PROPHET II:
The potential for global energy savings from high-efficiency distribution transformers

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The potential for global energy savings from high-efficiency distribution transformers

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Contents

List of figures

List of tables

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Acronyms and abbreviations

AC	alternating current
AMDT	amorphous metal distribution transformer
APEC	Asia Pacific Economic Cooperation
BEE	Bureau of Energy Efficiency (India)
BIL	basic impulse insulation level
CCE	cost of conserved energy
CDM	Clean Development Mechanism
CEA	Central Electricity Authority (India)
CEM	Clean Energy Ministerial
CENELEC	Comité Européen de Normalisation Électrotechnique [European Committee for Electrotechnical Standardisation]
CFR	Code of Federal Regulations (USA)
CGO steel	conventional grain-oriented steel
CLASP	Collaborative Labeling and Appliance Standards Program
CNIS	China National Institute of Standardization
CO_2	carbon dioxide
CRGO steel	cold-rolled grain-oriented steel
CSA	Canadian Standards Association
DL	design line
DOE	Department of Energy (USA)
DNO	Distribution Network Operator
DSO	distribution system operator
EAC	equivalent annual cost
EN	European Norm (see European standard)
ESCO	energy service company
EU	European Union
European standard	A standard adopted by a European standardisation organisation
GDP	gross domestic product
GVA	gigavolt-amp
GWh	gigawatt-hour
HEPL	high-efficiency performance levels
HEPS	high energy performance standard
Hz	Hertz
IEC	International Electrotechnical Commission
IEA	International Energy Agency

IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
kV	kilovolt (i.e. 1000 volts)
kVA	kilovolt-ampere
kW	kilowatt
kWh	kilowatt-hour
LRMC	long-run marginal cost
MEPS	minimum energy performance standards
Mt	million tonnes
MVA	megavolt-ampere
MW	megawatt
MWh	megawatt-hour
NDRC	National Development and Reform Commission
NEMA	National Electrical Manufacturers Association
NOx	nitrogen oxide
NPV	net present value
OECD	Organisation for Economic Co-operation and Development
PCB	polychlorinated biphenyl
PEI	peak efficiency index
PF	power factor
Pk	load-dependent load losses (winding losses)
Po	no-load losses in the core
PURPA	Public Utility Regulatory Policies Act
SEAD Initiative	Super-efficient Equipment and Appliance Deployment Initiative
SEEDT	Strategies for Energy Efficient Distribution Transformers
SO_2	sulphur dioxide
T&D	transmission and distribution
TCO	total cost of ownership
TEPS	Target Energy Performance Standards
TOC	total ownership cost
TSO	transmission system operator
TWh	terawatt-hours
UEC	unit energy consumption
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

US(A)	United States (of America)
VAT	value-added tax
W	watts

EXECUTIVE SUMMARY

This report presents an update of the 2005 Leonardo Energy 'PROPHET' report, *The Potential for Global Energy Savings from High Efficiency Distribution Transformers* (Targosz 2005). The current report continues the story since the original PROPHET study and supplies much new information while retaining the original core material of the study. The audience for this report is product energy efficiency policymakers, utility regulators, corporate personnel with an interest in transformers and others with a policy, commercial, industrial or academic interest in the topic of distribution transformers and the reduction of losses in electricity networks.

Distribution transformers are a critical component of the electricity system powering our modern society. By helping to lower voltages in distribution networks to the levels that are needed by end users, they comprise part of the voltage transformation system enabling high-voltage power transmission and distribution (T&D) necessary to lower overall network energy losses. Compared with other electrical equipment, distribution transformers are very efficient, typically incurring losses of just 2–3% in transforming electricity from one voltage level to another. However, the fact that almost all electricity is passed through transformers prior to its final use means that opportunities to reduce losses in distribution transformers are highly significant for improving the efficiency of electricity networks as a whole. On average, power is passed through four transformers from the point of generation to final demand, and each one of these incurs some losses. Technical losses in electricity networks vary from a few percent to ~12% of the total energy transported, and on average roughly one-third of these losses occur in distribution transformers.[1] Nor are these losses uniform, as application of the most advanced technology can reduce distribution transformer losses by over two-thirds compared to standard designs. How cost-effective this is depends on a number of locally specific factors, including how efficient the default technology is compared to the alternative, but typically reducing distribution transformer losses by one-third is cost-effective using today's equipment and power prices. When long-run, marginal forward cost planning is taken into account, the cost-effective savings can be even greater, and if the value of environmental externalities are required to be included by regulation the cost-effective optimum moves to an even higher efficiency level.

The economics of efficient transformers are favourable

More-efficient transformers usually have a higher bill of materials than less-efficient models and hence their first cost (price) is somewhat higher. However, such is the volume of energy passed through a typical distribution transformer that the cost of the losses, although small in percentage terms, greatly exceeds the incremental purchase price of an energy-efficient transformer within a few years. The total cost of ownership (TCO; i.e. the cost of purchase and of operation where the cost of the lost energy is factored in) of more-efficient transformers can be significantly lower than for less-efficient models, and payback periods of 2–13 years are typical. Distribution transformers have a useful life of more than 30 years on average and often much longer. The incremental cost of purchasing a higher-efficiency model can be paid back many times over the transformer's service life. Figure ES1 shows how the life-cycle cost of a 400 kVA transformer can vary as a function of efficiency and the real interest rate applied on the capital, from which it is clear that higher-efficiency designs have lower life-cycle costs unless very high interest rates are assumed.

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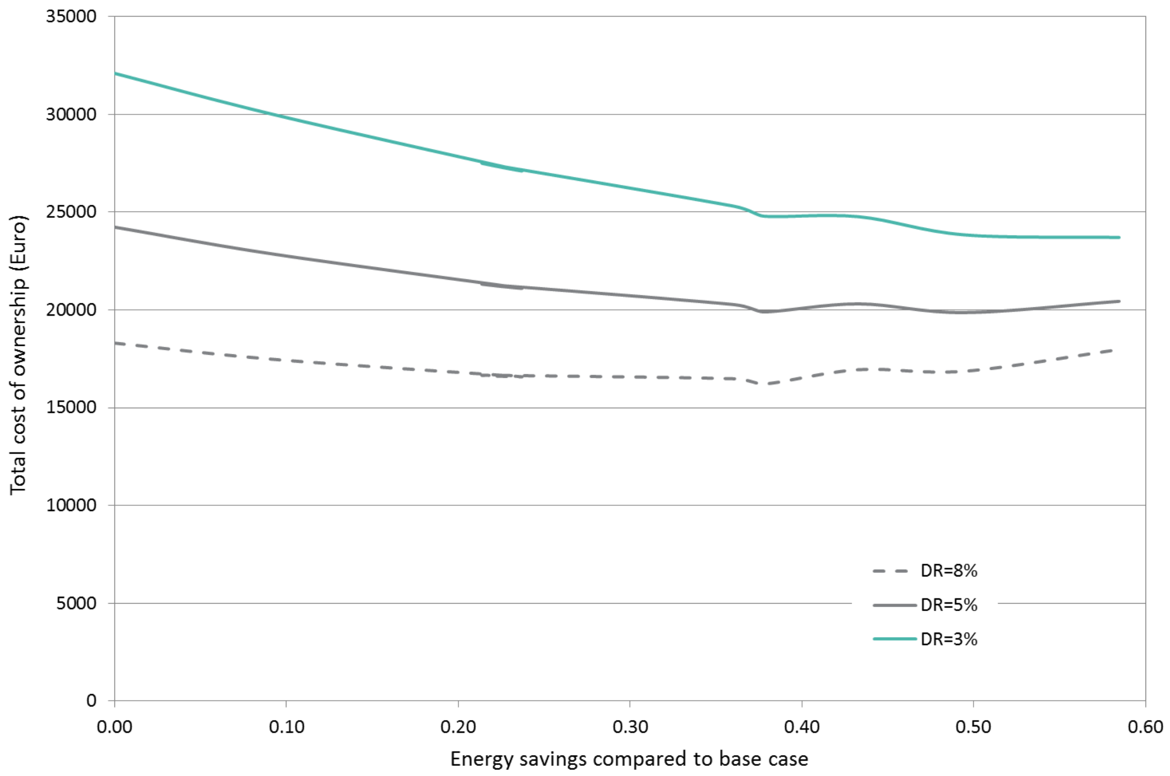
[1] The remaining losses will occur in the cable and line networks, so the actual proportion depends on the ratio of circuit losses to transformer losses, which also depends on the network topology and use of higher voltages within the network.

Figure ES1. Transformer total cost of ownership as a function of efficiency. Example for a 400kVA unit.



Source: Derived from VITO 2011.

