC definition of rated power (kVA) and efficiency. Due to the impact of insulation on the performance of a dry-type transformer, when preparing this comparison, transformers with similar primary voltages and insulation ratings were included to the greatest extent possible. Brazil, Mexico, India, and Vietnam do not have efficiency programmes for dry-type transformers; therefore, these countries are not included in this section of the report.

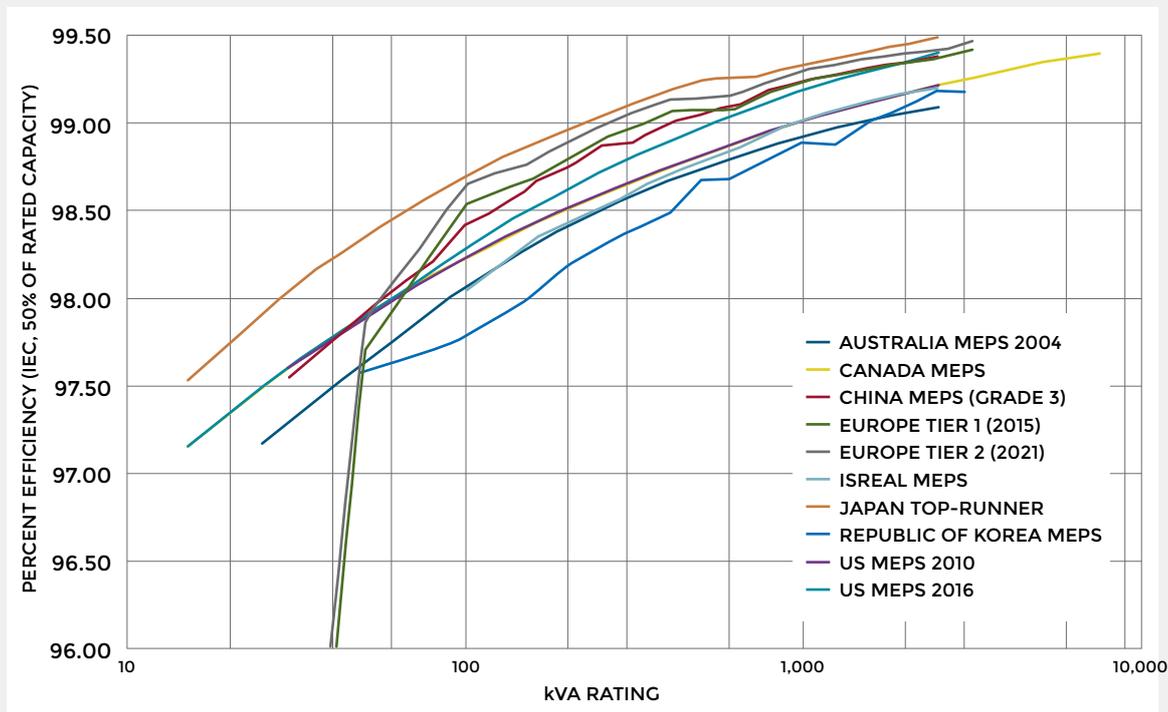


Figure 8: Efficiency programmes at 50% load for three-phase dry-type distribution transformers²⁸

Note:
For Canada, the dry-type MEPS regulations extend to 7,500 kVA.

Figure 8 efficiency curves show that all the countries are clustered together within approximately 0.5 per cent on the efficiency scale at any given power rating (kVA). The slope of the curves is generally consistent as well, although the EC's Tier 1 and Tier 2 appears to have a much steeper slope below 100 kVA and then goes off the chart below 50 kVA. As stated above for the liquid-filled transformers, the fact that the IEC adopted the European curves, this same issue with very low ambition on small power ratings is also prevalent in IEC 60076-20. Policymakers may wish to review and make adjustments to these requirements, given that these small power ratings are popular in small and emerging distribution networks.

The Republic of Korea has the lowest MEPS requirements in dry type, as is the case with liquid filled; however, the Republic of Korea's level of ambition is not as low on the dry type relative to the other countries as it is for the liquid filled. The highest level of ambition in MEPS in the above graph is the Japanese Top Runner programme. The new US DOE MEPS that take effect in 2016 are approximately in the middle of all the curves presented. Although difficult to see due to the superposition of lines, the Canadian, Israeli, and US DOE 2010 MEPS are all approximately the same.

3.2 HARMONISATION OF REGULATIONS AND STANDARDS AND THE IEC

Harmonisation of energy performance and test procedures is a means of facilitating technology diffusion and trade objectives. Harmonised test methods encourage trade, conformity assessment, comparison of performance levels, technology transfer and the accelerated adoption of best practice policy. For example, if energy efficiencies are used internationally in performance schemes, and if transformers are to be imported/exported, it is necessary to specify the measurement uncertainty levels of test methods to ensure that the manufacturer, the customer and the energy regulator all get the same result when testing distribution transformers. Both governments and manufacturers stand to gain from the harmonisation of testing methods. Benefits to governments include:

- lower development costs for preparing a test method
- comparative test results for products sold domestically and in neighbouring economies
- the ability to transpose and adapt analyses from other markets to determine appropriate domestic efficiency requirements
- adopting minimum performance thresholds and applying them as a starting point in a domestic regulatory programme

- adopting a common set of upper thresholds that can be used for market pull programmes such as labelling and incentive schemes and
- faster and less expensive testing—for compliance and other purposes—as harmonised testing creates a larger choice of laboratories that can conduct product tests.

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 and/or product labelling compliance. In an ideal world, manufacturers would conduct the testing and the result would be universally accepted by these markets as being accurate and representative of the performance of their product. A harmonised test method also enables them to look ahead to longer-term rewards for innovation around advanced product designs that will be more energy-efficient and have lower life-cycle costs for consumers. Having a consistent test method enables countries to establish a common set of efficiency thresholds, which would not only be broad enough to encompass all current market circumstances, but which also include aspirational efficiency thresholds as pointers for future market development.

3.2.1 IEC 60076 TEST METHODS

When setting MEPS, most economies around the world base their test methods on IEC 60076. In some cases, there are minor modifications that have been made due to specific or unique requirements. The economies that fall into this group that uses

or references IEC 60076 are: Australia, Brazil, China, EU, India, Israel, Japan, New Zealand, the Republic of Korea, and Vietnam. The two major economies who deviate from using IEC are Canada and the US.

The set of international standards covering power transformers is published under IEC 60076, Power Transformers, and is prepared and maintained by IEC Technical Committee 14. The Committee covers standards for power transformers, tap changers and reactors for use in power generation,

transmission and distribution. Table 13 lists the main standards documents the Committee has published. The IEC standards addressing specifically power transformer tests (PTT) and power transformer energy performance related tests (EPT) are highlighted in the EPT/PTT column.

Table 13: List of standards for IEC 60076 power transformers

IEC STANDARD	TITLE OF IEC STANDARD	NOTES
IEC 60076-1 ed3.0 (2011-04)	Part 1: General	EPT
IEC 60076-2 ed3.0 (2011-02)	Part 2: Temperature rise for liquid-immersed transformers	EPT
IEC 60076-3 ed3.0 (2013-07)	Part 3: Insulation levels, dielectric tests and external clearances in air	PTT
IEC 60076-4 ed1.0 (2002-06)	Part 4: Guide to the lightning impulse and switching impulse testing- Power transformers and reactors	PTT
IEC 60076-5 ed3.0 (2006-02)	Part 5: Ability to withstand short circuit	PTT
IEC 60076-6 ed1.0 (2007-12)	Part 6: Reactors	
IEC 60076-7 ed1.0 (2005-12)	Part 7: Loading guide for oil-immersed power transformers	
IEC 60076-8 ed1.0 (1997-10)	Part 8: Application guide	
IEC 60076-10 ed1.0 (2001-05)	Part 10: Determination of sound levels	PTT
IEC 60076-10-1 ed1.0 (2005-10)	Part 10-1: Determination of sound levels - Application guide	
IEC 60076-11 ed1.0 (2004-05)	Part 11: Dry-type transformers	EPT
IEC 60076-12 ed1.0 (2008-11)	Part 12: Loading guide for dry-type power transformers	
IEC 60076-13 ed1.0 (2006-05)	Part 13: Self-protected liquid-filled transformers	
IEC 60076-14 (2013-09)	Part 14: Design and application of liquid-immersed power transformers using high-temperature insulation materials	
IEC 60076-15 ed1.0 (2008-02)	Part 15: Gas-filled power transformers	
IEC 60076-16 ed1.0 (2011-08)	Part 16: Transformers for wind turbine applications	
IEC 60076-18 ed1.0 (2012-07)	Part 18: Measurement of frequency response	PTT
IEC/TS 60076-19 ed1.0 (2013-03)	Part 19: Rules for the determination of uncertainties in the measurement of losses in power transformers and reactors	EPT
IEC/TS 60076-20:2017	Part 20: Energy efficiency	EPT
IEC 60076-21 ed1.0 (2011-12)	Part 21: Standard requirements, terminology, and test code for step-voltage regulators	

A brief description of each of the above standards from IEC 60076 can be found in Annex C of this report. All of these standards are available for purchase from the IEC webstore.²⁹

3.2.2 IEC RECOMMENDED EFFICIENCY LEVELS

The IEC convened a technical committee to develop a specification providing guidance on energy efficiency levels for power transformers. The published specification, IEC TS 60076-20:2017(E), states its objective as: “to promote a higher average level of energy performance for transformers” due to the “need for energy saving and reduction of the emission of greenhouse gases.”

The IEC specification proposes two methods of defining an energy efficiency index and three methods of evaluating the energy performance of a transformer:

- the Peak Efficiency Index (PEI) incorporating a Total Cost of Ownership approach
- the no-load and load losses at rated power for rationalisation of transformer cores and coils for transformers generally produced in large volumes; and
- the efficiency at a defined power factor and particular load factor (typically at 50 per cent).

In the technical specification³⁰, the IEC provides two levels of recommended requirements for each of these three methods of evaluating the energy performance of a transformer. IEC Level 1 is for a modest level of energy performance and IEC level 2 establishes a more ambitious level. Importantly, IEC notes that the level of ambition chosen in a particular country should be economically validated for the intended application.

4. SUPPORTING POLICIES

WHAT?

A brief discussion of product labelling, communication, and education programmes. Product labelling explores the different label types, including endorsement and comparative. The communication discussion focuses on stakeholder empowerment through raising awareness and disseminating information.

The promotion of more energy-efficient transformers is supported by a number of policy instruments and programmes around the world. Examples of these policy instruments include:

- Minimum Energy Performance Standards (MEPS) - (see previous chapter)
- Voluntary or mandatory product labelling
- Financial incentives, subsidies and tax breaks - (see next chapter)
- Communication and educational materials
- Tools including on-line calculators and smart-phone apps for buyers
- On-site metering and audits
- Technical support and advice on procurement
- Support for R&D and demonstration projects

WHY?

Provides information on supporting policies, the second part of the U4E Integrated Policy Approach, which is critical to understanding and securing the support required to accelerate the market penetration of energy-efficient transformers.

NEXT?

Some key questions to keep in mind:

- What labelling schemes exist or have been tried in my country in the past?
- Which type of label will be the most effective way to communicate appropriate choices to transformer specifiers and purchase decision makers?
- Can we adopt existing labelling schemes with proven validity and effectiveness?
- How do we secure the correctness of the claims on the label or compliance to the criteria for affixing the label?
- Has our country convened an energy efficiency communications campaign in the past? If so, what worked and what didn't work? Are there lessons to be learned?
- Who would lead a national communications campaign in our country?

4.1 LABELLING

Product labelling is one of the most direct and effective means of delivering information about energy performance. When implemented well, it can be one of the most cost-effective energy-efficient policy measures. For transformers, there are most often two main groups of labels – endorsement labels and comparative labels:

- **Endorsement** - For products that meet or exceed a specified set of criteria; recognises premium models in the market (see Figure 9)
- **Comparative** - Facilitates comparison between products on energy or other performance aspects in a discrete set of categories and categorical comparative which is similar to comparative but replaces the A to G or Star rating with a continuous sliding scale.

Figure 9:
Example of a
distribution
transformer
label from
India, Bureau
of Energy
Efficiency



In addition to the type of label employed, transformer labels can be either mandatory or voluntary. For mandatory labels, a government requires that all manufacturers and importers apply the label to the product and/or have it clearly visible for on-line sales. Voluntary labels can be administered by governments or other entities and participation in the programme is optional.

Energy labelling schemes can be beneficial for some commercial or industrial products. They can have a significant impact accelerating the market penetration of energy-efficient models. Defining energy classes for power and distribution transformers is straightforward compared to other industrial and custom-built products and would enable governments, programme designers and other transformer specifiers to more easily identify top performing transformers in their markets. Table 14 identifies a number of economies that have energy labelling schemes for transformers. Both endorsement and comparative labels are in place, some voluntary and some mandatory.

Table 14: Countries that have labelling programmes for power transformers³¹

COUNTRY	ENDORSEMENT LABEL	COMPARATIVE LABEL	TYPE OF LABEL
CHINA	x	x	Voluntary & Mandatory
INDIA		x	Mandatory
JAPAN		x	Mandatory
MEXICO	x		Voluntary
REPUBLIC OF KOREA	x		Voluntary
US	x		Voluntary

In general, for labelling schemes to be successful, they should be designed for the needs, benefit, and convenience of consumers. It is advisable to conduct appropriate consumer research and convene focus groups when designing labels. It can be beneficial to adopt an existing labelling scheme with proven effectiveness. This would help avoid a proliferation of different labels that distract or confuse customers and reduce compliance costs and complexity for manufacturers and importers. Product labels should be easy to understand.

The success of any labelling scheme depends on its credibility. Whether the public trusts the information on the packaging is crucial. Less reputable companies may be tempted to abuse the label by claiming compliance while being unable or unwilling to invest in the necessary quality measures.

4.2 COMMUNICATION AND EDUCATION

Awareness-raising campaigns support good governmental policies and programmes. Effective communication and education campaigns should gain the active support of the key stakeholders. They should focus on the range of benefits and outcomes that end users will enjoy as a result of seeking out and selecting higher efficiency transformers. If end users can feel good about the outcome, they are more motivated to take an interest in seeking out information and to understand why it is meaningful to their purchasing decision. Dry, factual messages will have less impact than positive, beneficial statements.

Programme implementers should avoid developing complicated or technical text, graphs or charts. Messages should be

factual enough to be compelling but also user friendly and simple to be memorable. Some successful energy efficiency communications campaigns have focused on the following benefits and attributes:

- Monetary savings
- National pride
- Energy efficiency and energy savings
- Convenience (long-life)
- A simple and hassle-free switch
- Environmental responsibility
- Political and economic advantages and
- Energy security and reliability.

4.2.1 DESIGNING A COMMUNICATIONS CAMPAIGN

The success of a communications campaign depends on its design. Objectives should be established in line with policy goals. The objectives should be specific, measurable, attainable, relevant and time bound (SMART). They determine the choice of communication tools and messages as well as evaluation parameters.

The communication messages should be simple and relevant to the audience. Messages should make the desired behaviour attractive and easy and should clearly demonstrate the benefits to end users. Usually, monetary savings are a strong motivator in all communications campaigns about efficiency, but in some countries messages that tap into a sense of national pride may resonate as strongly.

Communication plans should be flexible. They should allow for adjustments based on monitoring results and any circumstantial changes. Project-management skills are needed to successfully manage the launch and ongoing operation of the campaign. Diagnostic skills are used to recognise whether the campaign fulfils its expectations. If the campaign falls short of its goals then its problems must be addressed.

Identifying the target audience for a campaign is critical. This helps in tailoring the messaging. Table 15 provides information on the communication interests of the different target audiences. It includes their primary interests and their areas of involvement with respect to energy efficiency.