The macro-scale value proposition: energy, economic and carbon savings potentials

The installed power capacity of the world's distribution transformer stock is estimated to have reached 13 848 GVA in 2014 and is projected to rise to 22 400 GVA by 2030. Some 8.5% of global power production was lost in T&D networks in 2011, of which roughly 87% was due to technical losses.[2] Approximately one-third of these losses occur in distribution transformers, thus an estimated 657 TWh of electrical energy per annum was attributable to distribution transformer losses.

So how much can be saved with the adoption of higher-efficiency distribution transformers? Estimates indicate that the global technical savings potential is 402 TWh per annum by 2030 (1.3% of projected global electricity consumption and equivalent to the output of approximately 150 157 coal-fired power plants of 500 MW) with the broader use of technology that is already available today. This would avoid 201 million tonnes of annual CO_2 emissions and some US$28 billion in annual wholesale power costs (at current prices). The cost-effective savings potential will depend on future incremental costs for higher-efficiency transformers that are sensitive to fluctuations in material costs and in future wholesale power prices, but the savings are likely to be of the order of half of this value. However, with long-life capital stock, annual savings figures can be misleading. The transformers being installed today will be in service for at least 30 years (some units in Europe have remained in service for 70 years) and annual savings need to be aggregated over the stock service life to evaluate the overall benefits of higher efficiency.

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[2] Non-technical losses can be much larger in some economies than others, especially when power theft or limited metering is commonplace.

Market barriers and regulatory practices hinder investment in efficient solutions

About 80% of all distribution transformers are used by electricity network utilities, with the remainder being used by industry and large commercial users. In general terms, electric utilities tend to focus more on longer-term, life-cycle costs, while commercial and industrial customers are not. For both customer types, there are a variety of market barriers or failures that can prevent these users from opting for transformer designs with the lowest total cost over the transformer's service life, and these hinder the market from adopting cost-optimised solutions. One example of a market failure would be network utilities that have no economic penalty from losses on the distribution network. If regulations were crafted to allow them to earn a return on investments that reduce losses, they would respond to that incentive. However, in many cases, regulatory structures simply allow the cost of losses to be passed through to the end user. As all electricity retailers using the same network will pay the same network usage fee, retailers servicing the same customer area will pass these network loss costs on to their final customers without being able to influence the losses incurred in the network. Under these circumstances, network utilities will have an economic incentive to minimise their investment in loss-reduction technologies, such as higher-efficiency transformers (which are generally more expensive), if they receive none of the benefit arising from that investment. This kind of split incentive can readily develop if a utility's regulatory framework is not mindful of the risk. However, even when best practice network regulation addresses this issue, problems of split incentives still occur within utility or industrial organisations because of the tendency for capital expenditure (Capex) and operations and maintenance (Opex) budgets to be managed separately. If adequate safeguards are not put in place, Capex budget managers will have an incentive to procure equipment at least cost, rather than at least cost over the product life cycle, i.e. with the cost implications of the choice of design on operational expenditure also factored into the initial procurement decision. Nonetheless, the key issue is that losses are not a cost to the utility unless either (a) the utility is required to buy the losses (as is the case in France and Belgium, for example) or (b) the regulator mandates that losses are included in any investment appraisal, which is to be sanctioned by the regulator. In the latter case, the regulator should not reimburse investments where losses are not included in the cost evaluation. In addition, some incentive payments can also be made to direct investments.

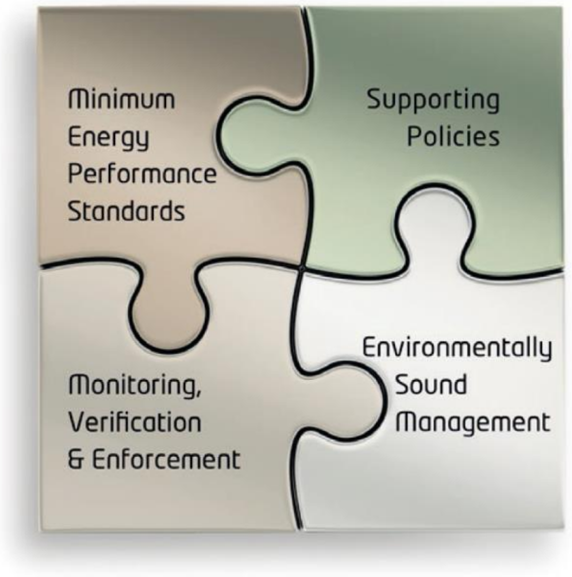
Other barriers also hinder the development of a fully efficient market, including low visibility of losses, low priority given to addressing them and insufficient expertise on how to specify transformer tenders to achieve the lowest TCO. For these reasons there has been a growing appreciation among policymakers, whether they are responsible for regulating utilities or for product energy efficiency, that a portfolio of policy measures are required to ensure investments in transformers are made in line with the objective of maximising the economic and environmental performance of power distribution and transformation.

The Integrated Policy Approach

Product market-transformation strategies need to be designed for the long term, providing a mechanism for the sustained phasing-out of inefficient products from the market, while ensuring an environmentally sound management system to collect and recycle decommissioned transformers. To address these issues and guarantee a robust market transition, the United Nations Environment Programme's en.lighten initiative developed a concept called the 'Integrated Policy Approach' (IPA).

The IPA has four core elements, as shown in Figure ES2. This process highlights the importance of a multi-stakeholder consensus, incorporating the needs and priorities of public and private sector partners, non-governmental organisations, civil society and financing institutions.

Figure ES2. Integrated Policy Approach for a rapid transition to energy-efficient distribution transformers.



Source: UNEP 2012 (reproduced with permission).

Minimum energy performance standards (MEPS) are regulatory measures specifying minimum energy performance levels for products sold in a particular country or region. For transformers, these measures typically include minimum efficiency or maximum losses. The objective of MEPS is to serve as a market push, whereby all products sold into the market either meet or exceed these requirements. MEPS requirements should be reviewed regularly to ensure regulation keeps pace with technology evolution and cost of energy.

Supporting policies comprise a variety of tools used to help ensure that the MEPS are successful. This includes, for example, economic incentives and fiscal instruments, communication and information campaigns, product labelling and endorsement schemes, etc. Supporting policies work by enabling all market players to be aware of and engage in an effective transition to high-efficiency technologies and practices.

Monitoring, verification and enforcement (MV&E) activities involve effective and timely market surveillance systems to ensure that all products placed on the market in a given economy comply with the MEPS requirements. These activities depend on a functional system of monitoring, controlling and testing facilities capable of ensuring compliance and enforcement of energy-efficiency standards. Without a robust MV&E programme, substandard products will continue to enter national markets in increasing numbers, reducing energy and financial savings.

Environmentally sound management (ESM) encompasses all phases of a product’s life cycle, including: materials used in manufacturing; manufacturing processes; packaging; distribution; use; collection; and recycling. One of the most critical components of ESM involves the treatment of transformers that have been taken out of service. This piece of the programme works to ensure that metals and any oil are recovered, reused and recycled and that any toxic material, such as polychlorinated biphenyls (PCBs), are disposed of appropriately.

Measuring and disclosing energy performance provides visibility

Transformer energy efficiency needs to be measured in a verifiable way at each loading level and defined using a standardised energy-performance metric to facilitate ranking and comparison. Recent trends in international standardisation are moving towards globally harmonised definitions of transformer efficiency supported by coordinated development of energy-efficiency tiers by international product policy regulators. These tiers offer a set of 'off the peg' efficiency levels that both private-sector procurement policy and public policy measures can make use of in accordance with need. The energy efficiency of transformers also needs to be communicated into the market, and many governments have developed mandatory or voluntary labelling schemes that provide a common basis to communicate relative efficiency.

One size does not fit all: optimal selection depends on the distribution network

Measurement of transformer efficiency does not stop at the rating plate. If losses are to be minimised it is also important to meter power flows and load levels to optimise the performance of transformers within power distribution networks. This is especially true as transformer efficiency is highest when load losses equal no-load losses. This point of maximum efficiency as a function of transformer design and efficiency declines on either side of the maximum efficiency point, although absolute losses become lower as the load decreases. Although this is not current practice, specification of the right transformer for the expected load profile is an important aspect of loss-minimisation strategies. Transformer losses can be further reduced by optimising the network, sectionalising so as to spread the load optimally between connected transformers. This will also have the advantage of improving voltage regulation and reducing the impact of transformer and circuit outages, because during any outage the affected load will be smaller.

Minimum energy performance standards are growing in popularity

As shown in Figure ES3,[3] as of 2014 some 15 economies, representing approximately 54% of the installed stock of distribution transformers by capacity, have adopted energy-efficiency requirements or incentive programmes promoting energy-efficient designs.