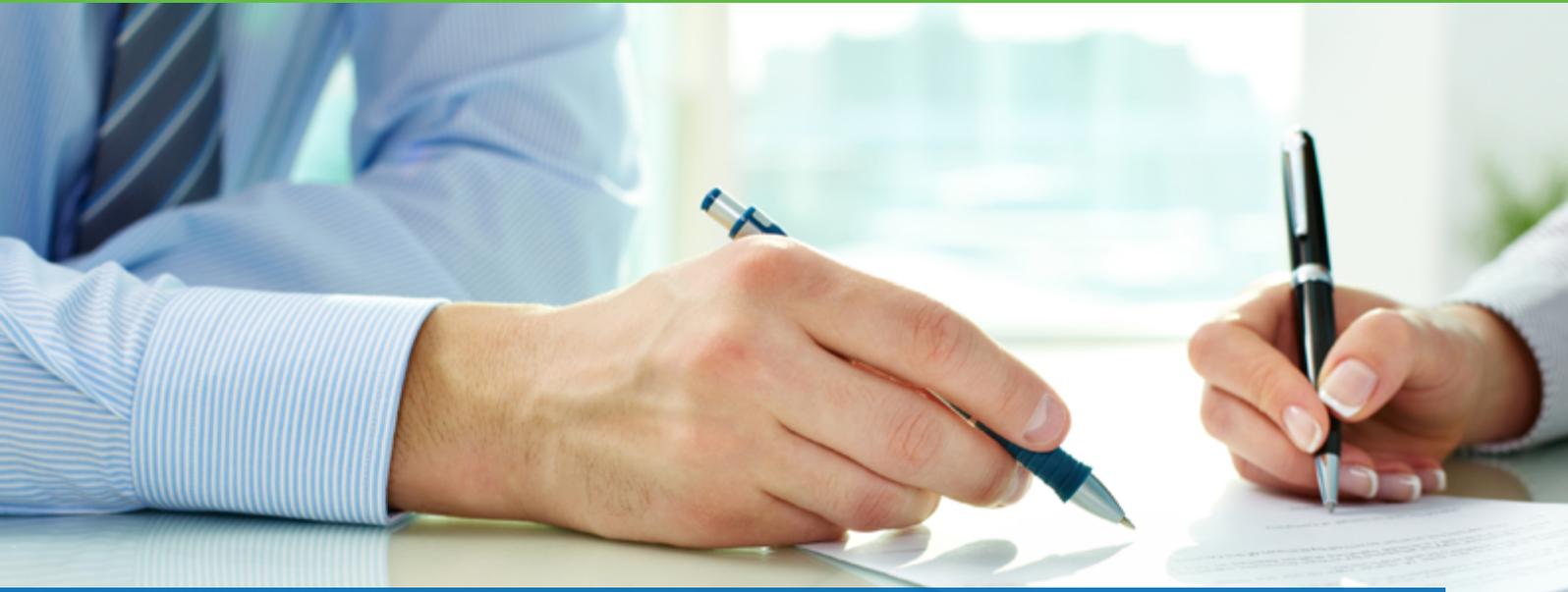
Table 15: Communication campaign stakeholders and areas of interest and involvement

TARGET AUDIENCE	PRIMARY INTERESTS	AREAS OF INVOLVEMENT
PUBLIC INSTITUTIONS <ul style="list-style-type: none"> Political executive and legislature Regulatory bodies particularly electricity regulators Standards bodies Accreditation bodies Enforcement officials Customs authorities 	<ul style="list-style-type: none"> Reduce need for new power plants, reduce GHG emissions, while improving the national economy Protect domestic industry and jobs while respecting trade obligations and opportunities. Ensure market transformation to energy-efficient products 	<ul style="list-style-type: none"> Policy formulation, legislation, funding and human resource support for energy efficiency market transformation programme Support to regulatory initiatives and policy implementation Evaluation and monitoring of programme against established targets Public procurement policy Standards and regulations Incentives and subsidies Testing lab accreditation Product registration Compliance testing and enforcement Communication campaigns
POWER UTILITIES	<ul style="list-style-type: none"> Increase energy access Improve power quality and reliability Lower running costs of the transmission and distribution of electricity 	<ul style="list-style-type: none"> Transformer maintenance programmes Total cost of ownership (i.e., life-cycle cost evaluation) when purchasing new transformers System design taking into account efficiency Incentive and subsidy programmes for commercial and industrial facilities
SUPPLY CHAIN <ul style="list-style-type: none"> Transformer manufacturers Transformer repair facilities Industry associations Dealers System integrators 	<ul style="list-style-type: none"> Seek competitive advantage, improved market share Minimise costs, seek return on new investments Be seen as an environmentally sensitive, responsible corporate citizen Gain public recognition 	<ul style="list-style-type: none"> Assist regulators in determining level of ambition and timeline Upgrade capacities for design, manufacture, testing and marketing of energy-efficient transformers Ensure accurate energy labelling Act as change agents Facilitate direct and indirect end-user communication
END USERS <ul style="list-style-type: none"> Energy Maintenance managers Purchasing agents Facility managers 	<ul style="list-style-type: none"> Ensure sustainable corporate performance—financial, environmental Reduce costs and improve productivity 	<ul style="list-style-type: none"> Develop company energy policy, transformer-maintenance policy, procurement policy Acquire information and develop capacity to make informed decisions about the savings associated with a switch to efficient transformers Conduct energy audits
OTHERS <ul style="list-style-type: none"> Civil society Environmental organisations Educational institutions Research and training institutes Media and general population 	<ul style="list-style-type: none"> Reliable and affordable electricity Clean air, water and soil Education and training to understand the implications of inefficient equipment and safety considerations related to PCBs 	<ul style="list-style-type: none"> Assist public institutions with the development and implementation of sustainable appliance policies Identify best practices and policies Publish formal and informal education and training materials Increase awareness about the role of transformers and opportunities to improve efficiency Support for sustainable appliance policies among general population

Communications and education programmes can work to promote energy-efficient transformers in any country. For example, ICA has established, and continues to develop, an online learning portal that consists of expert lecturers presenting on a range of topics, including energy-efficient transformers.³²

Transformer manufacturers offer some on-line communications tools as well, which promote the consideration of losses in the design specification of a transformer order. For example, ABB Transformers offers a total cost of ownership calculator³³ which converts cost of no-load (A-Factor) and load losses (B-Factor) to net present value (\$/W). ABB notes that the greater the net present value, the higher the penalty placed on those specific losses. These factors are then multiplied by their respective transformer no-load (W) and load losses (W) and summed together with the purchase price to come up with the total cost of ownership. When comparing like designs, the offering with the lowest total cost of ownership would be selected as it would be the most economical when considering purchase price, loss of revenue and capital investment.

Governments may also choose to raise awareness and have a communications campaign around the eradication of PCBs. Starting in the late 1920s, PCBs were used as a cooling fluid in electrical transformers for nearly 50 years because of their electrical-insulating and fire-retardant properties. However, they have a high environmental toxicity and represent a highly significant public and environmental health risk. There is still a need to eliminate old transformers and ensure the environmentally sound disposal of PCBs in large parts of the world.³⁴



5. FINANCE AND FINANCIAL DELIVERY MECHANISMS

WHAT?	<p>This chapter addresses topics relating to financing of energy-efficient transformers, including both sources of financing and implementation vehicles and mechanisms. Some of the topics covered in this chapter include overcoming first-cost barriers, traditional and innovative financing mechanisms, energy service companies, bulk public procurement schemes and electric utility demand side management programmes.</p> <p>This chapter is divided into two parts. The first part is a high-level summary of the sources of funding that countries can access to supplement their own domestic public and private sector funds. The second part concentrates on the implementation practices and delivery mechanisms that are driven by financial incentives to help facilitate successful market transition to energy-efficient transformers.</p>
WHY?	<p>Affordability of efficient transformers can be a significant market barrier. This chapter addresses how public finance, multilateral development finance and climate finance, in coordination with the private sector, can help address this barrier through financial schemes, innovative market delivery and other mechanisms.</p>
NEXT?	<p>Some key questions to keep in mind:</p> <ul style="list-style-type: none"> • Which economic policies, regulatory structures and/or financial incentive programmes could be effective in facilitating market transformation in our country? • Which stakeholders should we engage to learn about financing opportunities, and work with to encourage the creation of new market-delivery mechanisms? • What new market-delivery mechanisms could be effective in our country? • Are there bilateral or multilateral sources of technical assistance, grants or finance which would stimulate and accelerate the efficient transformer market?

5.1 SOURCES OF FINANCE

Enabling a market transition to energy-efficient transformers often requires policy interventions and financial incentives. To be successful in achieving market transformation, countries need to follow an approach that helps in overcoming market and other barriers, increases local investor confidence, and mobilises private sector investments and participation. Governments can achieve this objective by promoting an enabling economic environment that facilitates the purchase and installation of energy-efficient transformers.

Initial higher cost of energy-efficient transformers could make them unaffordable for some utilities and end-use industrial and commercial customers in developing countries. Overcoming first-cost barriers to market adoption requires the involvement of policy makers and institutions and the identification of financial resources to support a market shift to efficient transformers.

Public finance can be used in a manner that maximises the leveraging effect of private sector capital. Advanced planning and blending of financial resources with appropriate mechanisms is essential to managing the financial ecosystem, including risk-sharing and cost-sharing arrangements. In this context, multilateral finance can further complement public finance sources in helping to scale-up investments and expand the impact in the area of energy-efficient transformers. Such funding can be applied to develop and strengthen the regulations and standards and their enforcement, as well as supporting policies like promotional schemes and rebates to industrial and commercial customers, and other financial incentive mechanisms.

Several sources of finance exist to help support energy efficiency programmes, particularly for resource-constrained countries. This section identifies some of the sources. Readers are directed to the “Policy Fundamentals Guide”, which provides

an overview along with case studies and hyperlinks to various sources of finance for energy efficiency projects and programmes in general.

- **Domestic sources of finance**—the most direct way for governments to pay for energy-efficient transformers marketing and communication programmes is to allocate public funds from the domestic budget. Another option, commonly used in the US is for electric utilities to promote them through incentives offered to their industrial and commercial customers under traditional Demand Side Management (DSM) schemes.
- **Private sector finance**—financial institutions are starting to understand the compelling aspects of energy efficiency and are developing suitable financing mechanisms. The economics and financing of efficient transformers is attractive and offers an incentive to invest in energy efficiency that is recovered through energy savings. Examples of private sector finance that could be used to help support the purchase of transformers include bank loans, third-party financing, performance contracting through ESCOs and green investment funds.
- **Sources of development finance**—some developing countries that do not have adequate public finance and resources to support a technology phase-out or largescale deployment programme, may seek nondomestic sources of finance, such as the Asian Development Bank, the European Bank for Reconstruction and Development, and the World Bank. Nondomestic sources of finance can provide concessional funding to governments (including soft loans and guarantees) to help trigger market transformation through large-scale deployment programmes, along with initiating phase-out programmes, raising investor confidence, and attracting private investors.

- **Climate financing**—financing mechanisms designed to reduce greenhouse gas emissions often provide grants and low-cost loans, which can be blended with other sources of finance to help scale up the implementation of energy efficiency programmes, including for energy-efficient transformers. Examples of climate financing that could be applied to energy-efficient transformers include the GEF, Green Climate Fund, Clean Development Mechanism, Nationally Appropriate Mitigation Actions and Climate Investment Funds. These financing mechanisms require robust measurement and verification of greenhouse gas emissions reduction in addition to that of energy savings.

CASE STUDY: Madhya Pradesh Energy Efficiency Improvement Investment Programme, India

In Madhya Pradesh, where 70 per cent of the population live in rural areas, the aging and overloaded distribution lines and transformers were incurring excessive technical losses and delivery of poor quality power. To ensure good quality 24-hour power supply to rural households, the government of Madhya Pradesh has been undertaking a distribution improvement programme that aims to establish separate feeders for agricultural pumps and households, higher-voltage distribution systems, installed meters and a strengthened 33 kV network.

The Asian Development Bank invested in the improvement of the operational efficiency of the electricity distribution system in Madhya Pradesh, including in energy-efficient electricity distribution transformers across 15 project districts. The total budget for this completed project was \$200 million.

For more information [click here](#).

CASE STUDY: Madhya Pradesh Power Sector Reform, India

The UK Department for International Development (DFID) provided technical assistance of £19.7 million to the Energy Department, government of Madhya Pradesh and the power utilities in generation, transmission, and distribution. The objective is to support policy and institutional reforms to make the power sector viable in the medium and long-term by ceasing to be a drain on the state finances and to enable the state to spend more on social sectors.

DFID support includes: (a) distribution loss reductions; (b) energy efficiency and Demand Side Management; (c) private participation in generation; (d) distribution franchisee Public Private Partnerships (PPPs); and (e) a financial restructuring plan. The project ran from 2005-2012 and had a financial restructuring budget of £5.5 million.

For more information [click here](#).

5.2 FINANCING AND DELIVERY MECHANISMS

Examples of financial mechanisms that are often used for the purchase of transformers include:

- Utility regulatory frameworks
- Energy Savings Performance Contracting through ESCOs
- Public-private partnerships

5.2.1 UTILITY REGULATORY FRAMEWORKS

Losses in the transmission and distribution system need to be covered by additional generation, which costs money and can put a strain on already limited generating assets. The objective of progressive regulatory frameworks is to find an optimal economic balance that protects the interests of the end-use customers while ensuring the utility can benefit from energy efficiency investments in its own network. If network operators are given sufficient incentive, they will evaluate the costs and benefits of reducing losses and take action to optimise the level of losses in the most efficient way, including the purchase of energy-efficient transformers.

Other regulatory and operational issues, such as energy efficiency schemes, infrastructure planning, and network reconfiguration can also have an impact on the treatment of losses. Any measures or actions focused on reducing or smoothing the demand for energy, (re)locating generation plants closer to demand, upgrading the voltage level of the network

and of course, improving the efficiency of transformers will have a positive impact on losses.

Regulators should ensure that purchasers are not unintentionally penalised for buying more expensive but more efficient transformers under any price control formula. Utilities and large facilities owners should be able, encouraged, and incentivised to buy the most economically efficient transformers using a cost of losses capitalisation formula that properly reflects the cost of electricity used to supply the losses.

This cost should also take account of the emissions and environmental impacts of the electricity used over the lifetime of the transformer. The incentive should operate irrespective of whether the utility is responsible for buying or generating the electricity needed to supply system losses and would apply even when MEPS are in force.

CASE STUDY: Financial Incentives 2007-2014, Italy

Resolution ARG/elt 348/07 of the Electricity and Gas regulatory measure in Italy defined the setting for the remuneration of investments made in the distribution network. The rate of return on capital net invested was fixed at 7 per cent a year. When this return on investment was applied to transformers in substations it resulted in new low loss transformers being included. The measure resulted in more energy-efficient transformers being installed and all transformers of this kind ensured the dimensional requirements of existing substation specifications.

Initially, the Authority's resolution only planned an incentive for the replacement of existing transformers, but subsequently, with Resolution ARG/elt103/10 of 30 June 2010, the language was amended to: 'Investment for replacement of existing transformers MV/LV in substations of transformation with new low loss transformers.' The incentives for electricity distributors were extended also to the installation of new low loss transformers in both existing or newly built substations.

These incentives helped accelerate the transition to the subsequent adoption of European Regulation EU No 548/14 and were cancelled after the regulation took effect.

5.2.2 ENERGY SAVINGS PERFORMANCE CONTRACTING THROUGH ESCOs

An ESCO is a business providing a broad range of turn-key energy solutions which can include upgrades to electrical systems in commercial buildings and industrial facilities as part of a larger energy efficiency scheme. ESCOs conduct energy audits to identify cost-effective opportunities for refurbishing or replacing equipment and improving operating practices. ESCOs often act as project developers for a comprehensive range of energy efficiency measures and assume the technical and commercial risk.

ESCOs that use a guaranteed savings model provide a guarantee on the energy savings (they assume the technical risk)

for any efficiency improvements that are undertaken. The client assumes the credit risk, as their credit is used to secure a loan to pay for the retrofit. The client repays the loan and the services of the ESCO through the money that is saved on their utility bill.

In the case of a shared savings model, the ESCO borrows from a bank or invests its own funds, assuming both the credit and technical risks. The guaranteed savings model enables more comprehensive projects and a greater number of projects to be undertaken since the credit of each client is leveraged, rather than relying on the credit of the individual ESCO.

5.2.3 PUBLIC-PRIVATE PARTNERSHIP FINANCING AND DELIVERY MODEL

PPP are mechanisms enabling governments to fund and operate services through contracts with private companies. They come in a wide variety of structures and formats. Finance can be sourced from either the public sources or the private sector or both, depending on the design of the partnership contract.

The private sector brings its implementation expertise to a project usually considered within the public domain, and assumes much of the financial or performance risk.

The PPPs offer a mechanism under which they can take-on large-scale projects with private-sector financing and management expertise, while retaining management control and key decision powers. While this has not been used for transformers, this is a potential mechanism that might be considered.

According to the European Investment Bank, PPP transactions in the EU stood at €15.8 billion in 2010. About 1,400 deals have been implemented over the past two decades.

5.3 UTILITY PURCHASING PRACTICES

When purchasing distribution transformers, utilities will often use a purchasing practice referred to the total cost of ownership or whole life costing, which involves the capitalisation of losses. This approach to specifying and purchasing transformers is used to minimise the total investment over the lifetime of a transformer, enabling a utility to maximise its energy savings at the lowest cost. Loss capitalisation takes time to determine the correct factors to apply but helps provide answers to the following questions:

- At what cost should the lost energy be evaluated?
- What is the load factor that should be applied?
- What is the internal rate of return that needs to be applied to any discounting?
- What interest rates should be applied to the capital purchase?

The biggest issue with loss capitalisation is that it needs to look at the life of the transformer that typically exceeds 25 years and represents the length of time that utilities could use for discounting the asset values in their accounts.

The whole life costing model is intended to attribute a present value to the whole life costs of operating the transformer in its proposed location. To achieve this, the loss factors typically developed for an annualised cost method can be used as inputs to a discounted present value calculation method looking into the future to develop the whole life costing model. However, each purchaser may prefer different approaches based on historical methodologies.

By using this whole life costing approach, future changes such as load growth or reductions can be factored into the calculation. In this method the discounted present value of the cost of energy consumed in transformation throughout the life of the transformer is added to the purchase price. The lowest total cost being the preferred option, which may not be the lowest purchase price.

When purchasing a transformer, a utility will include a statement expressing its valuation of no-load and load losses. These two valuations are expressed on a cost per Watt basis, where the cost is in the same currency as the purchase order. For instance, in the US, a utility would specify its no-load and

load-loss valuation in dollars per Watt (\$/W). The transformer manufacturer then uses this information in their design process and prepares a design that trades off higher first cost against lower lifetime operating cost. The higher the valuation of losses, the more efficient a transformer design.

When assessing the various bids, the following equation is used by the utility for selecting the lowest total cost of ownership for the transformer designs specified:

$$\text{Total cost of ownership} = \text{Purchase Price} + \text{Valuation of Core Loss} + \text{Valuation of Load Loss}$$

In this equation, the purchase price represents what the manufacturer would charge the utility for the purchase. This price is a reflection of the materials and construction techniques, and thus more efficient transformers will tend to have higher purchase prices.

The valuation of core loss is a calculation that assigns a value to each watt of loss in the core of the transformer. In other words, if core losses are valued at 5 \$/W and a transformer design has 100 W of core loss, then the valuation of core loss entered into the total cost of ownership calculation will be \$500. Adding valuation of losses allows the overall design assessment result in the most cost-optimised purchase decision for the utility. It serves to offset the higher first cost of an energy-efficient design due to the fact that lower losses associated with the more efficient design will result in a lower operating cost associated with core losses.

The valuation of load loss is very similar to that of valuing core loss. Each watt of load loss is multiplied by the value of the load losses to arrive at a total cost associated with the load loss that should be incorporated into the purchasing decision.

In other words,

$$\text{Valuation of core loss} = A \times \text{core loss (W)}$$

$$\text{Valuation of load loss} = B \times \text{load loss (W)}$$

Where:

$$A = \text{equivalent first cost of core losses (\$/W)}$$

$$B = \text{equivalent first cost of load losses (\$/W)}$$

Utilities around the world have developed and customised ways to calculate the valuation coefficients, A and B.

The following formula is used to calculate the net present value factor which is then applied to the two annualised loss factors to obtain a whole life cost estimate.

$$C = [a \times (1 + b)^n + b - a] / [(1 + b)^n - 1]$$

(Eqn. 4-3)

Where:

C - is the cost per \$ annual cost of losses

a - is the cost of capital borrowed

b - is the interest rate payable on deposits

n - is the expected life of the transformer

If it is assumed that the cost of a loan is 7.5 per cent, the interest payable on deposits is 5 per cent and the life of the transformer is taken as 40 years then C equals 0.0833.

The capitalised value of the losses over the life of the transformer as detailed in the equation (2) is then as follows:

$$A = \text{Total cost of No load loss is then } 876/C = 876/0.0833 = \$10,516/\text{kW}$$

$$B = \text{Total cost of Load loss is then } 181.3/C = 181.3/0.0833 = \$2,176/\text{kW}$$

The estimated whole life cost for assessment of the designs is the values of no-load and load losses multiplied by the above A and B and added to the purchase price.

Total whole life cost of transformation is then determined as follows:

$$\begin{aligned} \text{Total cost of ownership (\$)} = & \\ & \text{purchase price (\$)} + (10,516 \times \text{no load loss}) \\ & + (2,176 \times \text{load loss}) \end{aligned}$$

As these methods make some basic assumptions of future costs and operating data, some degree of sensitivity analysis may be required to optimise the formula prior to issue as part of a contract. Factors that are uncertain over the life of the transformer include the demand profile, interest rates, cost of capital and energy costs.

The example above gives a single cost for the energy consumed. There is no reason why the two loss factors could not have different costs attributed to them.

Any expected load increase to which the transformer will be subjected through its life can be considered as part of this analysis. The expected life of the transformer and the cost of financing may be treated in more detail to also arrive at the figures.

There are many different methods that can be used in making a discounted cash flow or net present value calculation and the above example uses only one of these. Another approach, the annualised cost of capital, is shown in Annex D.

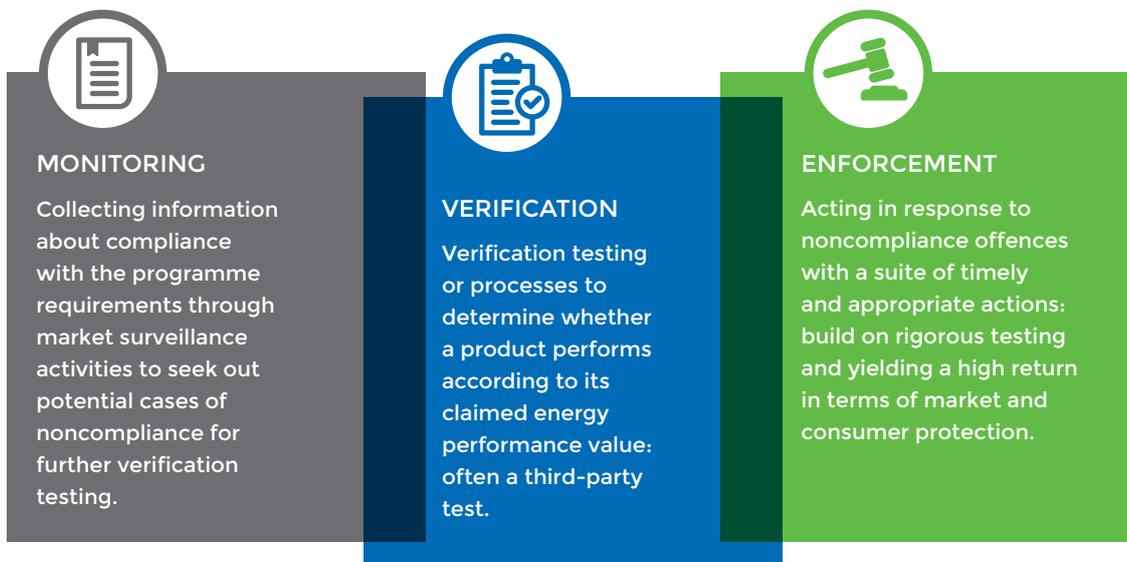


6. MARKET MONITORING, VERIFICATION AND ENFORCEMENT

WHAT?	Clarifies the critical importance of MVE to ensuring a level playing field so businesses comply and consumers benefit. Highlights the central importance of government in establishing and maintaining a robust market-surveillance programme.
WHY?	Just as police enforce the law and prevent crime, national governments must work to monitor, verify and enforce regulations and standards to ensure the policies and programmes created to transform their respective markets are followed. Robust MVE schemes are absolutely fundamental to achieving successful policy-driven market transformation outcomes.
NEXT?	<p>Some key questions to keep in mind:</p> <ul style="list-style-type: none"> • How can market surveillance improve the effectiveness and impact of the regulations? • Do we have the legal framework around which to structure a complete MVE scheme? • Which government ministries oversee product safety standards and requirements? Could their function be expanded to include additional regulations and standards enforcement? • What are the costs and benefits of running a market surveillance programme? • Can we simplify the implementation, by adopting existing international regulations, standards and MVE schemes such as the IECEE CB-scheme?

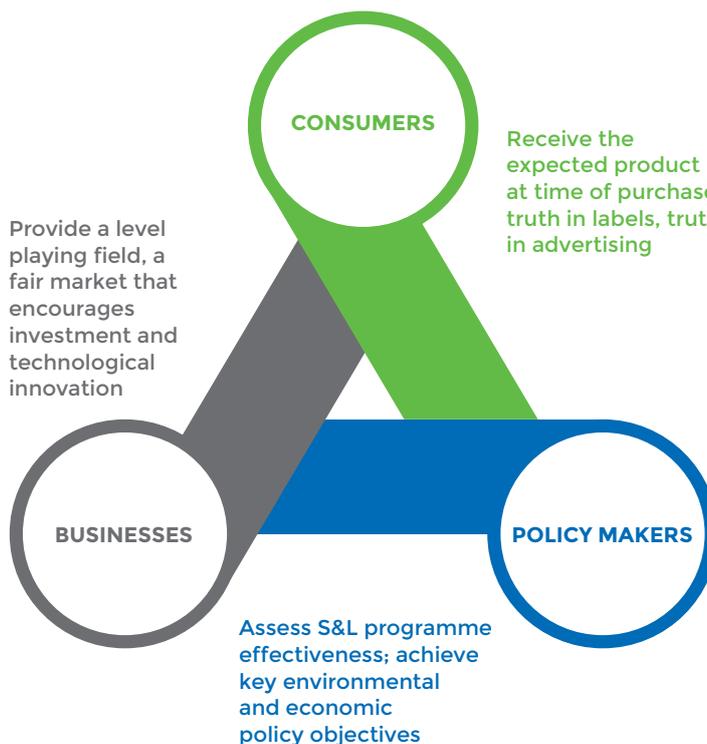
MVE is an indispensable component of the U4E Integrated Policy Approach. It revolves around monitoring markets, verifying compliance and enforcing the regulation on companies that fail to meet them. Figure 10 highlights the fundamental aspects of MVE.

Figure 10: Fundamental aspects of the MVE process



Effective MVE schemes ensure a level playing field. Manufacturers comply with standards and labelling programmes, enabling consumers and companies alike to benefit. Considering the three main stakeholders involved, industry, consumers and governments, MVE offers benefits to all, as depicted in Figure 11.

Figure 11: MVE benefits to stakeholders



The goal of MVE is to ensure the integrity of market-transformation programmes. It does this by minimising the negative costs associated with the sale of noncompliant products after the effective date of a regulation.

6.1 LEGAL AND ADMINISTRATIVE FRAMEWORK

A strong foundation within the national legal framework is crucial for an MVE scheme. This foundation should encompass legal authority, enforcement powers and penalties. The legal framework for an energy efficiency enforcement regime will depend on the national governance structure, on existing legislation and on the infrastructure and design of the MVE process.

Legal frameworks must clearly delineate responsibilities between the different government agencies that implement MVE nationally, including the agency responsible for coordinating the MVE scheme, and other agencies such as customs, standards and metrology that will have central roles. The framework could bestow the authority for an agency to issue fines and block the sale of noncompliant products from entering the market.

The operational framework within which the enforcement authority operates should be transparent. This improves compliance rates through clear communication and understanding of the MVE scheme.

MVE schemes for transformers may also need to address PCBs, which were used in the past as a cooling fluid in some electrical transformers because of their electrical-insulating and fire-retardant properties. PCBs have a high environmental toxicity and represent a very significant public and environmental health risk. Virtually all governments have signed the Stockholm convention to eradicate PCBs from their markets by 2025.³⁶ Part of the responsibility of the national MVE scheme may include ensuring that PCBs are taken out of service and disposed of safely.

6.2 FINANCING MONITORING, VERIFICATION AND ENFORCEMENT SCHEMES

The costs of a national MVE scheme vary. They depend on the scope of the programme as well as local or regional factors, such as labour and services costs. When planning how to allocate funding for an MVE scheme, the managing agency typically takes into account the relative scale of the harm caused (including the cost of wasted energy, loss of consumer confidence and the frequency of noncompliance).

More resources are allocated toward addressing cases of noncompliance. They have the greatest impact and occur frequently. Budget allocation should be an evidence-driven, risk-based process that is transparent and defensible.

The areas of an MVE scheme which incur costs are listed below:

- **Establishment costs**—setting up a main office and possibly field offices with new equipment
- **Staff costs**—hiring and training/capacity building the staff, covering the key areas of administration, investigation and management, and in specialist areas such as customs officials and test labs
- **Communications**—informing the market about the regulations, the MVE scheme and enforcement proceedings, as deterrence is highly cost effective; and
- **Legal and enforcement action**—the MVE agency needs to have (and be seen to have) sufficient funding to use its full range of legal powers.

The success of an MVE scheme depends on identifying a secure and sustainable source of funding that will be maintained for a given market. Governments must assess what is equitable and feasible and construct a solution that will fit within their framework. Robust MVE schemes require good market awareness, sampling, and testing.

The most common source of funding is the government's own general operating

budget. This does not need to be the only source of funding. Cost-recovery from suppliers can also be another source of funding, with many programmes around the world introducing cost-recovery elements to their schemes. Cost recovery can be partial or complete and can be achieved through, for example, registration fees, verification testing fees, and enforcement fines.

Many programmes collect funds from suppliers during registration. This may take the form of an annual payment, a one-off payment for a specified period or a higher initial fee followed by a smaller annual payment. Registration fees are generally levied on product models rather than brands or suppliers, as this best reflects the costs involved.

An increasing number of programmes require that products have third-party certification. This comes from an independent body as a condition of entry to the programme. While this is not cost-recovery per se, it can reduce the costs of the programme. This is because the system administrator is in effect delegating some of the responsibility for ensuring products meet the necessary requirements to third parties that are paid by the product suppliers.

Support for MVE schemes can also be derived from stakeholders in the market. Collaboration and cooperation with industry or civil society may provide additional resources. Including through joint testing programmes, by providing expertise, supporting data collection and sharing, or even providing testing facilities. Prior to engaging in this form of collaboration, the goals of cooperating need to be established. Some contributions may not be admissible as a foundation for legal action. There may be a conflict of interest in using industry funding to legally prove noncompliance of competitors in the market.

6.3 COMPONENTS OF A ROBUST MVE PROGRAMME

UN Environment has published a guidance note³⁷ on the development and maintenance of market baselines and market-monitoring activities. The note is aimed at policymakers who wish to establish or update policies to facilitate the transition to efficient

transformers. It provides a practical resource for those developing a market baseline for the first time, or those who are looking to update existing baselines for market monitoring purposes.

CASE STUDY: Industrial and Tertiary Product Testing and Application of Standards (INTAS) Project, Europe

The INTAS project started in March 2016. It addresses the need to support European Market Surveillance Authorities (MSAs) deliver compliance with Ecodesign requirements for large industrial products including transformers.

INTAS provides technical and cooperative support as well as training activities to MSAs in charge of enforcing Ecodesign regulations. INTAS also supports industry to be sure of what their obligations are under the Ecodesign Directive and to deliver compliance in a manner that will be broadly accepted by MSAs. By doing so, INTAS fosters a common European approach to the delivery and verification of compliance.

For more information [click here](#).

6.3.1 PRODUCT REGISTRY SYSTEMS

Product registration systems offer an initial compliance gateway. Suppliers register compliant products with the regulatory authority. The registration process requires manufacturers to submit test results on the products and certify that the product performance meets the regulations, standards and any labelling requirements before the product can be placed on the market.

Governments set up product registration systems via legislative and regulatory authority. Mandatory registration systems are in place for products with energy labelling in Australia, Canada, China, New Zealand, Singapore, and the US, among others. Registration systems are designed to meet the needs of many different stakeholder groups, as shown in Table 16.