The losses that can be expected from the current policies can be compared with those that would have occurred had those policies not been adopted. This comparison is presented in Figure ES4.

Overall losses are projected to be 154 TWh lower in 2030 as a result of the MEPS which have currently been adopted. In 2050, the current MEPS would be expected to save 282 TWh per year; however, much deeper savings are possible if more countries adopt MEPS and the degree of stringency is increased.

Economies with MEPS and/or energy labelling for distribution transformers now account for 75% of global electricity consumption, but the rate of growth in electricity demand is faster in those economies that currently have no policy measures in place for transformers; these are projected to account for 44% of the increase in global electricity demand by 2035. Therefore, there is considerable potential for transformer losses to be reduced further through the broader adoption of MEPS and energy labelling/efficiency-rating disclosure requirements to render transformer efficiency more visible to those that procure and use the equipment.

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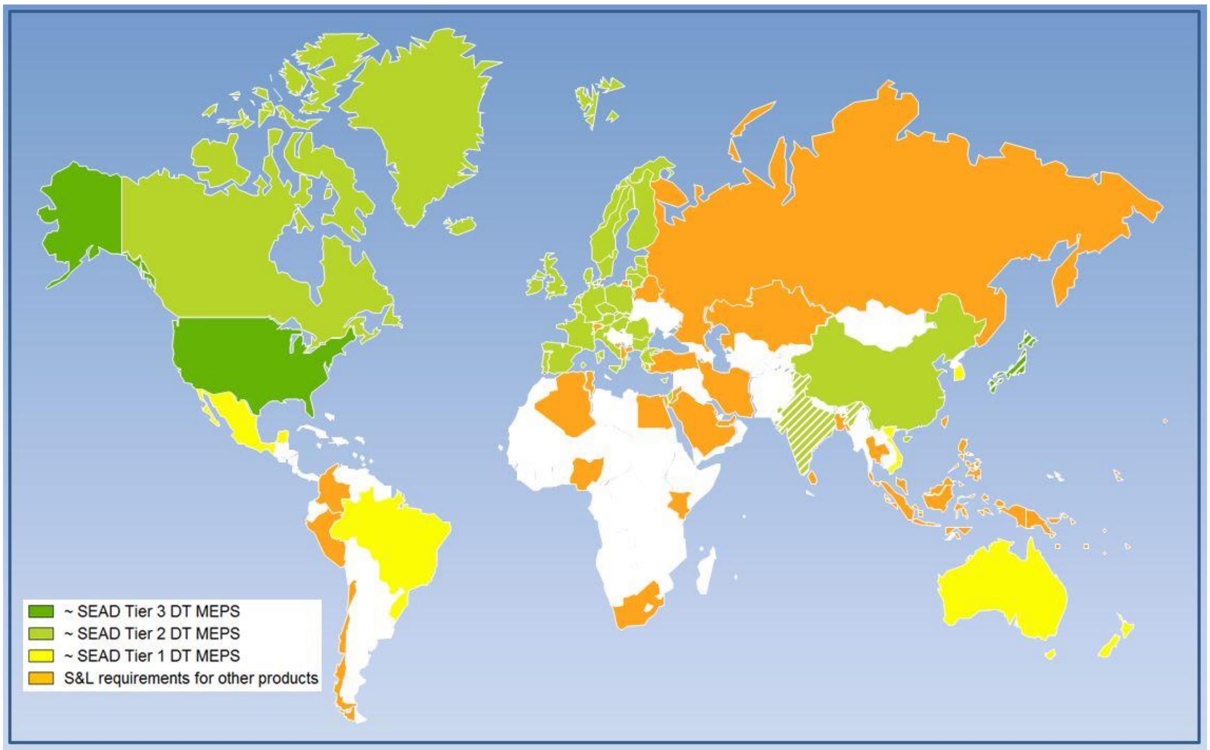
[3] See section 7.4 for an explanation of the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative energy-efficiency tiers for distribution transformers. The most and least stringent MEPS currently adopted are roughly equivalent to SEAD Tiers 3 and Tier 1, respectively.

Figure ES3. Countries with efficiency standards or labels to promote energy-efficient distribution transformers ('S&L requirements for other products' = countries with efficiency standards or labels in place for products other than transformers) (DT = distribution transformer; MEPS = minimum energy performance standards; S&L = standards and labelling) .



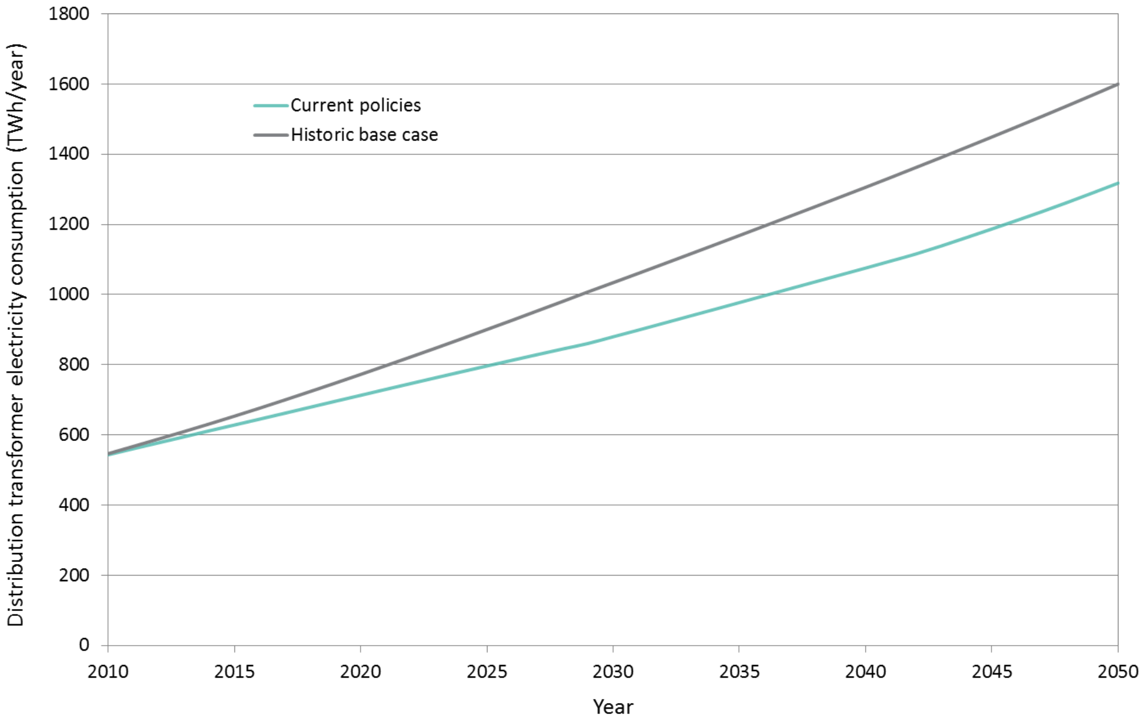
Source: UNEP 2012 (reproduced with permission).

Utility regulation appropriate for future-facing markets will be key

Since the majority of distribution transformers are used by distribution network operators (DNOs), it is important to develop and adopt effective economic incentives to minimise the consequences of network technical losses with regard to the overall cost of electricity. The activities of distribution utilities are poised for rapid change as the growth in demand for electricity services continues to expand and as the technical requirements of the network evolve to take account of greater use of renewable and distributed generation resources, bidirectional energy flows, smarter control and operation of the network, and new end uses, with significant implications for future load profiles such as electric vehicles. These changes also have implications for the optimal procurement and management of the transformer park, given the need for procurement actions to be made today to meet service requirements many decades into the future and the importance of this equipment with regard to network losses. In practice, with local generation and consumption, the throughput of the utility transformer will be less and the savings potential from low 'load losses' will be reduced, so there may need to a preferential focus on reducing 'no-load losses'. In such cases, voltage regulation requirements for the transformer may have greater significance than economic considerations in determining the appropriate level of load losses.

While utility regulators have focused much discussion and intellectual effort on how to establish the most appropriate regulatory environment to foster productive smart-grid development, considerable attention has also been given to the topic of network loss reduction and how best to ensure utilities have an adequate incentive to reduce their technical losses to levels that are consistent with the best-value service for final customers. Best practice has been shown to involve the

Figure ES4. Projected global energy losses in distribution transformers with current policies and with the pre-policy historic base-case scenario.



creation of pseudo market-simulating incentives to stimulate loss reduction investment by DNOs, in recognition that they are essentially natural monopolies, yet also ensure adequate regard for quality of service and that there is no incentive to 'gold plate', i.e. to overinvest in network infrastructure to the detriment of service value for money. Chapter 5 of the current report presents examples and analysis of current regulatory practice, including the impact that electricity sector liberalisation has on best regulatory practice.