For more information on product registry databases, see the recent UN Environment publication on **Developing Lighting Product Registration Systems**.³⁸

Table 16: Product registry system users and their potential needs

STAKEHOLDER	POTENTIAL USER NEEDS
POLICYMAKERS/ GOVERNMENT	Provides a record of baseline data to support policymaking; expands the evidence database for market surveillance; serves as a storehouse of ancillary information and data about products on the market
MANUFACTURERS, IMPORTERS AND WHOLESALERS	Facilitates declaration of conformity with regulatory or voluntary requirements; provides information about innovation in product design (fostering competition and innovation); strengthens brand credibility; helps to ensure a level playing field
CONSUMERS (E.G. INDUSTRIAL USERS, UTILITIES)	A database of product-specific information in the public domain; opportunity for advanced features through apps or other tools, doing product searches; enhances transparency of communication about product performance
OTHERS	Registry information can be used to determine product performance for market pull programmes that incorporate financial incentives or other incentives.

6.3.2 TEST LABORATORIES

Measurement of the performance of a product, as part of a coordinated MVE strategy, provides the foundation for the effective implementation of energy-efficient transformer policies and regulations.

Product testing constitutes the cornerstone of any product compliance certification report, whether for a voluntary or mandatory programme.

Having a national laboratory can be a prestigious asset to manage. However, laboratories are expensive facilities to establish, commission, earn accredited and maintain. There needs to be a certain

minimum level of business in a given market to sustain the laboratory, and to ensure it has adequate revenue with which to operate and maintain its calibration and accreditation. Countries with smaller economies may consider outsourcing laboratory test needs to neighbouring countries.³⁹ For transformers, smaller units may be sampled and tested in a laboratory, but larger units—due to their excessive size and weight—may need to be tested either at the manufacturer’s facility or in the field.

Table 17 depicts the essential elements for the reliable operation of a testing laboratory.

Table 17: Essential elements for the reliable operation of a test laboratory

ELEMENT	ESSENTIAL ELEMENTS
TRACEABILITY AND ACCREDITATION	<ul style="list-style-type: none"> • Linking measuring equipment to SI unit • Accreditation to IEC standards for appropriate test standards (e.g. IEC 60076 family of standards) • Proficiency testing
CALIBRATION	<ul style="list-style-type: none"> • Externally calibrated • Internal equipment calibration • Monitoring laboratory conditions
UNCERTAINTIES	<ul style="list-style-type: none"> • Confidence intervals • Determining the uncertainty
TESTING	<ul style="list-style-type: none"> • General considerations • Measurement equipment/meters
DOCUMENTATION AND HOUSEKEEPING	<ul style="list-style-type: none"> • Laboratory record keeping system • Storage conditions • Length of time.

6.3.3 PROACTIVE COMMUNICATIONS

Communication is a critical element of any successful MVE scheme. For manufacturers and importers, it helps to ensure they are aware of their legal obligations and what happens if they were found to be non-compliant. For consumers, it lets them know that their government is working hard for them, ensuring that the national market for a given product offers a fair and level playing field. Communications can also be a powerful tool in gaining the respect of the regulated businesses and improving compliance rates—for example, taking quick action to minimise market damage and making it visible, as a deterrent to others.

It is necessary for governments to develop a communications plan. This plan should be fine tuned and appropriate for the domestic market. It should take into account all the main stakeholders involved in the supply chain and the importance of communicating key messages to them about the requirements themselves, the

risk of detection and sanctions, and any corrective action taken. Governments may choose to list the number and frequency of surveys and tests, identify plans for future compliance work and publish information about their work. Some governments may also consider identifying products and brands that are non-compliant (also called the “name and shame” approach).

Governments can offer a number of tools, training and guidance to improve compliance rates. They can offer training courses to explain regulatory requirements or maintain a regulatory hot-line or email service to answer questions that the suppliers may have. They can publish a frequently asked questions (FAQ) website, and provide guidance on compliance reporting and documentation requirements. All of these approaches help to minimise the costs of demonstrating compliance and will thereby help to ensure higher compliance rates and more successful outcomes.

6.3.4 MARKET MONITORING

A critical function of a government market-surveillance authority is to regularly monitor the market. By doing this they ensure that the products being supplied to the market are compliant.

UN Environment has studied the approach that laboratory personnel may follow when conducting testing. In another report⁴⁰, UN Environment provides recommendations for processes to follow for testing products, interpreting testing results, and using them to inform policy making. This testing report covers topics such as (a) identifying

testing objectives; (b) determining where to test products; (c) adopting appropriate test standards; (d) selecting parameters to be tested; and (e) conducting testing and applying test results. The recommendations in this report focus on the identification of which type of products should be monitored, determining how performance testing data is used, determining where the testing will be conducted (e.g. national, regional, third party), and ensuring test results are accurate and correctly interpreted.

6.3.5 REGULATORY ENFORCEMENT

In cases of noncompliance, the enforcement authorities should carefully consider the degree of noncompliance. By doing this they can respond with a proportionate enforcement action. The available enforcement actions should be flexible, enabling the enforcement authority to assess the non-compliance situation and initiate a proportionate action. The penalties and powers of the enforcement authority should be set out in law.

Many enforcement authorities develop an “Enforcement Pyramid” to inform and manage their enforcement response strategies. The bottom of the pyramid typically features more informal actions, while the top of the pyramid should reflect the most severe enforcement response to non-compliance (see Figure 12). The pyramid can be populated to be most effective for the national enforcement strategy, in accordance with the legal requirements and resources available to the enforcement authority, and the characteristics of the programme and its participants and stakeholders.

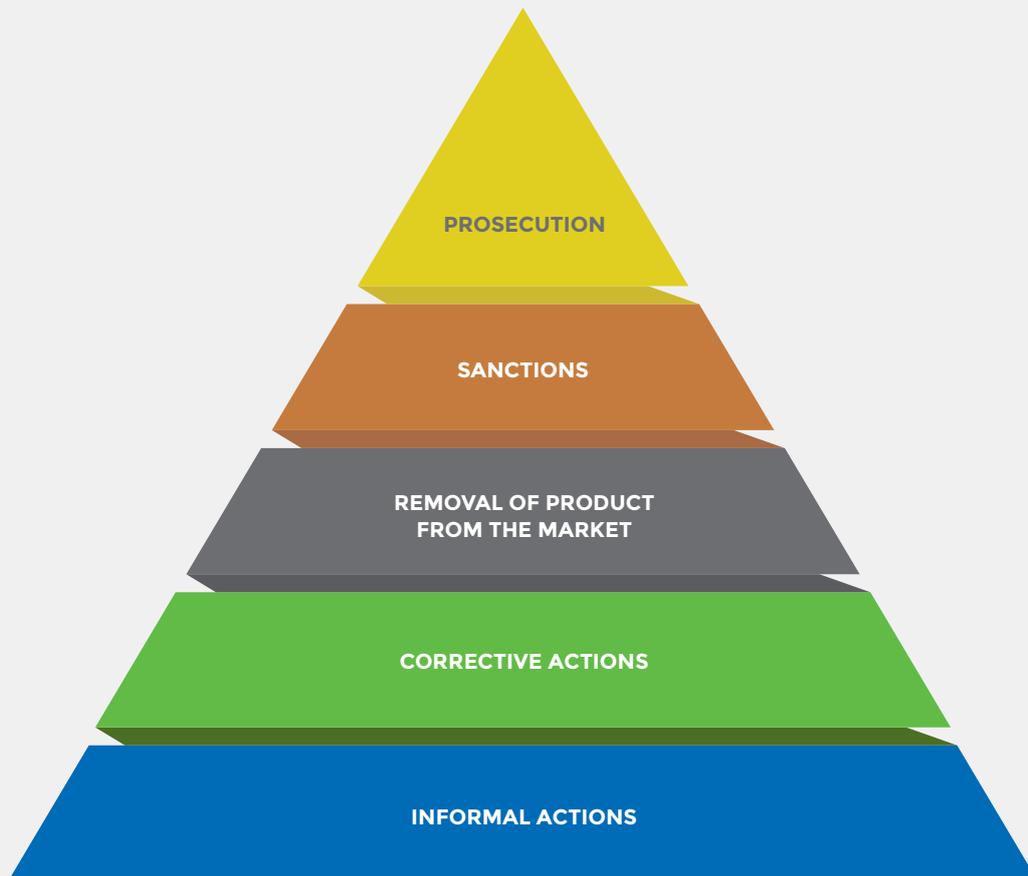


Figure 12:
Pyramid of escalating enforcement for non-compliant manufacturers or importers⁴¹

For more information on effective enforcement schemes, please see a recent UN Environment report⁴² that serves as a practical resource to policy makers on the steps to follow when implementing a national enforcement programme. This report covers (a) legal and administrative foundation for enforcement; (b) enforcement budget and activity planning; (c) identifying types of non-compliance; and (d) communicating to stakeholders. Although this report is written about lighting, many of the same principles of MVE presented in that report are also applicable to transformers.



7. ENVIRONMENTAL SUSTAINABILITY AND HEALTH

WHAT?	Provides a summary of the importance of the environmental aspects of recycling and cleaning used transformers and correct disposal of PCBs.
WHY?	All transformers contain materials that can be recycled, recovered or reused, as well as some materials that could be hazardous if simply dumped in a landfill. By establishing a national collection and recycling scheme, a “circular economy” objective can be achieved.
NEXT?	<p>Some key questions to keep in mind:</p> <ul style="list-style-type: none"> • What waste collection and recycling schemes are already being conducted in our country? • Who are the critical players who would need to be informed and/or participate in planning an equipment recycling scheme? • What are the financial requirements of such a programme, and how can we find the resources to cover them (which approach will work best in our country)? • What are some of the human and environmental health issues associated with transformers?

Environmentally sound management incorporates the concept of a product's full life cycle. It begins from raw materials used in manufacturing through to end-of-life recovery and recycling. This approach gives regulators a suitable framework to analyse and manage the performance of goods and services in terms of their impact on the environment.

When life-cycle management principles are applied to transformers, the assessment concentrates on the following three stages:

- **Production:** focuses on the raw materials and production techniques involved in manufacturing the product, including hazardous substances. The production phase is a natural point of intervention for hazardous substance regulators in the product life cycle.
- **Usage:** focuses on the environmental impact of transformers during the use phase (i.e. from power plant related emissions) but can also include health and safety aspects (including PCBs from installed stock and refurbished units that have been contaminated).
- **End of Life:** focuses on the end-of-life management of transformers, highlighting current regulatory frameworks, examples of best practices in establishing, managing and financing end-of-life collection; recycling and environmentally sound management; and disposal. For transformers, disposal can be complicated by the fact that the transformer may contain cooling fluids with pure PCB or contaminated with PCB that need to be disposed of safely.

Life-cycle assessments (LCA) conducted on transformers have concluded that the usage stage is the most important from an environmental impact point of view: “When considering results of the LCA it can be concluded that the biggest environmental impact is the use phase. This is primarily due to the transformer losses; therefore, the environmental impact of the use phase depends on the type of energy source that is being used.”

Optimisation across these stages requires minimising the environmental impacts during each stage. This approach includes maximising energy efficiency and transformer product life and minimising environmental impact at the design and manufacturing stages, while ensuring

the sustainable management of used transformers. This is consistent with global international policies reducing and safely managing hazardous waste, including the Stockholm Convention.

As some installed transformers contain PCBs, care is needed as PCBs are characterised by their persistence, bioaccumulation, potential for long-range transport and adverse effects on humans and wildlife. The Stockholm Convention on Persistent Organic Pollutants, including PCBs, was adopted by the international community and entered into force in 2004. As of 2017 there are 181 signatories to the Stockholm Convention (180 states and the EU). Signatories to the Stockholm Convention can no longer produce PCBs and are required to stop using equipment contaminated with PCB by 2015. Existing equipment, such as transformers, that contain PCBs may be used until 2025 and need to be disposed in an environmentally-sound manner by 2028.

UN Environment and other agencies are supporting countries to ensure that PCB use ceases after 2025. Support includes guidance to develop and update national inventories, capacity building and establishing proper storage of discontinued equipment and ensuring environmentally sound management of all PCB oils. For more information on the specific status in a country, please see the document entitled “Consolidated assessment of efforts made towards the elimination of polychlorinated biphenyls”⁴⁴ and visit the PCB Elimination Network website.⁴⁵

The implementation of environmentally sound management requires the following elements to be taken into account: (1) policy and legal framework; (2) collection schemes and related awareness raising activities; (3) transportation, storage and final disposal strategies; and (4) financial mechanisms to cover the running costs.

7.1 POLICY AND LEGAL FRAMEWORK

To have a required and enforceable national programme, governments must have a legal framework for electronic waste and hazardous waste management. This encourages the development of initiatives in the country or region for relevant international conventions.

Policymakers should consult their country's Stockholm Convention Focal Point⁴⁶ and consult National Implementation Plans⁴⁷,

which describe the baseline assessment of PCBs and the legal framework for dealing with existing equipment containing PCBs.

In addition to PCBs, policymakers should also consider policies for any other hazardous materials. Limits should be set in line with the international best practice standards. Limits should be reviewed regularly and adjusted to account for technical progress.

CASE STUDY: Disposal of PCBs from Transformers, Southern Africa

Through a regional GEF-funded project in Southern Africa, UN Environment is working with 12 countries to dispose of PCBs from existing transformers in a safe and environmentally sound manner.

According to the project's estimates, there are more than 10,000 transformers containing PCBs in the region, amounting to approximately 2,000 tonnes of contaminated oils.

Currently, most countries lack the legal framework for handling PCBs and owners of the transformers are often unaware of the risk to the environment and human health. Compounding that risk is the fact that PCB fluids are sometimes mixed with mineral oils during routine transformer maintenance, and subsequently reused in previously uncontaminated transformers.

The GEF and UN Environment project in Southern Africa has the objective of reducing the environmental and human health risks by putting in place a cost-effective and socially responsible environmentally sound management plan for PCBs. Some of the activities included in the project are:

- Developing of national and regional PCB regulations
- Providing training for inspectors and controls officials to ensure market monitoring and verification are properly completed
- Adopting phase-out plans at the national level with utility owners and other transformer owners; and
- Establishing a regional mechanism to complete the collection of PCBs and licensing companies to collect, drain and transport PCBs.

For more information [click here](#).

7.2 COLLECTION SCHEMES

Improper handling, collection, storage, transportation or disposal of hazardous materials—in particular, PCBs—and waste can lead to releases of pollution that can persist in the atmosphere, soil, water, and a source of human exposure through food. Collection and disposal programmes for PCBs and more broadly transformers are important because they can promote the recovery of other materials found in the end of life of transformers, including metals and oil. Recycling and reuse of transformers may offer secondary commercial opportunities in developing countries that decide to implement collection and recycling systems.

Before recycling of transformers or use of existing parts, they have to be cleaned of PCBs. Even very small amounts of PCB can contaminate new fluids, and the transformers will become once more equipment that can no longer be used after 2025.

7.3 RECYCLING PROGRAMMES

At the end of the service life of a transformer, a high rate of recycling can be expected due to the value of the metals used in the construction of the transformer. Policy measures encouraging the environmentally sound management of used transformers should be coupled with technologies that capture and securely clean the transformer from future contamination of PCBs and ensure more energy-efficient transformers are delivered to the market. No processing to recover PCBs is allowed to parties to the Stockholm Convention and recycling of other transformer components is only possible if cleaned of PCBs.

Regulators can explore and adopt approaches encouraging the collection and recycling of used transformer units, bearing in mind they cannot be contaminated with PCBs (to avoid cross-contamination). These approaches should be adapted to national conditions, taking into account any local manufacturing and scrap metal dealers. If effectively designed and managed, these policies can create jobs in collection and recycling, while at the same time reducing overall environmental impact.

7.4 FINANCING ENVIRONMENTALLY SUSTAINABLE MANAGEMENT

Decisionmakers address policy questions related to designing collection schemes. These schemes address when, to what extent, and in what manner consumers pay. Regulators should look at the market and decide which stakeholders will support the programme.

Due to the high value of the windings and core steel virtually all transformers taken out of service are recycled. This recycling is self-financed through the scrap value of the metals being recycled. For this reason, financing is generally not necessary to ensure recycling of transformers at the end of life; however, were it required, then governments may consider sources of financing that have been used for other end use products like lighting products and refrigerators. These are listed below:

- **Full cost internalisation**—reflecting individual producer responsibility, this mechanism establishes a direct incentive for competition and design improvement.
- **Advance disposal fee systems**—industry manages fees in a so-called “eco-fee.” In this system, a small portion of the purchase price of a product supports an end-of-life management system.
- **Regional systems**—the establishment of regional systems can be the optimal solution in cases where national approaches are not financially viable to support recycling of transformers in one single country.

7.5 ESTER ELECTRICAL INSULATING FLUIDS

Liquid-filled transformers have their electrical windings immersed in a dielectric fluid to reduce electrical clearances and greatly improve cooling performance, thus making transformers more compact. For many years mineral oil has been seen as the fluid of choice for electrical transformers due to its favourable cooling and electrical performance. It does have, however, some short comings including flammability, poor environmental performance, low moisture tolerance, and corrosive sulphur.

An alternative cooling fluid to mineral oil is an ester-based fluid. They are classified as fire safe, are readily biodegradable, are free from corrosive sulphur compounds, and have excellent moisture tolerance. These attributes are important for environmental impact especially in areas such as Africa with pole- and ground-mounted transformers installed in remote areas without oil containment facilities. Ester fluids have also been shown to extend the life of electrical insulation, which prolongs the service life of the transformer.

Ester is a reaction product from the combination of an acid and an alcohol. Esters come in many forms, but the ester-based fluids used in transformers can be split into two groups, synthetic and natural. Synthetic esters are manufactured from carefully selected raw materials to give a finished product that is tailored to the specific application. Natural esters are derived directly from renewable natural sources, primarily seed oils such as soya bean, rapeseed oil or sunflower oil. The base oil is chosen to give the best possible fit to the application; however, unlike synthetic esters the properties of these base oils cannot be modified significantly. Thus to get a natural ester dielectric fluid that remains liquid at low temperatures, a compromise must be made, and a base oil with relatively poor oxidation stability is usually chosen. This means natural esters are only suitable for sealed equipment. Natural esters are best suited to temperate locations or indoor applications.



8. IMPLEMENTATION

WHAT?	Provides an overview of the approach governments may wish to follow when initiating a market-transformation programme for transformers in their national market.
WHY?	This section offers a summary/overview of the U4E's "Policy Fundamentals Guide".
NEXT?	Some key questions to keep in mind: <ul style="list-style-type: none"> • How do we initiate actions in our market to start promoting energy-efficient transformers? • What legislative/legal structures and programmes are necessary? • What stakeholder groups should be formed and involved in the process?

To support governments in promoting energy efficiency and removing obsolete and energy intensive transformer technologies from their markets, U4E has developed a step-by-step guide called "Policy Fundamentals Guide". This guide offers an overview of the key elements required to transform a national appliance market toward more energy-efficient products through the application of the U4E Integrated Policy Approach.

"Policy Fundamentals Guide" is crosscutting for all U4E priority products including lighting, residential refrigerators, air conditioners, transformers and electric motors. The approach can also be expanded to other energy-consuming products.

By following the approach outlined in the "Policy Fundamentals Guide," national governments and regional institutions can develop a clear vision and policy goals, identify specific objectives, and determine the required processes (such as identifying resource requirements, responsibilities and tracking performance to ensure transparency). By establishing a systematic plan, regions and countries ensure that the approach adopted is coherent and will save time, effort and resources.

While each section of the “Policy Fundamentals Guide” is outlined in detail in the guide, the actual components in the strategy may vary according to each country’s situation and needs. Therefore, the guidance should be adapted to meet the local context and needs.

The process should be led by governments or regional institutions with methodological support, guidance and technical advice from U4E (and/or other) experts. It should involve all relevant stakeholders to jointly determine priorities and the most appropriate pathways to achieve them.

The following is a brief overview of the “Policy Fundamentals Guide”:

Chapter 1

Introduction – provides an overview of the benefits of energy-efficient products and the U4E Integrated Policy Approach.

Chapter 2

How to Prepare for Programme

Implementation – introduces the organising bodies and overarching legislative and legal frameworks that need to be in place to operate an effective programme. It provides guidance on the resources required for implementing a programme and strategies for securing those resources. It also provides information on collecting data and prioritising products for inclusion in a programme.

Chapter 3

How to Design and Implement Market Transformation Programmes

– provides the basic steps to follow when designing and implementing market transformation policies—including market assessment, barrier analysis, regulations, standards, labels, awareness campaigns, and awards and recognition programmes. It provides case studies of effective implementation in countries across the world and recommendations for developing regional initiatives.

Chapter 4

How to Make Efficient Products Affordable

– addresses the critical issue of overcoming first-cost barriers to market adoption, including topics such as financing sources, approaches and stakeholders. Topics covered include energy service companies, financing programmes, bulk procurement schemes, and electric utility programmes. This section also describes how countries with subsidised electricity tariffs can use innovative schemes to drive efficiency.

Chapter 5

How to Establish and Improve Compliance Programmes

– discusses the importance of monitoring, verification, and enforcement (MVE) schemes from both a manufacturer’s and a consumer’s perspective. It also discusses the critical role of government in establishing and maintaining a robust market surveillance programme.

Chapter 6

Environmentally Sound Management

– provides a summary of the importance of safe and sustainable recycling and disposal programmes. It also touches on the development of health and safety standards for products, particularly those with toxic or harmful components.

Chapter 7

How to Measure Success and Improve Programmes

– describes the key components of an evaluation framework to measure the results from market transformation programmes and then use those results to improve programmes.

Chapter 8

Resources – presents reports and resources from energy-efficient appliance, equipment, and lighting programmes and experts around the world.



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ABOUT THE PROJECT

BEST PRACTICE CAPACITY BUILDING

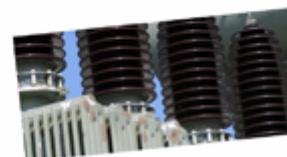
Introduction

On May 21 2014 the European Commission adopted the Ecodesign Regulation No 548 to ensure that transformers become progressively more efficient as new power transformers put into service in the EU internal market will have to fulfil minimum energy performance requirements.

Although power transformers are generally very energy performant devices, contributing to the overall energy efficiency of the power system, their energy performance can yield substantial savings when they are replaced by more efficient models.

INDUSTRIAL AND TERTIARY PRODUCT TESTING AND APPLICATION OF STANDARDS

TRANSFORMERS FANS



Consider the True Cost Of Transformer Losses

The preferred energies to fit the demand generation market in Spain. In particular, zero benefit from

Alonso Ramis / Jul 01, 2007

red energies to fit the generation market in solar and hydro benefit of tariffs, because they

TRANSFORMER LOSSES

can be

ge price that a

se losses stay constant during the year. The load or loading of the transformer. Thus, the cost of these losses to access the

DO METER STANDARDS NEED TO EVOLVE?

SENS

9. RESOURCES

Provides some additional resources and background material that can offer governments further assistance in developing schemes to promote energy-efficient transformers.

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- Sumper, Andreas and Baggini, Angelo, 2012. **Electrical Energy Efficiency: Technologies and Applications.** Available at <http://eu.wiley.com/WileyCDA/WileyTitle/productCd-0470975512.html>

- **Transformers**—a website offered by ICA that presents several publications focusing on the purchase of a premium, high-efficiency, copper-wound transformers, demonstrating the significant savings over the life of a transformer compared to other alternatives. Available at <https://www.copper.org/environment/sustainable-energy/transformers/>

Online Tools

- **Energy efficiency in transformers**—website offered by ABB providing many resources and case

studies on energy-efficient transformers. ABB offers its expertise to help ensure electric utilities, commercial and industrial customers, electrical contractors and other stakeholders are able to make a head start in meeting or exceeding the efficiency standards. Available at <http://new.abb.com/products/transformers/energy-efficiency>

- **Transformer Life-Cycle Cost (Total Cost of Ownership)**—website offered by ICA providing a description of the total cost of ownership approach, how to calculate the A and B factors and an example to show the impact of the calculation and the savings that would accrue to the company evaluating the losses. Available at https://www.copper.org/environment/sustainable-energy/transformers/education/trans_life_cycle.html

- **Transformer Loss Calculation Tool**—calculates losses for different types of transformers and CO₂ emissions. It gives you information about the most energy-efficient transformer during its life time. The evaluation of the most economic transformer will be done by the capitalized cost, payback time, and internal rate of return. This tool, therefore, gives additional information about the no-load and load loss evaluation (A and B factor), in case they are not known in advance. Available at: <https://www.dnvgl.com/services/transformer-loss-calculation-tool-70030>
 - **SMART UTILITY:** Consider the True Cost of Transformer Losses <http://www.tdworld.com/distribution-management-systems/consider-true-cost-transformer-losses>
 - **INTAS:** Industrial and tertiary product testing and application of standards <http://www.intas-testing.eu/transformers/intro>
 - **Electrical Energy Efficiency: Technologies and Applications,** Andreas Sumper, Angelo Baggini, ISBN: 978-0-470-97551-0 <http://eu.wiley.com/WileyCDA/WileyTitle/productCd-0470975512.html>
 - **Energy Efficiency Potential for Distribution Transformers in the APEC Economies;** Virginie Letschert, Michael McNeil, Jing Ke, Puneeth Kalavase of Lawrence Berkeley National Laboratory and Mahesh Sampat (EMS International Consulting, Inc.), LBNL-6682E, Environmental Energy Technologies Division, December 2013. <https://ies.lbl.gov/sites/all/files/lbnl-6682e.pdf>
 - **Energy PROPHET II:** The potential for global energy savings from high-efficiency distribution transformers; Paul Waide, Waide Strategic Efficiency Limited and Michael Scholand, N14 Energy Limited; 2014. https://www.researchgate.net/publication/270879463_Energy_PROPHET_II_The_potential_for_global_energy_savings_from_high-efficiency_distribution_transformers
- Other Relevant Resources**
- **American Council for an Energy-Efficient Economy (ACEEE)**—a nonprofit, 501(c)(3) organisation, acts as a catalyst to advance energy-efficiency policies, programmes, technologies, investments, and behaviours. Focusing on the US, ACEEE seeks to harness the full potential of energy efficiency to achieve greater economic prosperity, energy security, and environmental protection. ACEEE carries out its mission by: (1) conducting in-depth technical and policy analyses; (2) advising policymakers and programme managers; (3) working collaboratively with businesses, government officials, public interest groups, and other organisations; (4) convening conferences and workshops, primarily for energy efficiency professionals; (5) assisting and encouraging traditional and new media to cover energy efficiency policy and technology issues; and (6) educating consumers and businesses through our reports, books, conference proceedings, press activities, and websites. ACEEE was founded in 1980 by leading researchers in the energy field. Since then it has grown to a staff of about 50. ACEEE focuses on energy policy (federal, state, and local), research (including programmes on buildings and equipment, utilities, industry, agriculture, transportation, behaviour, economic analysis, and international initiatives).
 - **CLASP**—a nonprofit international organisation promoting for energy-efficiency standards and labels (S&L) for appliances, lighting, and equipment. CLASP improves the environmental and energy performance of the appliances and related systems, lessening their impacts on people and the world around us. CLASP develops and shares practical and transformative policy and market solutions in collaboration with global experts and local stakeholders. Since 1999, CLASP has worked in over 50 countries on six continents pursuing every aspect of appliance energy efficiency, from helping structure new policies to evaluating existing programmes.
 - **European Council for an Energy-Efficient Economy (ECEE)**—a membership-based nonprofit association. As Europe's largest and oldest NGO dedicated to energy efficiency, they generate and provide evidence-based knowledge and analysis of policies, and they

facilitate co-operation and networking. ECEEE members are found among private and public organisations, as well as among all those professionals from all sectors who share ECEEE's goals. ECEEE offers governments, industry, research institutes and citizen organisations a unique resource of evidence based knowledge and reliable information. ECEEE promotes the understanding and application of energy efficiency in society and assists its target groups—from policymakers to programme designers to practitioners—with making energy efficiency happen. ECEEE is registered as a Swedish organisation and has its secretariat in Stockholm. ECEEE participates actively in the European policymaking process, the organisation participates in a number of EU policymaking and advisory fora, and frequently comments on European energy policy through position papers and responses to public consultations. ECEEE has also held expert workshops and briefings for policymakers.

It has co-operated with the European Commission, the Parliament and the EU presidency, to hold expert seminars. These institutions appreciate the competence and integrity offered by ECEEE's network of members.

- **IEA**—an autonomous organisation working to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA's four main areas of focus are: energy security, economic

development, environmental awareness, and engagement worldwide. Founded in response to the 1973/4 oil crisis, the IEA's initial role was to help countries coordinate a collective response to major disruptions in oil supply through the release of emergency oil stocks. The IEA has a staff of 260 enthusiastic professionals (energy analysts, modelers, data managers/statisticians, technicians, secretaries and support staff) working together on global energy challenges.

- **SEAD Initiative**—an initiative of the Clean Energy Ministerial, SEAD seeks to engage governments and the private sector to transform the global market for energy-efficient equipment and appliances. SEAD initiated an international collaboration of technical and policy experts in solid-state lighting, which worked to promote alignment and improvements in the scope and stringency of international standards and labeling programmes. Current SEAD member governments include Australia, Brazil, Canada, the EC, Germany, India, Indonesia, Mexico, Russia, Saudi Arabia, South Africa, Sweden, Republic of Korea, United Arab Emirates, UK; and China and the US maintain an observer status.



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ANNEX A. GLOSSARY

Compliance: conforming to a rule, such as a law, policy, specification or standard. Also, fulfilment by countries/businesses/individuals of emission reduction and reporting commitments under the UNFCCC and the Kyoto Protocol. (UNFCCC)

Full Procedure Verification Test: a test where all procedures for measurements and records stipulated in the entry conditions for an accreditation scheme have been followed.

Greenhouse Gases (GHGs): The atmospheric gases responsible for causing global warming and climate change. The major GHGs are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). Less prevalent but very powerful GHGs are: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). (UNFCCC)

Mercury (Hg): a metallic element, the only one that is liquid at room temperature.

Minimum Energy Performance Standard (MEPS): a mandatory minimum performance level that applies to all products sold in a market, whether imported or manufactured domestically. MEPS can be technology-neutral, or, can apply to specific technologies.

Peak Energy Demand: period in which electrical power is expected to be provided for a sustained period at a significantly higher than average supply level.

Power Factor: under periodic conditions, ratio of the absolute value of the active power P to the apparent power S:

$$\lambda = \frac{|P|}{S}$$

Note: Under sinusoidal conditions, the power factor is the absolute value of the active factor. (IEC)

Power Quality: characteristics of the electric current, voltage and frequencies at a given point in an electric power system, evaluated against a set of reference technical parameters. Note: These parameters might, in some cases, relate to the compatibility between electricity supplied in an electric power system and the loads connected to that electric power system. (IEC)

Rebound Effect: behavioural responses to the introduction of new, more efficient, technologies whereby consumers use the product in question more frequently or for longer because of its increased efficiency. This results in a reduction in the beneficial effects of the new technology.

Registration Verification: process of confirming that registered products meet the requirements of a programme's entry conditions.

Self-certification: practice of submitting information about one's product in a formal statement rather than being obliged to ask a third party to do so.

SI Unit: any of the units adopted for international use under the *Système International d'Unités*.

ANNEX B. COMPARISON OF MEPS BETWEEN DIFFERENT COUNTRIES

Comparing different MEPS based on performance indexes is sometimes difficult primarily due to differences in:

- Rated power definitions
- Reference temperatures
- Rated frequencies
- Rated maximum voltages of the equipment.

When comparing national energy efficiency standards for transformers around the world, some standards are comparable, but in others, there are underlying differences preventing direct comparisons. For example, transformers must operate at the frequency of the system where they are installed (i.e. 50Hz or 60Hz), and the efficiency of a transformer will vary slightly with the frequency of the network. Furthermore, some policymakers establish energy performance requirements for transformers on a basis of maximum losses for the core and coil at full load separately, while others establish maximum losses summed together for a particular rated power. Still other policymakers specify the efficiency at a percentage loading point.