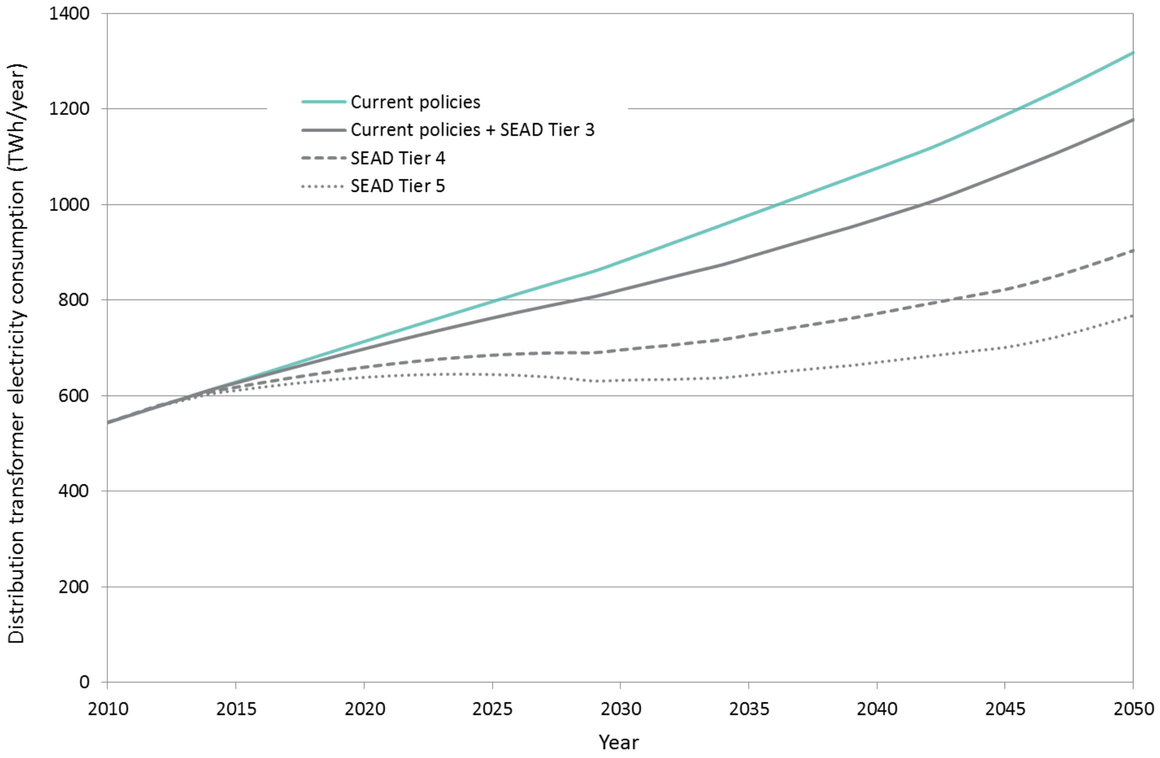
The global opportunity

The opportunity costs from a failure to access distribution transformer savings potentials through a more coherent policy framework are of such a scale that they would incur significant economic costs, lower competitiveness and substantial environmental damage. Thus, bolstering measures in this domain belong to a clear set of win–win policies that both improve the economy and support environmental sustainability objectives. While there are savings opportunities in other end uses that may produce equal or, in a few cases, larger savings in the 2020 or 2030 timeframe, transformers are part of the capital stock that have a very slow renewal cycle, so decisions regarding their level of efficiency in the near term will have consequences for many decades to come. This 'lock in' effect increases the importance of ensuring that near-term procurement decisions fully reflect longer-term value propositions as far as it is possible for these to be determined.

As an illustration of the magnitude of benefits that could be achieved, Figure ES5 indicates the annual global energy losses in distribution transformers that are projected with current policies, as well as what could be achieved if all economies installed new or replacement transformers at SEAD Tiers 3, 4 or 5 (see section 7.4).

Thus, it is not surprising that there is a growing international appreciation of the need to set remedial public policy frameworks to overcome the market failures and barriers that inhibit the optimal reduction of losses in electricity networks and distribution transformers. This has triggered

Figure ES5. Projected global energy losses in distribution transformers with current policies and with universal adoption of MEPS set at SEAD Tier 3, 4 and 5 efficiency levels.



many policy developments that are contributing to improvements in the efficiency of the transformers that are procured and used.

At the product level, there has been a growth in the adoption of MEPS and energy labels to prevent less-efficient designs from being sold into the market and to make the relative energy performance of transformers more fully visible within it. These efforts are supported through the technical standardisation process. Further efforts to develop a fully internationally harmonised test procedure, which will bring IEC and IEEE standards into full alignment, are to be hoped for. These could be coupled with the adoption of a common set of energy-performance tiers that will enable the efficiency of all transformers to be classified on a common basis but at the same time allow each economy and transformer procurer to set policy and/or purchase products at energy-efficiency performance levels that meet their needs. The pathway has been paved with the recent revision of IEC test procedures for power transformers and the co-publishing of joint, harmonised IEC/IEEE test procedures.

At the network utility level, regulators are increasingly adopting performance-based regulation for network loss production underpinned by quality-of-service standards to encourage reliable but more-efficient network operation.

In general, the objective of public policy with respect to the transformer market should be to create a policy environment which ensures that the procurement and operation of distribution transformers produces outcomes that minimise their economic and environmental impact over their service life. To help attain this goal the following recommendations are made.

Recommended actions

Following the research and analysis of the global distribution transformer market, several activities are recommended to help facilitate a global transition to energy-efficient distribution transformers.

Measures aimed at the product offer

- Ensure energy performance is visible in the market through the adoption of suitable, internationally harmonised, energy-performance test procedures and the creation of standardised energy-performance disclosure requirements, potentially including energy labelling.
- Ensure that test procedures and standards to accurately reflect operating conditions (e.g. load factors and load curves) are defined and that declared transformer energy performance is reliable, through the strengthening of accredited third-party testing and certification capability and by conducting adequate market monitoring, verification and enforcement activity.
- Adopt an internationally harmonised approach to setting energy-performance tiers that can be used in labelling/disclosure rating requirements. Such a scheme could be based upon SEAD Tiers 1–5 (section 7.4).
- Adopt MEPS set at cost-effective levels for the local economy. In practice these would need to be at the SEAD minimum efficiency level (Tier 1) or higher.
- Establish a programme designed to get manufacturers to invest in and develop new technologies that could further improve the efficiency of transformers (i.e. a research and development fund).

Measures aimed at the utility sector

- Ensure that distribution-utility technical losses are measured and/or accounted for and disclosed at an adequate level of resolution within the network, so that informed loss-reduction measures can be considered by the utility, auditor and regulator.
- Review the adequacy of utility-regulator incentives for loss reduction among network operators and introduce performance-based incentive regulation as appropriate to ensure the long-term cost of losses is minimised.
- Ensure that the enactment of loss-reduction incentives does not stimulate loss-reduction measures at the expense of investment in network reliability, by taking steps to tie loss-reduction performance incentives to satisfaction of quality-of-service requirements.
- Ensure that smart-grid development and investments are also a trigger for loss reduction in network transformers, both by ensuring that proper selection takes into account loading, operation and maintenance of the transformer stock and by ensuring that any transformer replacements or additions triggered through the need to improve the intelligence of the network are consistent with minimising new transformer TCO.
- Encourage or require utility companies to review their transformer procurement specifications to ensure that future losses at associated voltage levels are appropriately costed in their procurement tender specifications.

Measures aimed at the broader market

- Raise awareness of the opportunities among key stakeholders.
- Support and stimulate business models, such as energy service companies (ESCOs) and green revolving funds, that provide upstream financing to pay for a share of the value of the downstream energy savings and hence help to overcome incremental first-cost barriers for the private sector.
- Establish programmes that create market pull, to promote energy-efficient transformers that exceed the minimal energy-performance levels.
- Establish programmes to look at early retirement and upgrading of installed stock, taking advantage of lower losses, greater reliability and the opportunity to install smart-grid technologies to support the network.

- Consider the introduction of financial incentives and fiscal measures to stimulate procurement of higher-efficiency transformers.
- Build capacity on best-practice procurement and operation of transformers, including toolkits for buyers on TCO/life-cycle cost and proper selection.
- Support the United Nations' Stockholm Convention objective of phasing out the entire global stock of polychlorinated biphenyl (PCB)-containing transformers and replacing them with energy-efficient models by 2025.
- Factor the value of pollution externalities into the economic valuations applied to transformer policy, including in the MEPS setting, when determining the value of fiscal or financial incentives and when setting performance-based incentives for distribution-network loss reduction.