In addition, there are some differences between how the power rating of a transformer is reported in different markets. In countries applying IEEE standards (generally North America), the rated power of the transformer is defined as the rated capacity at the output of the device—that is, it represents the available capacity at the load point. In other parts of the world employing IEC standards, the power rating (kVA) represents the rated input to the transformer—how much power is being supplied to a particular unit. When rated as the output (i.e. the IEEE method), the power rating excludes the core and coil losses when the transformer is operating, whereas for the input capacity (i.e. the IEC method), the power rating includes the transformer's losses.

The IEC test method is more common among countries with transformer efficiency requirements. The method selected also has an impact on how losses are treated in the efficiency metric. Efficiency is, broadly speaking, a measurement of power out divided by power in. However, the way that efficiency is calculated differs slightly between IEC and IEEE. This difference stems from a difference in how transformers are rated, i.e., the power capacity of a transformer. In IEC, the equation is based on the input power, while for IEEE, the equation is based on output power, as shown in the following equations:

$$\text{IEC Definition Efficiency} = \frac{\text{Power Input} - \text{Losses}}{\text{Power Input}}$$

$$\text{IEEE Definition Efficiency} = \frac{\text{Power Output}}{\text{Power Output} + \text{Losses}}$$

Where:

Power Output and Power Input are measured in Watts and are calculated by multiplying the power rating (kVA) of the transformer (IEEE or IEC method) by the per unit load (e.g. 50 per cent of rated nameplate);

Losses represents the sum of core and coil losses at the per unit load point; where **core loss** is the power loss in the core at rated voltage and **coil losses** are the square of the **per unit load** times the coil losses at rated capacity.

Per unit load is the decimal equivalent of the percentage of rated load supplied by the transformer, such as 0.50 for 50 per cent of rated capacity.

Although the first point above is apparent, in practice it is not considered, since both the IEC and IEEE refer to the same numerical values of rated powers in their series. Similarly, also loss values defined per IEEE standards cannot be compared directly with the same figures specified to IEC standards because they are referring to different rated powers (see Table 18).

Table 18: Illustrative comparison of power rating (kVA) conventions, IEC and IEEE

ITEM	IEC METHOD	IEEE METHOD
POWER RATING (KVA)	50 kVA	48.6 kVA
CORE LOSSES	0.190 kW	0.190 kW
COIL LOSSES	1.250 kW	1.250 kW
EFFICIENCY	$= (\text{kVA} - \text{losses}) / \text{kVA}$	$= \text{kVA} / (\text{kVA} + \text{losses})$
EQUATION	$= (50 - (0.190 + 1.250))/50$	$= 48.6 / (48.6 + (0.190 + 1.250))$
RESULT (%)	97.12	97.12

ANNEX C. IEC 60076 TEST STANDARDS

The set of international standards covering power transformers is published under IEC 60076, Power Transformers, and is prepared by IEC Technical Committee 14 (IEC TC14). The scope of the IEC TC14 is the standardisation in the field of power transformers, tap-changers and reactors for use in power generation, transmission and distribution. Generally these transformers have power ratings above 1 kVA single phase and 5 kVA polyphase with a higher voltage winding of 1,000 V or more, however the scope includes lower voltage transformers and regulators used in power delivery

applications. Excluded: - Instrument transformers - Testing transformers - Traction transformers mounted on rolling stock - Welding transformers - Transformers for applications covered by Technical Committee 96.

Figure 3 on page 41 lists the main IEC TC14 published standards documents. The IEC standards addressing specifically power transformer tests (PTT) and power transformer energy performance related tests (EPT) are highlighted in the EPT/PTT column.

The following provides more detail on the above cited standards.

IEC 60076-1 ed3.0 (2011-04)–Power transformers–Part 1: General

This part of IEC 60076 applies to three-phase and single-phase power transformers (including auto-transformers) with the exception of certain categories of small and special transformers.⁴⁸ When IEC standards do not exist for certain categories of transformers, this part of IEC 60076 may still be applicable either as a whole or in part. For those categories of power transformers and reactors which have their own IEC standards, this part is applicable only to the extent in which it is specifically called up by cross-reference in the other standard. The updated edition of this standard includes the following technical sections that were not in the previous version:

- definition of harmonic content
- subclause on transport
- functional method of specification
- connection symbols for single phase transformers
- safety and environmental requirements
- requirements for liquid preservation systems
- clause on DC currents
- vacuum, pressure and leak tests on tanks
- facilities for condition monitoring and environmental and safety considerations.

IEC 60076-2 ed3.0 (2011-02)–Power transformers–Part 2: Temperature rise for liquid-immersed transformers

This standard applies to liquid-immersed transformers, identifies power transformers according to their cooling methods, defines temperature rise limits and gives the methods for temperature rise tests. This new edition includes the following significant technical changes with respect to the previous edition:

- the winding hot-spot temperature rise limit was introduced among the prescriptions

- the procedures for the temperature rise test were improved in relation to the new thermal requirements
- five informative annexes were added to facilitate the implementation of this standard.

IEC 60076-3 ed3.0 (2013-07)–Power transformers–Part 3: Insulation levels, dielectric tests and external clearances in air

IEC 60076-3:2013 specifies the insulation requirements and the corresponding insulation tests with reference to specific windings and their terminals. This International Standard applies to power transformers as defined by IEC 60076-1. It also recommends external clearances in air. It gives details of the applicable dielectric tests and minimum dielectric test levels. Recommended minimum external clearances in air between live parts and between live parts and earth are given for use when these clearances are not specified by the purchaser. For categories of power transformers and reactors that have their own IEC standards, this standard is applicable only to the extent in which it is specifically called up by cross reference in the other standards. This third edition of IEC 60076-3 cancels and replaces the second edition published in 2000, and constitutes a technical revision.

IEC 60076-4 ed1.0 (2002-06)–Power transformers–Part 4: Guide to the lightning impulse and switching impulse testing–Power transformers and reactors

This standard gives guidance and explanatory comments on the existing procedures for lightning and switching impulse testing of power transformers to supplement the requirements of IEC 60076-3. Also generally applicable to the testing of reactors (see IEC 60289), modifications to power transformer procedures being indicated where required. The standard provides information on wave shapes, test circuits including test connections, earthing practices, failure detection methods, test procedures, measuring techniques and interpretation of results.

IEC 60076-5 ed3.0 (2006-02)–Power transformers–Part 5: Ability to withstand short circuit

This standard identifies the requirements for power transformers to sustain without damage the effects of overcurrents originated by external short circuits. It describes the calculation procedures used to demonstrate the thermal ability of a power transformer to withstand such overcurrents and both the special test and the theoretical evaluation method used to demonstrate the ability to withstand the relevant dynamic effects.

IEC 60076-6 ed1.0 (2007-12)–Power transformers–Part 6: Reactors

The standard applies to the following types of reactors: shunt reactors; series reactors including current-limiting reactors, neutral-earthing reactors, power flow control reactors, motor starting reactors, arc-furnace series reactors; filter (tuning) reactors; capacitor damping reactors; capacitor discharge reactors; earthing transformers (neutral couplers); arc-suppression reactors; smoothing reactors for HVDC and industrial application.

IEC 60076-7 ed1.0 (2005-12)–Power transformers–Part 7: Loading guide for oil-immersed power transformers

This standard is applicable to oil-immersed transformers and describes the effect of operation under various ambient temperatures and load conditions on transformer life.

IEC 60076-8 ed1.0 (1997-10)–Power transformers–Part 8: Application guide

This standard provides information to users about certain fundamental service characteristics of different transformer connections and magnetic circuit designs; system fault currents; parallel operation of transformers, calculation of voltage drop or rise under load; selection of rated quantities and tapping quantities; application of transformers of conventional design to convertor loading; measuring techniques and so on. This standard cancels and replaces IEC 60606.

IEC 60076-10 ed1.0 (2001-05)–Power transformers–Part 10: Determination of sound levels

This standard defines sound pressure and sound intensity measurement methods by which sound power levels of transformers, reactors and their associated cooling auxiliaries may be determined. Is applicable to transformers and reactors covered by the IEC 60076 series and the IEC 61378 series, without limitation as regards size or voltage and when fitted with their normal cooling auxiliaries.

IEC 60076-10-1 ed1.0 (2005-10)–Power transformers–Part 10-1: Determination of sound levels–Application guide

This standard provides supporting information to help both manufacturers and purchasers apply the measurement techniques described in IEC 60076-10. This standard describes the sources and characteristics of transformer and reactor sound, provides practical guidance on making measurements, and discusses factors that may influence the accuracy of the methods. It applies to transformers and reactors together with their associated cooling auxiliaries.

IEC 60076-11 ed1.0 (2004-05)–Power transformers–Part 11: Dry-type transformers

This standard applies to dry-type power transformers (including auto transformers) having values of highest voltage for equipment up to and including 36 kV and at least one winding operating at greater than 1,1 kV. This standard applies to all construction technologies.

IEC 60076-12 ed1.0 (2008-11) –Power transformers–Part 12: Loading guide for dry-type power transformers

This standard applies to dry-type transformers according to the scope of IEC 60076-11. It provides the means to estimate ageing rate and consumption of lifetime of the transformer insulation as a function of the operating temperature, time and the loading of the transformer.

IEC 60076-13 ed1.0 (2006-05) Power transformers—Part 13: Self-protected liquid-filled transformers

The standard applies to high-voltage/ low-voltage self-protected liquid-filled and naturally cooled transformers for rated power 50 kVA to 1,000 kVA for indoor or outdoor use having a primary winding (high-voltage) with highest voltage for equipment up to 24 kV; a secondary winding (low-voltage) with highest voltage for equipment of 1,1 kV.

IEC 60076-14 ed2.0 (2013-09) –Power transformers—Part 14: Design and application of liquid-immersed power transformers using high-temperature insulation materials

This standard provides specification, design, testing and loading information for use by both the manufacturer and user of liquid-immersed power transformers employing either high-temperature insulation or combinations of high-temperature and conventional insulation. Is applicable to:

- power transformers designed in accordance with IEC 60076-1
- convertor transformers designed to IEC 61378 series
- arc furnace transformers; and
- covers the use of various liquid and solid insulation combinations.

This new edition includes the following significant technical changes with respect to the previous edition:

- enhancement of insulation system descriptions
- clarification of temperature rise limits; and
- the addition of overload temperature limits.

IEC 60076-15 ed1.0 (2008-02) –Power transformers—Part 15: Gas-filled power transformers

This standard applies to gas-filled power transformers (including auto-transformers) and to all construction technologies. This standard may be applicable as a whole or in parts to other transformers.

IEC 60076-16 ed1.0 (2011-08) –Power transformers—Part 16: Transformers for wind turbine applications

This standard applies to dry-type and liquid-immersed transformers for rated power 100 kVA up to 10,000 kVA for wind turbine applications having a winding with highest voltage for equipment up to and including 36 kV and at least one winding operating at a voltage greater than 1,1 kV.

IEC 60076-18 ed1.0 (2012-07) –Power transformers—Part 18: Measurement of frequency response

This standard covers the measurement technique and measuring equipment to be used when a frequency response measurement is required either on-site or in the factory either when the test object is new or at a later stage. This standard is applicable to power transformers, reactors, phase shifting transformers and similar equipment.

IEC/TS 60076-19 ed1.0 (2013-03)–Power transformers—Part 19: Rules for the determination of uncertainties in the measurement of losses in power transformers and reactors

This standard is a Technical Specification (TS), it illustrates the procedures that should be applied to evaluate the uncertainty affecting the measurements of no-load and load losses during the routine tests on power transformers. Even if the attention is especially paid to the transformers, when applicable the specification can be also used for the measurements of reactor losses, except large reactors with very low power factor.

IEC/TS 60076-20:2017–Power transformers—Part 20: Energy efficiency

This technical specification (TS) is applicable to transformers in the scope of IEC 60076-1. It proposes two methods of defining an energy efficiency index and introduces three methods of evaluating the energy performance of a transformer. The appropriate method is chosen by agreement between purchasers and manufacturers or according to local regulations.

IEC 60076-21 ed1.0 (2011-12) –Power transformers–Part 21: Standard requirements, terminology, and test code for step-voltage regulators

This standard provides a description of design types, tables of 50 Hz and 60 Hz ratings, supplementary ratings, construction, and available accessories are provided. Methods for performing routine and design tests applicable to liquid-immersed single and three-phase step-voltage regulators are described. Winding resistance measurements, polarity tests, insulation power factor and resistance tests, ratio tests, no load loss and excitation current measurements, impedance and load loss measurements, dielectric tests, temperature tests, routine and design impulse tests, short-circuit tests, control tests, calculated data, and certified test data are covered.

ANNEX D. TOTAL COST OF OWNERSHIP FOR VALUING LOSSES (ANNEX A FROM IEC TS 60076-20:2017)

CAPITALISATION OF LOSSES

A.1 General theory, concept of capitalisation

Capitalisation of losses is an effective means of minimising the total cost of transformers, taking into account the initial cost of the transformer and the lifetime cost of the electricity supplying the losses. Capitalisation of losses will increase the initial cost of the transformer over the value that is required to meet the basic specification, but the additional investment is justified by the capitalisation calculation and the consequential reduction of losses.

In essence, the process of capitalisation involves the calculation of the value today of the savings from reduced losses over the lifetime of the transformer. This means that the energy savings need to be calculated along with their yearly value. In turn, this means that the cost of the electricity saved needs to be predicted over a 30 to 50 year period for the analysis. The production of energy consumed in losses and the cost of electricity, considered for each year of the analysis period and discounted at an appropriate interest rate to represent their value today, gives the total value of losses to be evaluated against the cost of reducing the losses.

This calculation of the net present value of electricity in the future is inevitably a prediction, and thus involves a significant degree of uncertainty. The calculation of the appropriate capitalisation factors involves judgement and a sophisticated financial approach and should be carried out by experts with specialist knowledge of the issues. The capitalisation factor may be subject to significant regional variations due to differences in electricity production and distribution, and the cost of capital.

The tender for the transformer is then assessed on the basis of the initial cost plus the capitalised value of load and no-load losses so that the transformer with the lowest overall lifecycle costs (TCO = total cost of ownership) can be selected.

The capitalisation of losses is considered as the best method of optimizing the economic efficiency of the transformers.

Depending on the forecast economic conditions, the use of the capitalisation formula can result in transformer efficiencies better than those given in the tables. In these circumstances, using a higher efficiency transformer is appropriate.

If using the capitalisation formula would result in transformer efficiencies lower than those in the table, then the value in the table shall be used as a minimum because this represents a minimum standard reflecting established practices justified by long-term sustainable environmental considerations.

The initial cost of the transformers is not the only cost, and it should be associated with the cost of the installation under circumstances where sizes and weight are limited by infrastructure or transport considerations. These restrictions need to be included in the transformer specification, and the transformer optimised within these limitations.

All parameters and equations provided here represent basic explanations of the most important parameters, such as energy price and discount rates. A deeper investigation for each parameter by the user is recommended.

A.2 Impact of capitalisation values

Increasing the capitalisation values will result in a decrease in losses and an increase in initial cost, size and weight up to the point at which the cost of further decreasing the losses equals the capitalisation values, or to the point where the extra size and weight exceeds the limits in the specification.

It is important that relevant external factors such as carbon prices are included in the costs saved – these may already be included in the cost of electricity through the ETS⁴⁹ scheme or may need to be added in separately.

The capitalisation values represent the avoided costs associated with the marginal cost of energy due to no-load and load losses saved.

A.3 Capitalisation formula

A.3.1 General

To be fully relevant, capitalisation should be based on the forecast cost of energy for each year of the transformer's life, and on the actual losses during this period, and relate these future cash flows to today's money using the appropriate discount rate.

The losses used for capitalisation evaluation should include the cooling losses, with the no-load losses for the part always on, and with the load losses for the variable part.

The total cost of ownership is then defined by:

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

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 the rated voltage and rated frequency, on the rated tap;
- P_{c0}** is the cooling power (kW) needed for no-load operation;
- P_k** is the load loss (kW) due to the load, measured at the rated current and rated frequency on the rated tap at a reference temperature;
- P_{cs}** is the total cooling power (kW) needed for operation at the rated power (including three-winding operation if any);
- A** is the factor representing the cost of capitalisation of no-load losses in cost per kW;
- B** is the factor representing the cost of capitalisation of the losses due to load in cost per kW.

In the event that different transformer technologies are used, additional differences related to installation costs should be considered.

A.3.2 Calculation of factor A

A is the cost of capitalisation of no-load losses in cost per kW.