Share the load through cooperative work with international partners

Given the global scale of the potential for cost-effective long-term savings in distribution transformers, the common nature of the problems faced and the body of previous and existent efforts to address the barriers to higher energy efficiency, it is recommended that stakeholders seek to work cooperatively in the field to combine and leverage their resources for greater benefits at lower cost. Such cooperation expedites knowledge transfer, minimises duplicative effort and unnecessary fragmentation and generally accelerates progress. Some existing efforts that can be built upon include:

- IEC/IEEE cooperative efforts in standardisation
- the SEAD Initiative on energy-efficiency tiers
- the Leonardo Energy and IEA 4E best-practice dissemination efforts.

Thus far, most of this international cooperative effort has focused on elements linked to product policy, standardisation and awareness-raising. In the future this could be extended to include greater communication on utility regulation and energy-management best practice. In general, it is recommended that the scale of such cooperation be increased to foster more rapid spread of best practice.

1. Introduction

Key messages

- This study updates the 2005 report on transformers and aims to help policymakers, utility regulators and others with an interest in the energy performance of transformers.
- All electricity is passed through multiple transformers as it is transported from generating plant to end user.
- While transformers are very efficient, losses still occur and have an important effect on the scale of the whole electricity network.
- Network losses account for 8.5% of all electricity production globally, equivalent in magnitude to 70% of the world's nuclear power production. Slightly more than one-third of this accounted for by losses in distribution transformers.
- There is considerable potential to reduce these losses through the use of more-efficient distribution transformers. Modern technology can reduce losses by up to 80% (UNEP 2011), although typical savings are not so high.
- In recent times, a growing number of economies have adopted minimum energy performance standards for distribution transformers. These are projected to save 191 TWh of final electricity consumption in 2035 compared with what would have been otherwise expected without these measures. Cumulatively, from 2010 to 2035 these measures are projected to save 2289 TWh of electricity, some 1144 Mt of CO_2 emissions and energy worth US$229 billion at current prices.
- While current policies are projected to produce cumulative savings of 5992 TWh, 2996 $MtCO_2$ and US$599 billion of energy costs by 2050, universal adoption of SEAD Tier 3 level transformers would be expected to produce cumulative savings of 8540 TWh, 4270 $MtCO_2$ and US$854 billion of energy costs over the same period. Universal adoption of SEAD Tier 4 level transformers is projected to produce cumulative savings of 13 611 TWh, 6806 $MtCO_2$ and US$1361 billion of energy costs by 2050, and universal adoption of SEAD Tier 5 level transformers is projected to produce cumulative savings of 16 210 TWh, 8105 $MtCO_2$ and US$1621 billion of energy costs.

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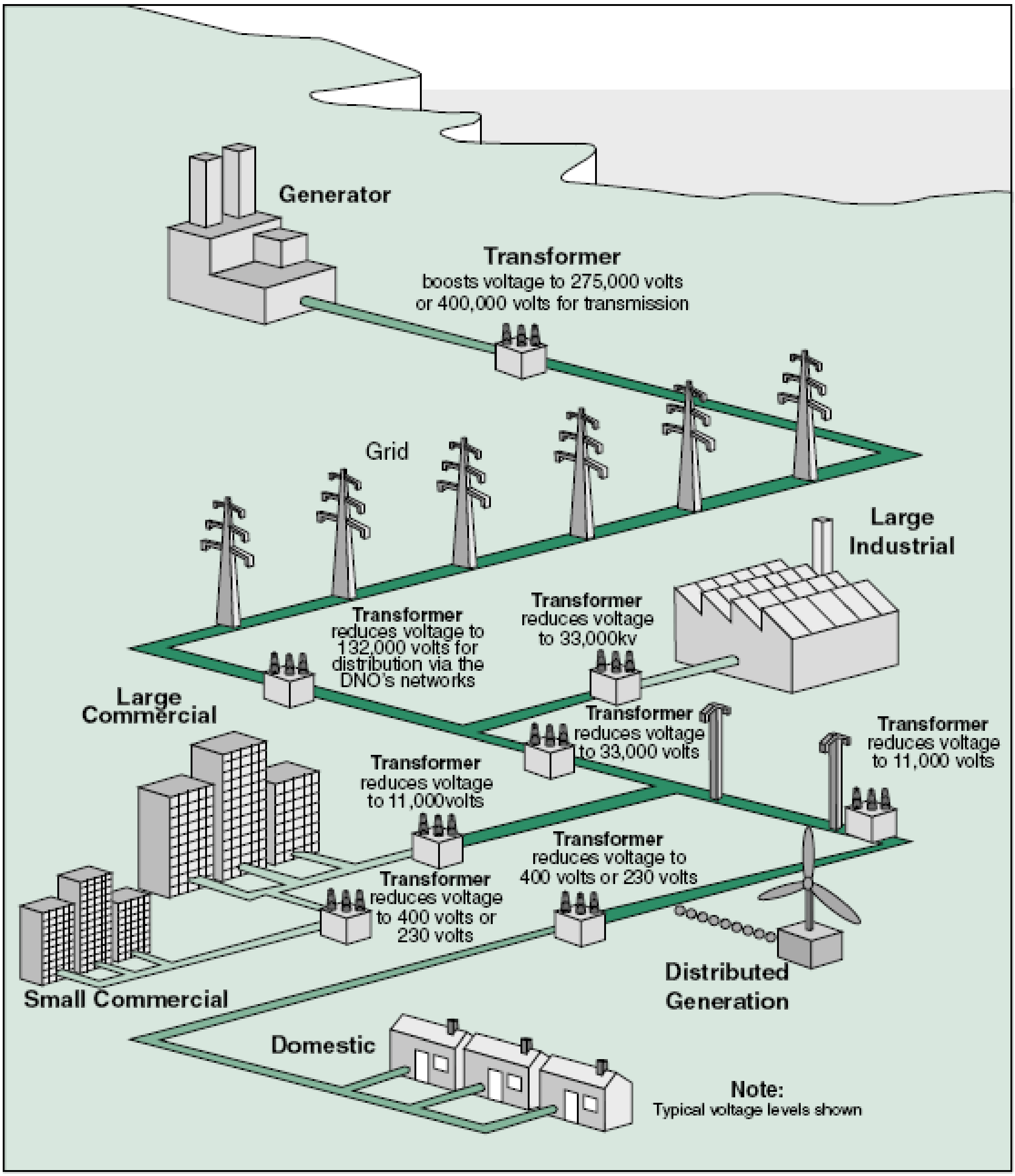
1.1 Electricity networks

Electricity networks are used to transport energy generated in power stations or renewable energy sites to the final point of demand. In most electricity supply systems, energy needs to be transported over long distances, but during this process, losses are incurred in the network. These losses are generally proportional to the square of the current being carried and this means that use of higher voltages will contribute to lower currents and thereby reduce network losses. In addition to lower losses, another advantage of using higher network voltages is that the voltage drop in the network caused by load is avoided.

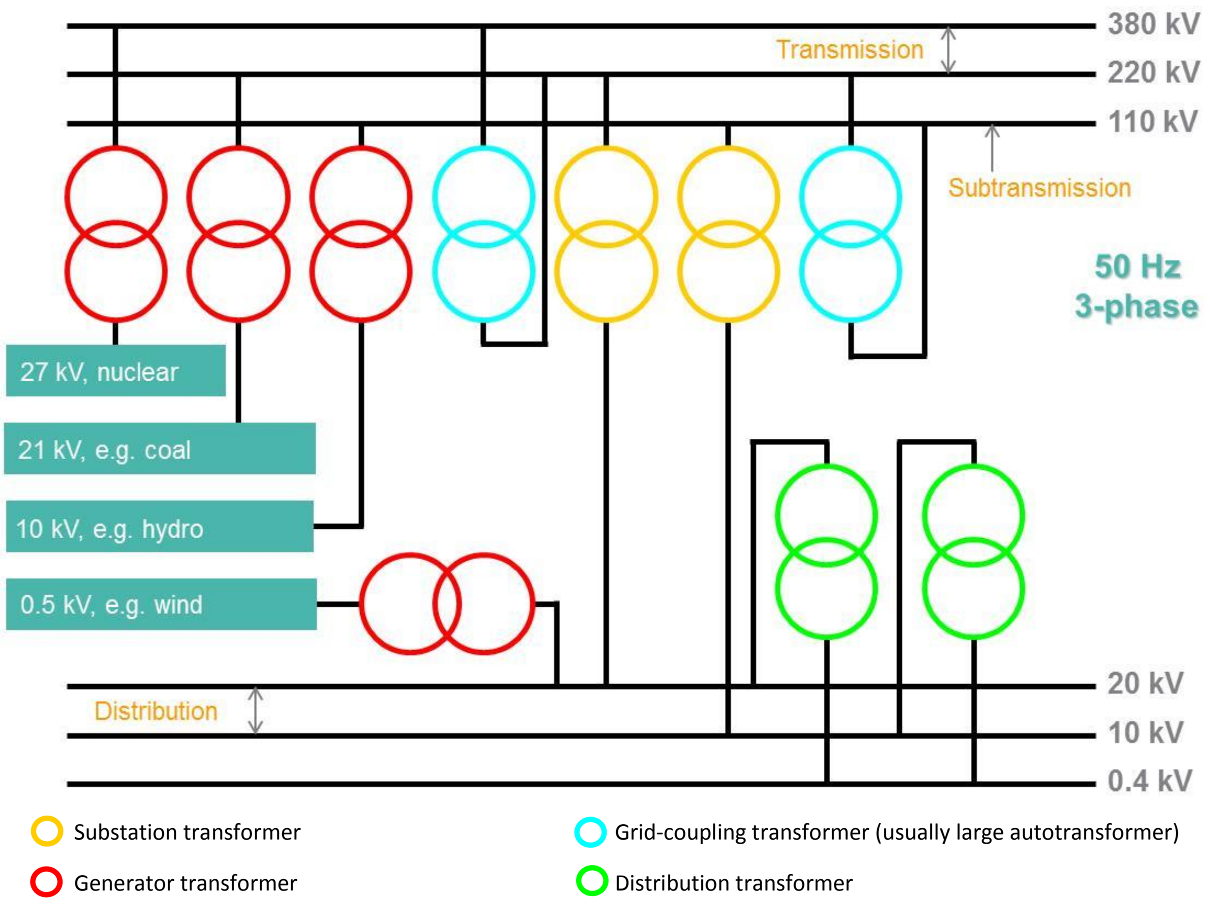
A network is predominantly comprised of the power lines that connect the power plant with the final point of demand; however, in order to minimise losses and ensure safe usage, transformers are used to reduce the load current in the transmission line between the generating plant and the distributuion network. An example of an electricity network is shown in Figure 1-1.

Figure 1-1. Example of an electricity network.



Source: House of Commons – The future of Britain's electricity networks.
http://www.publications.parliament.uk/pa/cm200910/cmselect/cmenergy/194/19402.htm

Figure 1-2. Example of a public electricity network structure.



Source: Kindly supplied by R. Targosz.

The part of the network used to transport energy at high voltages is referred to as the ‘transmission system’, whereas when the voltage has been stepped down the system of transformers and power lines used to distribute it to local users is known as the ‘distribution system’ (Figure 1-2). A clear functional and commercial distinction is made between each system, and in most modern power systems there are different operators responsible for generation, transmission and distribution. Those managing the transmission system are known as the ‘transmission system operators’ (TSOs), while those managing the distribution system are called ‘distribution system operators’ (DSOs) or sometimes ‘distribution network operators’ (DNOs).

In fossil-energy and nuclear power stations, electricity is usually generated at voltages of 10–30 kV and is then stepped up using large power transformers (LPTs), which are known as ‘generator step-up transformers’, to voltages in the range of 220–800 kV or higher for transport within the transmission system. These higher-voltage lines are used to transport bulk power, whereas somewhat lower-voltage lines, known as the ‘sub-transmission network’, are used to distribute power to the local distribution networks. Wind farms and solar photovoltaic sites usually start with a generator voltage less than 1 kV and use two step-up transformers to reach transmission- or subtransmission-line voltages.

Substations are high-voltage electric facilities that serve to switch generators, equipment and circuits or lines in and out of an electrical network. The transformers used in these substations are used to step the alternating current voltages up or down, or sometimes to change alternating current to direct current, or vice versa.

Transmission substations are usually sited at major transmission nodes either to step up voltage from generators into the transmission lines or, at the other end of the transmission lines, to give flexibility to transmission channels and connect to subtransmission power lines. In large substations linking transmission to subtransmission lines, the transformers or autotransformers installed there are known as ‘bulk supply transformers’. These can be either step-up or step-down transmission substations, but the transformers used within them need to have a high capacity and hence are large power transformers.

Distribution substations are used to step down voltage from subtransmission lines to lower voltages for the distribution network, or within branches of the distribution network to further step down for final use. Distribution transformers are used in distribution substations and have a significantly lower capacity (approximately three orders of magnitude) than power transformers.

On average, electrical energy undergoes four voltage transformations between being generated and being consumed, and as a result a large number of transformers of different classes and sizes are needed in the transmission and distribution (T&D) network, with a wide range of operating voltages. The first voltage step-down from transmission voltages is a transformation to 36−150 kV. This is often the level at which power is supplied to major industrial customers or for subtransmission. The distribution companies then further transform power down to the consumer mains voltage using distribution transformers (defined in the section below, ‘Transformer types’). In many parts of the world, including Europe, China and Africa, the final consumer voltage is 400/230 V; in North America it is 120/240 V. Distribution transformers operated and owned by electricity distribution companies are responsible for supplying about 70% of low-voltage electricity to final users and represent about 80% of distribution transformer stock by installed capacity (Targosz et al. 2012). The remaining share of distribution transformers are owned and used by industrial and large commercial customers and account for the step-down transformation of power in the remaining share of the low-voltage market.

Given that the majority of the world’s electricity passes through several different transformers prior to use, the energy efficiency of the electrical network – including transformers and conductors – is extremely important in both economic and environmental terms. Electricity production accounts for 41% of global anthropogenic energy-related greenhouse gas emissions and 45% of capital expenditure in the world’s energy system. Furthermore, demand for electricity is forecast to grow at a faster rate than demand for other final energy forms for the foreseeable future (WEO 2012), thus measures to improve the efficiency of both supply and demand are an essential aspect of international policy objectives to realise a secure, affordable and sustainable energy economy.

The level of losses in a network is also strongly determined by the voltage levels used and the number of voltage transformations required. In established networks these are often governed by historical network planning decisions, which now determine the network topology and economic value of losses which can be targeted. However, with aging networks there is also the possibility of up-rating the voltage, particularly at medium voltage, at little extra cost. This can increase the capacity of the network and simultaneously substantially reduce the voltage drop incurred, which reduces line losses. Such actions also reduce the probability of short circuits and hence raise the quality of supply while facilitating the connection of larger numbers of distributed generators.

1.1.1 Transformer types

Transformers are passive devices that use the principle of induction to step the voltage of the energy supplied up (increase) or down (decrease) depending on the design and purpose of the transformer. The voltage of energy is increased prior to transporting power down high- and medium-voltage transmission lines in order to reduce the losses in the power lines. Voltage is stepped down when it is near the point of final demand for safe local distribution and for safe use in final electrical end-use devices. A series of different types of transformers are used in this process, depending on the application being served.

Distinction between transformer types by power

There is no fully harmonised definition for the different types of transformers in use around the world; however, the International Electrotechnical Commission (IEC) has a set of transformer categories that are differentiated based on transformer capacity in the standard IEC 60076-7, the transformer loading guide:

- distribution transformer – power transformer with a maximum rating of 2500 kVA three-phase or 833 kVA single-phase
- medium power transformer – power transformer with a maximum rating of 100 MVA three-phase or 33.3 MVA single-phase
- large power transformer – power transformer exceeding 100 MVA three-phase or 33.3 MVA single-phase.

Another distinction is made between power transformers and distribution transformers. Large power transformers are most often used in the transmission of electricity, which requires very high voltages in order to reduce the current being carried in the transmission lines. These units can be found at generating power stations stepping up to transmission voltage and at electrical substations converting the transmission voltages back down to a subtransmission circuit. From these circuits, the voltage is further reduced by transformers into electricity distribution circuits for commercial, industrial and household customers.

Although not consistent in every market around the world, generally transformers with a maximum voltage rating of 36 kV or less are called ‘distribution transformers’. These transformers are aptly named because they reside in the distribution circuits of electrical grids in residential and commercial areas. Distribution transformers most often reduce voltage (i.e. high-voltage primary, low-voltage secondary), and provide power directly to customers or to another feeder line at a (lower) interim distribution voltage.

In certain markets, such as those in North America, there is a subcategory of distribution transformers called ‘low-voltage distribution transformers’, which are designed with a primary voltage less than or equal to 600 V. These transformers are most often dry-type units and are frequently found in commercial buildings or facilities, working to reduce internal network losses.