The no-load losses and their associated cooling losses are present as soon as the transformer is energized. Therefore, the capitalisation cost is the valorization cost of energy multiplied by the operating time over the full life expectancy of the transformer as shown in Equation (A.2):

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

where

O_{0j} is the operating time of the transformer at year j in h;

C_j is the valorisation of the energy at year j in cost per Wh if losses are expressed in W;

i_j is the real discount rate at year j in per unit;

n is the life expectancy of the transformer in years.

NOTE 1: Discount rates can be expressed in either real (excluding inflation) or nominal (including inflation) terms, with both leading to identical answers providing the associated cash flows are also expressed in similar terms. However, the use of real discount rates simplifies the calculations as it assumes that all costs rise identically at the rate of inflation. If a particular cost rises in excess or below inflation, for example the marginal cost of electricity, then this excess above inflation can be more easily dealt with through a modification of the discount rate used. Accordingly, all discount rates used in this analysis are real.

For simplification, if the discount rate is considered constant and the cost of energy (in real terms) equal to that at the mid-life of the transformer, then assuming that the transformer is always energized, at year n Equation (A.2) can be simplified to the form shown in Equation (A.3):

$$A = 8760 \times C_{n/2} \times \frac{\frac{1}{1+i} (1 - (\frac{1}{1+i})^n)}{1 - \frac{1}{1+i}} = 8760 \times C_{n/2} \times \frac{1 - (\frac{1}{1+i})^n}{i}$$

where

$C_{n/2}$ is the evaluation of the energy at mid-life of the transformer in cost per kWh if losses are expressed in kW;

i is the discount rate fixed over the whole life of transformer (n years);

n is the useful economic life of the transformer in years, which in the past has been close to the transformer's physical life expectancy (30 to 50 years).

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

A.3.3 Calculation of factor B

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

The load of a transformer can usually be split between the fixed load which is constant and present all year round, and the variable load which depends on ambient conditions and may be present only part of the time. Figure A.1 illustrates this load split.

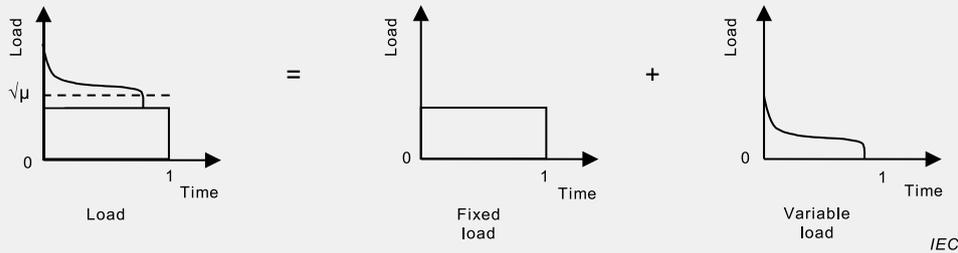


Figure A.1:
Load profile

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

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

where

T is equivalent to one year; if $k(t)$ is defined per h T is 8760 h; if $k(t)$ is defined per minutes T is 525600 min;

$k(t)$ is the load factor as a function of time.

The load losses capitalisation cost comes as the sum of the load factors multiplied by the cost of energy and corrected by the increase of load and the increase of transformer installed base. In Equation (A.5), the losses are split into two parts, with each one weighted by its time base utilization:

$$B = \sum_{j=1}^n \frac{\mu \times c_j \times (O_{aj} \times T_{aj} + O_{fj} \times T_{fj})}{(1 + i_j)^j} \left(\frac{1 + C_{\mu j}}{1 + C_{aj}} \right)^{2j}$$

where

μ is the average load loss factor as defined in Equation (A.4);

C_j is the total cost of the energy at year j in cost per Wh if losses are expressed in W;

i_j is the discount rate at year j in per unit;

O_{aj} is the operating time of the transformer at variable load during year j in h;

O_{fj} is the operating time of the transformer at fixed load during year j in h, usually 8760 h if the transformer is operated all year round;

T_{aj} is the share of variable load in the total load loss factor at year j ;

T_{fj} is the share of fixed load in the total load loss factor at year j ;

$$T_{aj} + T_{fj} = 1$$

n is the life expectancy of the transformer in years;

$C_{\mu j}$ is the rate of load loss factor increase at year j ;

C_{aj} is the rate of installed power increase at year j .

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

If the transformer is energized all year round and if the cost of energy is considered constant and equal to the energy evaluation at the mid-life of the transformer, and if usage of the transformer is assumed as invariant during its whole life, and if the discount rate is considered constant, then the formula can be simplified as shown in Equation (A.6):

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

where

μ is the average load loss factor as defined above;

$C_{n/2}$ is the valorisation of the energy at the mid-life of the transformer in cost per Wh if losses are expressed in W;

i is the discount rate in per unit;

O_a is the operating time of the transformer at variable load in h;

O_f is the operating time of the transformer at fixed load in h, usually 8760 h if the transformer is operated all year round;

T_a is the share of variable load in the total load loss factor;

T_f is the share of fixed load in the total load loss factor;

$T_a + T_f = 1$

n is the life expectancy of the transformer in years;

C_μ is the rate of load loss factor increase;

C_a is the rate of installed power increase.

As a further simplification, if the load factors and load profile are assumed to remain constant in the future, then the formula may be simplified as shown in Equation (A.7):

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

For the meaning of the symbols, refer to Equation (A.5).

A.3.4 Use of A and B for tender evaluation

In a transformer enquiry, the user should give the values of A and B in terms of monetary value per kW (for example, €/kW). This allows the manufacturer to offer the most economical transformer taking into account the TCO implied by the capitalisation values.

During the tender evaluation process, the purchaser will evaluate each bid according to the TCO calculated using Equation (A.1) incorporating the guarantee load and no-load losses provided by the manufacturers.

The transformer manufacturer will therefore optimize the TCO in such way that the value of a reduction of losses is greater than the associated cost increase of the transformer.

The most economical transformer will be the one offering the lowest total cost of ownership as calculated with Equation (A.1). The economical evaluation of the bids should be based on this TCO.

A.3.5 Determination of factors A and B

Utility companies will already probably have a corporate value for factor A based on strategic policies, energy mix, governmental and political decisions, incentives for environmental concerns and prospective scenarios, discount rates, and investment time horizons. Factor B is normally derived from factor A by means of standardised loading profiles.

Industrial or private customers not subject to such considerations can determine values A and B in a simple manner with the formulae defined in this paragraph using the inputs defined as follows.

$$(A.8) \quad A = 8760 \times C_{n/2} \times \frac{1 - \left(\frac{1}{1+i}\right)^n}{i} \quad \left| \quad B = 8760 \times C_{n/2} \times \frac{1 - \left(\frac{1}{1+i}\right)^n}{i} \quad (A.9)$$

where

n is the useful economic life of the transformer in years;

$C_{n/2}$ is the forecast cost of electricity at mid useful economical life of the transformer in terms of monetary value per kWh;

i is the discount rate set by the company as appropriate for the investment proposed in p.u. By default, the weighted average costs of capital should be used unless an alternative specific rate has been calculated for the investment.

NOTE: The sensitivity of the capitalization value to n decreases as n increases. The higher the cost of the energy, the greater the savings from a lower loss level will be, thus justifying a higher initial cost of the transformer. The lower the discount rate, the higher the present value of the losses will be. A low discount rate justifies high spending on reducing losses.

Determining load and operating time can be simplified as, for most of the industry, the base load is predominant and therefore T_a can be considered as negligible. The formula can then be simplified as shown in Equation (A.10), where μ can be well approximated:

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

where

S_r is the rated power of the transformer;

S is the average forecast load.

In the calculation of A (see Equation (A.8)), if the transformer is not energised continuously, the yearly 8760 h can be adjusted to reflect the actual use of the transformer. For example, a two-shift industry would typically have a ratio of 2/3, resulting in 5 840 h.

In the calculation of B (see Equation (A.9)), if the transformer is not loaded continuously, the yearly 8760 hours can be adjusted to reflect the actual use of the transformer. For example, a two-shift industry would typically have a ratio of 2/3, resulting in 5 840 h.

ANNEX E. IMPROVING ENERGY PERFORMANCE OF TRANSFORMERS

A transformer can be made more energy-efficient by improving the materials of construction (e.g. better-quality core steel or winding material) and by modifying the geometric configuration of the core and winding assemblies. Making a transformer more energy-efficient (i.e. reducing electrical losses) can often be a trade-off between more expensive, lower-loss materials and designs, and the value a customer attaches to those losses. For a given efficiency level, the no-load and load losses are generally inversely related: reducing one usually increases the other, as shown in Table 20.

Table 19: Loss-reduction interventions for transformers

OBJECTIVE	APPROACH	NO-LOAD (CORE) LOSSES	LOAD (WINDING) LOSSES	EFFECT ON PRICE
DECREASE NO-LOAD LOSSES	Use lower-loss core materials	Lower	No change	Higher
	Better core construction techniques	Lower	No change	Higher
	Decrease flux density by increasing core cross-sectional area	Lower	Higher	Higher
	Decrease flux density by decreasing volts/turn	Lower	Higher	Higher
	Decrease flux path length by decreasing conductor cross-sectional area	Lower	Higher	Lower
DECREASE LOAD LOSSES	Use lower-loss conductor materials	No change/ lower	Lower	Higher
	Decrease current density by increasing conductor cross-sectional area	Higher	Lower	Higher
	Decrease current path length by decreasing core cross-sectional area	Higher	Lower	Lower
	Decrease current path length by increasing volts/turn	Higher	Lower	Lower
	Reduce core cross-section by increasing flux density through better core steels, reducing conductor length	Higher/no change	Lower	Higher

There are five approaches to reducing no-load losses shown in Table 20. One of these is a material-substitution option and four of them are transformer-design options. Each of these options is discussed briefly below:

- The use of lower-loss material to construct the core of the transformer will decrease the no-load losses, and very often it will have no impact on load losses. This can include, for example, using a laser-scribed thinner lamination of silicon steel in place of standard one, or using amorphous material in the core instead of silicon steel. In general, however, substituting with a lower-loss core material will result in higher manufacturing costs. Over the last 50 years, considerable advances have been made in the materials used for transformer cores offering lower watts of loss per unit magnetic flux. The use of better core-construction techniques can also reduce no-load losses by how the joints between the metal laminations are formed. These techniques can include, for example, using a distributed gap in a wound core, or a step-lap core. These solutions, however, involve the use of sophisticated core-manufacturing equipment that may, in turn, lead to an increase in price.
- Lowering the magnetic flux density by making the cross-sectional area of the core larger is also an option available to transformer designers. However, by increasing the size of the core, the length of the windings also increases, and thus resistive losses will increase. The overall impact on price is higher because more material is used in the transformer, in both the core and the coil, which also makes the transformer larger and heavier.⁵⁰
- Lowering the magnetic flux density by decreasing the volts per turn involves maintaining the same turns ratio of primary to secondary, but having more of each. This design approach results in longer windings, which will tend to

increase the load losses. The impact on price tends to be higher on account of the increased material being used in the design.

- Decreasing the distance the magnetic flux has to travel by reducing the wire size will also reduce no-load losses; however, it tends to increase load losses because the current density per unit cross-sectional area of the conductor increases. This design option tends to lower the price of the transformer because it reduces the conductor material used in the design.

There are five approaches outlined in Table 20 as techniques for decreasing load losses. For these design options, one is a material-substitution option and the other four are all design techniques. Each of these options is discussed briefly below.

- The use of lower-loss conductor materials—specifically, using copper instead of aluminium windings—will decrease the winding losses and would either have no impact or reduce no-load losses by improving the flux linking, allowing a designer to use a slightly smaller core. However, depending on material prices, this approach can lead to an increase in price.
- Load losses can be decreased by lowering the current density in the conductor through an increase in the cross-sectional area. This option of using a larger-gauge conductor will reduce load losses but will also tend to increase no-load losses as the core must be made larger for the additional conductor. This design option also tends to increase price because more material is used in the transformer.
- Load losses can also be decreased by reducing the current path length through a reduction in the cross-sectional area of the core. By having a smaller core, the transformer becomes more compact, and winding lengths can be reduced, lowering resistive losses in the conductor. This will, however, tend to increase the

losses in the core, as the magnetic flux intensity increases per unit area. Overall, this design option would tend to reduce the price, as there is less physical material being incorporated into the finished transformer design.

- Load losses can also be reduced by proportionally reducing the length of conductor used in both windings, so as to keep the same turns ratio. This design option will tend to increase the volts per turn of the transformer, which (within the same insulation class) will decrease conductor losses but tend to increase losses in the core. As with design option 3 described above, this approach would also tend to result in a lower price as there is less material incorporated into the finished product.
- Increasing flux density (permitted through the use of better materials), which can result in a smaller-diameter core with lower load losses due to smaller-diameter windings. This would increase no-load loss in terms of watts per kilogram, but the weight of core would be less and could also reduce core losses.

In practice, a combination of the above options is used by transformer designers to meet the desired energy performance level at the minimum initial cost, depending on the relative material costs prevailing at the time.

ANNEX F. IEC AND SEAD RECOMMENDED ENERGY PERFORMANCE LEVELS

Tables which are common to both the IEC technical specification and the European regulation are presented here for information (see Table 21 through 25).

Table 20: European ecodesign regulation: Minimum peak efficiency index requirements for large power liquid-filled transformers⁵¹

POWER RATING (kVA, IEC)	TIER 1 (%) (FROM JULY 2015)	TIER 2 (%) (FROM JULY 2021)
>3,150 and ≤4,000	99.465	99.532
5,000	99.483	99.548
6,300	99.510	99.571
8,000	99.535	99.593
10,000	99.560	99.615
12,500	99.588	99.640
16,000	99.615	99.663
20,000	99.639	99.684
25,000	99.657	99.700
31,500	99.671	99.712
40,000	99.684	99.724
50,000	99.696	99.734
63,000	99.709	99.745
80,000	99.723	99.758
≥100,000	99.737	99.770

Table 22 gives the draft maximum load and no-load losses for liquid-immersed medium power transformers with the high voltage winding rated as 24 kV and below and the secondary winding at 1.1 kV and below. Note too that the Commission is considering to allow higher (greater) losses for pole-mounted transformers that are not shown in this table.

Table 21: European ecodesign regulation: maximum full load losses for medium power liquid-filled power transformers⁵²

POWER RATING (kVA, IEC)	TIER 1 (FROM JULY 2015)		TIER 2 (FROM JULY 2021)	
	MAXIMUM LOAD LOSSES (W)	MAXIMUM NO-LOAD LOSSES (W)	MAXIMUM LOAD LOSSES (W)	MAXIMUM NO-LOAD LOSSES (W)
≤25	900	70	600	63
50	1,100	90	750	81
100	1,750	145	1,250	130
160	2,350	210	1,750	189
250	3,250	300	2,350	270
315	3,900	360	2,800	324
400	4,600	430	3,250	387
500	5,500	510	3,900	459
630	6,500	600	4,600	540
800	8,400	650	6,000	585
1,000	10,500	770	7,600	693
1,250	11,000	950	9,500	855
1,600	14,000	1,200	12,000	1,080
2,000	18,000	1,450	15,000	1,305
2,500	22,000	1,750	18,500	1,575
3,150	27,500	2,200	23,000	1,980

Table 23 gives the draft maximum load and no-load losses for dry-type medium power transformers with the high voltage winding rated as 24 kV and below and the secondary winding at 1.1 kV and below.

Table 22: European ecodesign regulation: maximum full load losses for medium power dry-type power transformers⁵⁵

POWER RATING (kVA, IEC)	TIER 1 (FROM JULY 2015)		TIER 2 (FROM JULY 2021)	
	MAXIMUM LOAD LOSSES (W)	MAXIMUM NO-LOAD LOSSES (W)	MAXIMUM LOAD LOSSES (W)	MAXIMUM NO-LOAD LOSSES (W)
≤50	1,700	200	1,500	180
100	2,050	280	1,800	252
160	2,900	400	2,600	360
250	3,800	520	3,400	468
400	5,500	750	4,500	675
630	7,600	1,100	7,100	990
800	8,000	1,300	8,000	1,170
1,000	9,000	1,550	9,000	1,395
1,250	11,000	1,800	11,000	1,620
1,600	13,000	2,200	13,000	1,980
2,000	16,000	2,600	16,000	2,340
2,500	19,000	3,100	19,000	2,790
3,150	22,000	3,800	22,000	3,420
2,000	18,000	1,450	15,000	1,305
2,500	22,000	1,750	18,500	1,575
3,150	27,500	2,200	23,000	1,980

Within the IEC TS/60076-20:2017 technical specification, there are other tables of peak-efficiency indexes and maximum losses at both 50 Hz and 60 Hz, and other indices, including the SEAD energy efficiency performance tiers for distribution transformers which are listed in Annex B of IEC 60076-20:2017.