‘Medium-voltage distribution transformers’ are those that have their primary (higher) voltage rated between 1 and 36 kV. These units can be both dry-type (including epoxy-cast resin), where the windings are cooled with air or another gas, or liquid-filled, where the windings are cooled with mineral oil or another insulating fluid.

For policymakers who are establishing regulatory requirements, labelling schemes or incentive programmes for distribution transformers, it may be necessary to develop a set of definitions for the covered products that are more precise than those given above. The IEC definitions offer general guidance, but because of differences in voltages observed in T&D networks around the world, it is difficult to establish one set of definitions that precisely covers all the appropriate voltages. Thus, within one national jurisdiction, it may be appropriate to complement the distinctions based on kVA ratings with additional distinctions based on voltages, insulation type, insulation rating, number of phases or other relevant product descriptors. Two examples of how the scope of coverage is defined in regulations that illustrate these distinctions are:

- Australia: 'Dry-type and oil-immersed type, three-phase and single-phase power transformers with power ratings from 10 kVA to 2500 kVA and system highest voltage up to 24 kV installed on 11 and 22 kV networks'[4]
- Canada: 'dry-type transformer means a transformer, including a transformer that is incorporated into any another product, in which the core and coils are in a gaseous or dry compound insulating medium and that (a) is either single-phase with a capacity from 15 to 833 kVA or three-phase with a capacity from 15 to 7500 kVA, (b) has a nominal frequency of 60 Hz, and (c) has a primary voltage of 35 kV or less and a secondary voltage of 600 volts or less.'[5]

1.2 Network losses

Energy losses throughout the world's electrical T&D networks amounted to 1788 TWh in 2011 (Table 1-1) (EIA 2014).[6] This is 8.5% of total production and is equivalent to the total electricity generation of Japan, the Republic of Korea, Australia and Hong Kong combined or 70% of the world's nuclear power production. In equivalent power terms this is roughly equal to 437 GW of electricity generation being wasted, almost the output of 20 Three Gorge Dam hydroelectric projects.

Table 1-1. Estimated network losses in the world (excluding theft)

	Losses (TWh)								Losses (%)*
	1980	1985	1990	1995	2000	2005	2010	2011	2011
Africa	18	30	30	37	54	63	81	80	12.2
Central & South America	38	51	74	104	132	152	170	170	14.9
China	24	40	43	74	94	171	257	270	6.0
India	21	34	57	79	155	180	192	222	22.8
Japan	25	29	41	46	47	50	49	48	4.7
Republic of Korea	2	3	4	9	12	14	18	17	3.6
Australia/ New Zealand	12	14	14	16	18	18	19	16	5.8
Rest of Asia/ Oceania	18	28	39	60	75	95	98	103	9.0
Europe	160	187	194	231	260	266	269	260	7.3
Former USSR	107	134	142	140	165	172	160	159	10.9
Middle East	7	14	20	33	51	85	109	107	12.4
North America	256	236	252	290	319	349	334	335	6.7
World	690	799	910	1119	1383	1617	1755	1788	8.5

* Losses are presented as a percentage of total electricity supply in each of these markets. In other words, network losses capture losses in transmission and distribution transformers, conductors/distribution wires, and other associated losses.

Source: EIA 2014.

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[4] AS 60076.11:2006 (dry type); AS 60076.1:2005 (oil immersed); AS 2374.1.2:2003/Amdt-12005.

[5] http://www.nrcan.gc.ca/energy/regulations-codes-standards/products/6875

[6] Network losses are difficult to assess for a variety of reasons. At any given moment, a utility knows how much energy goes into the network, but it does not know how much is consumed at the user side. Meters are often read on an annual basis, but not all at once, and not all on 1 January. So a distribution company must assign billed consumption over the years. The difference between billed consumption and power entered into the system is the system loss. Sudden drops in losses from one year to the next can be an accounting artefact, to come back the next year with a vengeance.

The share of world electricity production lost through the T&D networks has declined slightly compared to 2000, when it peaked at 9.5% of total world electricity production, and has now returned to the levels that were more typical of the early 1980s. The purely technical part of these losses, including losses in power cables and lines, power and distribution transformers, and metering losses, is estimated to be 7.4% of total generation, i.e. some 1566 TWh in 2011. Non-technical losses, such as electricity theft (see section 4.4) or revenue loss due to poor bill collection, are not included. However, losses reported in statistics that include both technical and non-technical sources vary dramatically by country, with losses as a share of production ranging between 2% and 60%.

While some level of losses is inevitable, Table 1-1 shows a variation in losses from less than 4% to more than 20%. This variation cannot be explained by size of country, size of the electricity system or population alone. In some countries, electricity theft is common and this unauthorised use of energy can represent an important proportion of the total energy lost in the network when compared to T&D losses. However, even within the OECD economies, T&D loss values range from 2.0% (Slovakia) to 16.4% (Mexico), with an average of 6.7%. The large spread in losses when theft is factored out implies that there is a large potential for reductions from implementation of technical improvements.

1.2.1 Trends in transmission and distribution

World T&D network lengths are forecast to rise from 68 million km in 2012 to 93 million in 2035 (WEO 2012). Distribution systems that deliver power over short distances are set to account for 88% of the increase in network length. Furthermore, the role of T&D grids is evolving and their functionality will need to increase and become more flexible in order to accommodate a growing proportion of variable renewables, distributed generation and smart-grid functionality. Future T&D networks are increasingly expected to make use of smart-grid functions, including digital communication and control strategies to optimise system operation, lower losses and facilitate the use of new types of load, with the rise in demand for electric vehicles being chief amongst them.

Tremendous levels of investment will be required to support these demands. Cumulative investment in the power sector from 2012 to 2035 is projected to be US$16.9 trillion in the New Policies Scenario of the International Energy Agency (IEA) (WEO 2012) and accounts for 45% of all energy-sector investment. Some US$7.2 trillion of this is in T&D assets, of which 60% is projected to occur in non-OECD countries and 40% within the OECD. China alone accounts for 25% (US$1.77 trillion) and India for US$0.63 trillion, while the USA and the EU require investment of US$1.03 trillion and US$0.84 trillion, respectively. Distribution investments dominate, taking 74% (U$5.3 trillion) of the T&D total.

In the OECD economies, about two-thirds of this T&D investment is projected to be for refurbishment and about one-third for demand growth, whereas in the non-OECD markets the values are roughly one-third for refurbishments and two-thirds for demand growth. These network costs are a large component of final end-user electricity prices. In the four largest EU economies (Germany, the UK, France and Italy), network costs accounted for an average of about US$0.052/kWh for household electricity prices in 2011, i.e. about 28% of the final tariff.

The estimated value of these network losses is indicated in Table 1-2. Globally, T&D losses were estimated to be worth US$113 billion in 2011 at wholesale electricity prices and about US$186 at final-user prices. These figures are projected to increase to US$207 billion and US$341 billion, respectively, by 2035 if losses as a share of generation remain constant and electricity prices increase by 15% on average.

Table 1-2. Estimated value of network losses in the world for 2011

	USA	China	EU	Japan	World
Wholesale price (US$/MWh)	48	55	83	100	63
O&M cost (US$/MWh)	5.5	4	3	3	4
Generation (TWh)	4100	4491	3215	1031	21081
Losses (TWh)	255	270	235	48	1788
Wholesale value of losses (US$, billions)	12.2	14.9	19.5	4.8	113.4
Approximate final value of losses (US$, billions)	21.5	22.6	32.3	8.0	186.3

Abbreviation: O&M = operation and maintenance.

Sources: EIA 2014 and IEA 2012.

Furthermore, the impact of losses is not confined exclusively to an economic cost. Globally, roughly 1056 million tonnes of CO_2-equivalent greenhouse gas emissions can be associated with these losses – more than the annual energy-related emissions of France, the UK and Spain combined.

1.2.2 The importance of distribution transformers

After losses in power lines, transformers are the second-largest source of losses in electricity networks. Line losses in conductors and cables will typically account for about half of system technical losses, whereas those in transformers will typically account for 45−50%. Distribution transformers alone are estimated to account for 36% of all global technical losses, although the precise share in any given electricity network depends on the system characteristics. Unlike lines or cables, transformers are relatively easy to replace. Furthermore, their efficiency is comparatively straightforward to classify, standardise and label. While transformers are very efficient devices compared to typical electrical end uses, the fact that almost all electricity passes through them, and usually several times prior to final use, means that any improvement in transformer efficiency can produce substantial energy savings. The most advanced modern distribution transformers can reduce losses by up to 80% compared to the least efficient (UNEP 2011), and hence the potential to reduce the losses incurred in distribution transformers is considerable.