The SEAD tiers offer another basis for establishing requirements for distribution transformers and were developed through an international survey conducted by SEAD of 13 distribution transformer regulatory programmes around the world. The following table presents the set of equations developed for both liquid-filled and dry-type transformers in single-phase and three-phase configurations. These equations yield a percentage efficiency at 50 per cent of rated load for 50Hz operation and the IEC definition of power rating (kVA). There were four equations developed for each group of distribution transformer, with Tier 1 being the least efficient and Tier 4 being the most efficient. A Tier 5 level was added by SEAD as an indicator of a future premium-efficiency level for market-pull programmes.

Table 23: SEAD efficiency equations for distribution transformers, 50Hz and IEC rated power (%)⁵⁴

TRANSFORMER TYPE	TIER 1	TIER 2	TIER 3	TIER 4	(TIER 5)
LIQUID-FILLED THREE-PHASE	$= 1 - \frac{0.0370}{S^{0.22}}$	$= 1 - \frac{0.0311}{S^{0.22}}$	$= 1 - \frac{0.0270}{S^{0.22}}$	$= 1 - \frac{0.0226}{S^{0.22}}$	$= 1 - \frac{0.0193}{S^{0.22}}$
LIQUID-FILLED SINGLE-PHASE	$= 1 - \frac{0.0355}{S^{0.22}}$	$= 1 - \frac{0.0295}{S^{0.22}}$	$= 1 - \frac{0.0254}{S^{0.22}}$	$= 1 - \frac{0.0210}{S^{0.22}}$	$= 1 - \frac{0.0169}{S^{0.22}}$
DRY-TYPE THREE-PHASE	$= 1 - \frac{0.0628}{S^{0.26}}$	$= 1 - \frac{0.0514}{S^{0.26}}$	$= 1 - \frac{0.0425}{S^{0.26}}$	$= 1 - \frac{0.0355}{S^{0.26}}$	$= 1 - \frac{0.0292}{S^{0.26}}$
DRY-TYPE SINGLE-PHASE	$= 1 - \frac{0.0620}{S^{0.30}}$	$= 1 - \frac{0.0490}{S^{0.30}}$	$= 1 - \frac{0.0412}{S^{0.30}}$	$= 1 - \frac{0.0351}{S^{0.30}}$	$= 1 - \frac{0.0310}{S^{0.30}}$

Table 24: SEAD efficiency equations for distribution transformers, 60Hz and IEEE rated power (%)⁵⁵

TRANSFORMER TYPE	TIER 1	TIER 2	TIER 3	TIER 4	(TIER 5)
LIQUID-FILLED THREE-PHASE	$= 1 - \frac{0.03584}{S^{0.227}}$	$= 1 - \frac{0.03019}{S^{0.227}}$	$= 1 - \frac{0.02627}{S^{0.227}}$	$= 1 - \frac{0.02203}{S^{0.227}}$	$= 1 - \frac{0.01851}{S^{0.227}}$
LIQUID-FILLED SINGLE-PHASE	$= 1 - \frac{0.0346}{S^{0.227}}$	$= 1 - \frac{0.02899}{S^{0.227}}$	$= 1 - \frac{0.02476}{S^{0.227}}$	$= 1 - \frac{0.02031}{S^{0.227}}$	$= 1 - \frac{0.01649}{S^{0.227}}$
DRY-TYPE THREE-PHASE	$= 1 - \frac{0.06352}{S^{0.26}}$	$= 1 - \frac{0.0527}{S^{0.26}}$	$= 1 - \frac{0.04383}{S^{0.26}}$	$= 1 - \frac{0.03682}{S^{0.26}}$	$= 1 - \frac{0.03045}{S^{0.26}}$
DRY-TYPE SINGLE-PHASE	$= 1 - \frac{0.04044}{S^{0.30}}$	$= 1 - \frac{0.03132}{S^{0.30}}$	$= 1 - \frac{0.02585}{S^{0.30}}$	$= 1 - \frac{0.02169}{S^{0.30}}$	$= 1 - \frac{0.01896}{S^{0.30}}$

For more information on the SEAD study, please visit the CLASP website available at <http://clasp.ngo/en/Resources/Resources/PublicationLibrary/2014/SEAD-Analyzes-Potential-for-Alignment-of-Distribution-Transformer-Efficiency-Levels>

FOOTNOTES

- 1 BIOIS and VITO (2011) Preparatory Study – Transformers; Final Report, Lot 2: Distribution and power transformers, Tasks 1 – 7; 2010/ETE/R106.
- 2 Electrical power is equal to voltage times current. Holding power constant, if the voltage is increased, the current will decrease proportionally. Since losses in transmission and distribution power lines are directly proportional to the square of the current carried in the wire, increasing the voltage and reducing the current reduces losses associated with the transmission and distribution of electrical energy.
- 3 U4E (2017) Adapted from design by MBizon available at: https://en.wikipedia.org/wiki/Electrical_grid#/media/File:Electricity_Grid_Schematic_English.svg
- 4 Attention should be given to fire resistant oils which contain polychlorinated biphenyls (PCBs). PCBs are a fire-suppression additive historically in common use for transformer oils: they are now banned under the Stockholm Convention.
- 5 kVA is an abbreviation for kilovolt-ampere, and is a measure of the rated power (i.e. capacity) that a transformer is designed to handle.
- 6 U4E (2007) UN Environment estimate, based on country transformer market assessment.
- 7 Ibid.
- 8 UN Environment (2017) Global market model to calculate energy savings potential of power transformers,
- 9 HEPS are published performance levels that are more ambitious than MEPS but are not mandatory. Governments tend to publish these to establish a 'premium' level that can be used for market pull programmes such as tax rebates and incentive schemes. In some countries, HEPS are indicative of future MEPS, providing the industry with advance notice of the direction that the government wishes to take the market.
- 10 U4E (2017) Adapted from "SEAD Standards & Labelling Working Group Distribution Transformers Collaboration: Part 1: Comparison of Efficiency Programmes for Distribution Transformers: A report citing the similarities and differences amongst the available distribution transformer test methods and efficiency levels." December 2013.
- 11 Goulden Reports (2015) The World Markets for Transformers 2015 to 2025.
- 12 For more information see: <http://chm.pops.int/Implementation/PCBs/Guidance/tabid/665/Default.aspx>
- 13 Electrical power is equal to voltage times current. If the voltage is increased, the current will decrease proportionally, holding power constant. Since losses in transmission and distribution power lines are directly proportional to the current being carried in the wire, increasing the voltage can reduce losses associated with the transmission and distribution of electrical energy.
- 14 U4E (2017) Adapted from design by MBizon available at: https://en.wikipedia.org/wiki/Electrical_grid#/media/File:Electricity_Grid_Schematic_English.svg
- 15 BIOIS and VITO (2011) Preparatory Study – Transformers; Final Report, Lot 2: Distribution and power transformers, Tasks 1 – 7; 2010/ETE/R/106.
- 16 UN Environment (2017) Estimate based on country transformer market assessment.
- 17 UN Environment (2017) Estimate based on country transformer market assessment.
- 18 UN Environment (2017) Global market model to calculate energy savings potential of power transformers.
- 19 Goulden Reports (2015) The World Markets for Transformers 2015 to 2025.
- 20 US Department of Energy's (DOE) Energy Information Administration (2015) International Energy Outlook. IEA, 2014, World Energy Outlook 2014.
- 21 UN Environment (2017) Global market model to calculate energy savings potential of power transformers.
- 22 UN Environment (2017) Global market model to calculate energy savings potential of power transformers.
- 23 European Commission (2014) EC regulation No 548/2014 of 21 May 2014 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to small, medium and large power transformers. Available at <http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1440506867412&uri=CELEX:32014R0548> .
- 24 N14 Energy Limited, TR & JR Blackburn Consulting, HVOLT Inc. and EMS International Consulting (2013) SEAD Standards & Labelling Working Group Distribution Transformers Collaboration, Part 1: Comparison of Efficiency Programmes for Distribution Transformers.
- 25 Super-efficient Equipment and Appliance Deployment (SEAD) initiative (2013) SEAD Standards & Labelling Working Group Distribution Transformers Collaboration: Part 1: Comparison of Efficiency Programmes for Distribution Transformers: A report citing the similarities and differences amongst the available distribution transformer test methods and efficiency levels. Available at <http://clasp.ngo/en/Resources/Resources/>

- PublicationLibrary/2014/SEAD-Analyzes-Potential-for-Alignment-of-Distribution-Transformer-Efficiency-Levels
- 26 Super-efficient Equipment and Appliance Deployment (SEAD) initiative (2013) SEAD Standards & Labelling Working Group Distribution Transformers Collaboration: Part 1: Comparison of Efficiency Programmes for Distribution Transformers: A report citing the similarities and differences amongst the available distribution transformer test methods and efficiency levels. Available at <http://clasp.ngo/en/Resources/Resources/PublicationLibrary/2014/SEAD-Analyzes-Potential-for-Alignment-of-Distribution-Transformer-Efficiency-Levels>
- 27 N14 Energy Limited, TR & JR Blackburn Consulting, HVOLT Inc. and EMS International Consulting (2013) SEAD Standards & Labelling Working Group Distribution Transformers Collaboration, Part 1: Comparison of Efficiency Programmes for Distribution Transformers.
- 28 Super-efficient Equipment and Appliance Deployment (SEAD) initiative (2013) SEAD Standards & Labelling Working Group Distribution Transformers Collaboration: Part 1: Comparison of Efficiency Programmes for Distribution Transformers: A report citing the similarities and differences amongst the available distribution transformer test methods and efficiency levels. Available at <http://clasp.ngo/en/Resources/Resources/PublicationLibrary/2014/SEAD-Analyzes-Potential-for-Alignment-of-Distribution-Transformer-Efficiency-Levels>
- 29 For more information see: <https://webstore.iec.ch>
- 30 This technical specification (IEC TS/60076-20) can be purchased at IEC's website available at <https://webstore.iec.ch/publication/28063> Several of the tables in the IEC standard also appear in the 2014 European Ecodesign regulation (EU No. 548/2014). The tables that are common to both the IEC technical specification and the EU regulation are presented in Annex F.
- 31 For more information see: www.clasp.ngo
- 32 The portal is available at <http://copperalliance.org.uk/education-and-careers/education-resources/copper-and-electricity-transformers-and-the-grid>
- 33 The calculator is available at <http://www.abb.com/product/ap/db0003db004283/f4a2f36855184744c125772700291244.aspx>
- 34 PCBs are banned by the Stockholm Convention on Persistent Organic Pollutants. There are 176 signatories to the Convention, and all parties are required to eliminate the use of PCBs in existing equipment by 2025 and ensure their environmentally sound waste management by 2028.
- 35 Financing large-scale elements such as end-of-life recovery and recycling of used transformers could also be sourced internally, through extended producer responsibility (EPR) approaches or other means.
- 36 PCBs are banned by the Stockholm Convention on Persistent Organic Pollutants. There are 176 signatories to the Convention, and all parties are required to eliminate the use of PCBs in existing equipment by 2025 and ensure their environmentally sound waste management by 2028.
- 37 UN Environment (2016) Efficient Lighting Market Baselines and Assessment, Guidance Note. Available at http://www.enlighten-initiative.org/portals/0/documents/Resources/publications/Efficient_lighting_market_baselines_and_assessment_February_2016.pdf
- 38 UN Environment (2016) Developing Lighting Product Registration Systems, Guidance Note. Available at http://www.enlighten-initiative.org/portals/0/documents/Resources/publications/Developing_lighting_product_registration_systems_February_2016.pdf
- 39 The use of existing lab capacities which are recognised according to the IECEE scheme ensures a defined level of quality and accuracy, and allows for international acceptance of test results. IECEE, the IEC System for Conformity Assessment Schemes for Electrotechnical Equipment and Components, is a multilateral certification system based on IEC International Standards. Its Members use the principle of mutual recognition (reciprocal acceptance) of test results to obtain certification or approval at national levels around the world. For more information see: <http://www.iecee.org/index.htm>
- 40 UN Environment (2016) Performance Testing of Lighting Products, Guidance Note. Available at http://www.enlighten-initiative.org/portals/0/documents/Resources/publications/Performance_testing_of_lighting_products_February_2016.pdf
- 41 UN Environment (2016)
- 42 UN Environment (2016) Enforcing Efficient Lighting Regulations, Guidance Note. Available at http://www.enlighten-initiative.org/portals/0/documents/Resources/publications/Enforcing_Efficient_Lighting_Regulations_February_2016.pdf
- 43 e.g. Miro Hegedic, Tihomir Opetuk, Goran Dukic of University of Zagreb and Hrvoje Draskovic of Koncar-Power Transformers Ltd., Zagreb, Croatia (2016) Life Cycle Assessment of Power Transformer Case Study. Available at https://bib.irb.hr/datoteka/824494.Life_cycle_assessment_of_power_transformer-case_study.pdf

- 44 Available at http://wedocs.unep.org/bitstream/handle/20.500.11822/13664/Consolidated%20PCB%20Assessment_2016.pdf?sequence=1&isAllowed=y
- 45 Available at <http://www.unep.org/chemicalsandwaste/what-we-do/science-and-knowledge/persistent-organic-pollutants-pops/pcb-forgotten-legacy>
- 46 Focal Point listing available at <http://chm.pops.int/Countries/CountryContacts/tabid/304/Default.aspx>
- 47 Available at <http://chm.pops.int/Implementation/NationalImplementationPlans/NIPTransmission/tabid/253/Default.aspx>
- 48 Examples of small and special transformers not covered under 60076-1 are: (1) single-phase transformers with rated power less than 1 kVA and three-phase transformers less than 5 kVA; (2) transformers, which have no windings with rated voltage higher than 1 000 V; (3) instrument transformers; (4) traction transformers mounted on rolling stock; (5) starting transformers; (6) testing transformers; (7) welding transformers; (8) explosion-proof and mining transformers; and (9) transformers for deep water (submerged) applications.
- 49 ETS: Emissions Trading System. The overall carbon content of electricity in Europe is controlled at an EU level through the ETS. This means that pan-European measures are used for controlling CO₂, as any national measures which are applied to reduce CO₂ simply provide scope for other countries to increase their CO₂ emissions to take advantage of the extra headroom then made available. Inclusion of CO₂ costs in the price of electricity is one measure to encourage CO₂ reductions without having dysfunctional effects.
- 50 The weight of a transformer can have an impact on installation. For example, a pole-mounted installation may be rated for a specific weight, and in certain situations, it may be replaced by a more efficient transformer that is heavier, requiring modifications to the installation site increasing costs.
- 51 This European ecodesign table is the same as “Table 3 - PEI values for transformers with Um > 36 kV or Sr > 3150 kVA” found in with IEC TS/60076-20:2017.
- 52 This European ecodesign table is the same “Table 4 - Maximum load losses and maximum no load losses for transformers with rated frequency equal to 50 Hz” found in with IEC TS/60076-20:2017.
- 53 This European ecodesign table is the same as IEC TS/60076-20:2017 Table 10 - Maximum load loss and maximum no load loss for transformers with rated frequency equal to 50 Hz.
- 54 These SEAD recommended tier equations is the same as “Table B.1 - Efficiency equations for transformers with a primary voltage of 36 kV and below, from 5 kVA to 1000 kVA single-phase and 15 kVA to 3,150 kVA three-phase, 50 Hz and 50 per cent load method A” found in with IEC TS/60076-20:2017.
- 55 These SEAD recommended tier equations is the same as “Table B.2 - Efficiency equations for transformers with a primary voltage of 36 kV and below, from 5 kVA to 1000 kVA single-phase and 15 kVA to 3,150 kVA three-phase, 60 Hz and 50 per cent load method B” found in with IEC TS/60076-20:2017.

PHOTO CREDITS

ABB..... 3, 8, 24, 57, 71