Table 1-3 gives an indicative breakdown of T&D losses, based on a limited number of case studies:

- in these case studies, typically one-third of losses occur in transformers and two-thirds in the rest of the system
- approximately 70% of losses occur in the distribution system.

The remainder of this report addresses the potential for high-efficiency distribution transformers as a technology to improve network losses. There are several good reasons for such a focus:

- distribution transformers represent the second-largest loss component in the network
- replacing transformers is easier than changing cables or lines
- transformers have a large potential for loss reduction. Materials and construction techniques exist to reduce losses by up to 80% compared with existing units (UNEP 2011).

Of course, voltage up-rating on refurbishment changes the operating voltage of the line/cable and the transformers so that the overall level of losses on that part of the system is more optimised.

The current (2014) estimated global stock of distribution transformers is 118 million units. Total installed power capacity is estimated to be 13 848 GVA (Figure 1-3), with an average unit capacity of 117 kVA and an average load factor of 39%. Table 1-4 shows estimated stocks from around the world, by country, in 2011.

Table 1-3. Breakdown of total transmission and distribution losses

	Proportion of transmission and distribution losses					Total
	Transmission transformers (%)	Distribution transformers (%)	Transmission lines (%)	Distribution lines (%)	Other	
USA						
Example 1	4.0	16.2	32.3	45.5	2.0	100
Example 2	2.2	36.5	10.5	43.0	7.8	100
Australia: example	2.0	40.0	20.0	38.0		100
UK						
Example 1	8.0	24.0	21.0	45.0	2.0	100
Example 2	10.0	32.0	15.0	43.0		100
Market assessment	10.0	35.0	15.0	35.0	5.0	100
Average	6.0	30.6	19.0	41.6	2.8	100

Source: Targosz 2005.

World demand for electricity is rising faster than for any other energy use. As a result, losses in distribution are also increasing in absolute terms, even if in some economies losses as a percentage of generation have declined somewhat. According to IEA projections, global electricity demand is set to rise from 22 146 TWh in 2011 to 38 424 TWh in 2030 – a 74% increase (Table 1-5) (WEO 2012).

Figure 1-3. Estimated and forecast installed capacity of distribution transformers around the world (C AM = Central America;FSU =Former Soviet Union; Indian Sub Con = Indian Subcontinent).

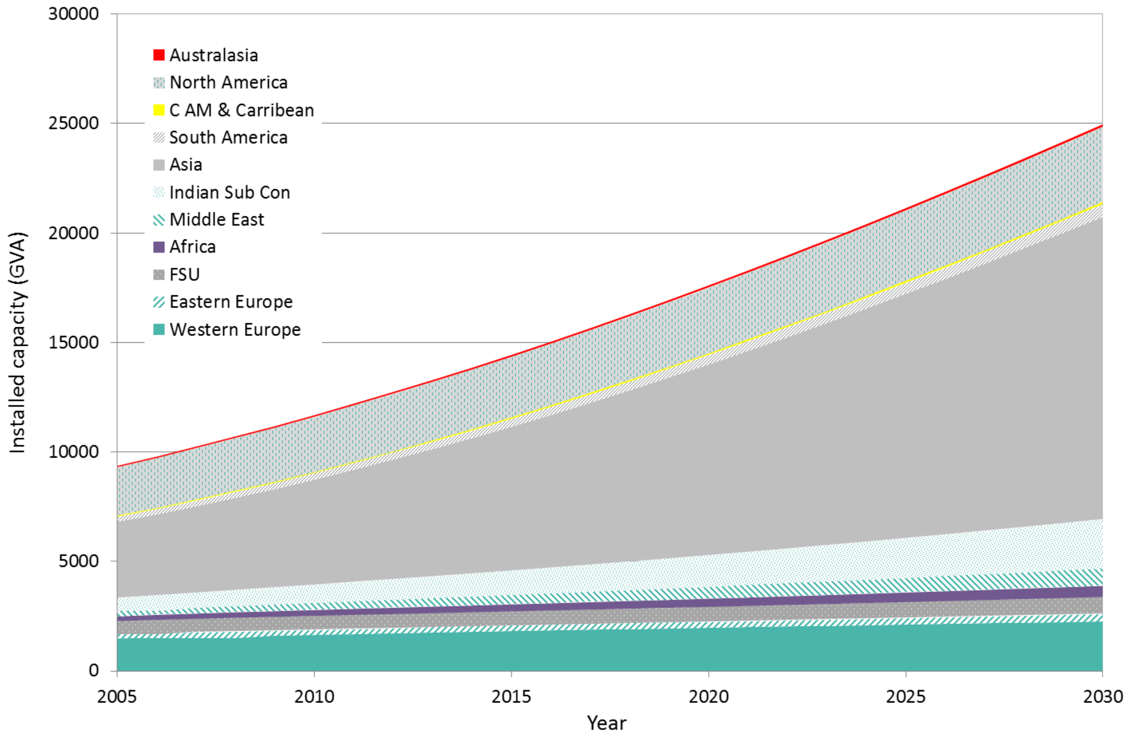

Table 1-4. Estimated global distribution transformer populations in 2011

	Total distributed electricity (TWh)	Distribution transformers capacity (MVA)	Stock (millions)	Average load factor (%)	Average capacity (kVA)	Annual sales (no. of units)
USA[1]	3780	2 206 900	31.6	34	73	780 000
Canada[1]	530	415 200	5.7	34	73	110 000
Australia[1]	230	110 640	0.67	27	493	31 000
Japan[1]	960	716 000	15.5	22	46	400 000
Republic of Korea[1]	426	107 700	1.48	50	73	46 800
Indonesia[1]	160	40 000	0.55	50	73	17 400
Mexico[1]	240	96 900	1.4	31	73	70 300
Russia[1]	814	206 000	2.82	50	73	89 400
Thailand[1]	148	52 050	0.71	36	73	51 800
China[2]	4221	2 299 246	7.2	50	32	980 715
EU[3]	2980	1 623 253	4.1	21	400	158 262
India[4]	753	410 171	4.2	–	97	–
Brazil	443	241 309	–	–	–	–

Sources: [1] Letschert et al. 2013; [2] Derived from Yuejin 2013 and EIA 2014; [3] Derived from VITO 2011; [4] Derived from EIA 2014 and Sandeep Garg, Indian Bureau of Energy Efficiency, personal communication 2014.

Table 1-5. Electricity generation to 2030 under a current policies scenario (TWh/year)

	1990	2008	2011	2020	2025	2030	2035
OECD North America	3801	5253	5402	5850	6135	6420	6676
OECD Europe	2632	3600	3692	3967	4172	4377	4576
OECD Asia Pacific	1127	1820	1903	2153	2238	2322	2398
Russia	1082	1038	1080	1206	1305	1404	1523
Rest of Eastern Europe/Eurasia	842	675	713	828	902	975	1042
China	650	3495	4418	7186	8386	9586	10 848
India	289	830	1041	1673	2154	2635	3256
Rest of non-OECD Asia	334	1012	1163	1614	2005	2396	2911
Middle East	240	771	870	1165	1383	1600	1851
Africa	316	621	695	916	1049	1181	1327
Latin America	507	1069	1170	1473	1647	1820	2016
World	11 820	20 184	22 146	28 031	31 373	34 716	38 424

Source: WEO 2012; 2011 and 2025 values are interpolated.

If distribution transformer losses were to remain constant as a proportion of generation they would also increase, as shown in Table 1-6, and reach 1050 TWh by 2035. However, in practice the impact of recently adopted policies (see Chapters 7 and 8) is expected to curb this growth by about 7.6% by 2030.

These estimates assume that on average about one-third of technical network losses will occur in distribution transformers; however, the exact proportion depends on the efficiency of the distribution transformer stock, which will often be influenced by previous policy efforts, the vintage of the stock,

Table 1-6. Estimated distribution transformer electricity losses (TWh) to 2035 under a no new policies scenario and assuming no reduction in losses as a share of generation over time

	2011	2020	2025	2030	2035	Losses as a proportion of generation (%)
OECD North America	119	129	136	142	148	2.2
OECD Europe	89	96	101	106	110	2.4
OECD Asia Pacific	40	45	47	49	51	2.1
Russia	38	42	45	49	53	3.5
Rest of Eastern Europe/Eurasia	28	33	36	39	41	4.0
China	88	143	166	190	215	2.0
India	41	66	85	104	129	4.0
Rest non-OECD Asia	38	52	65	77	94	3.2
Middle East	36	48	57	66	76	4.1
Africa	28	37	42	48	53	4.0
Latin America	46	58	65	72	80	4.0
World	591	749	845	941	1050	2.7

the distribution of transformers by capacity, the degree to which the loading of the transformer stock coincides with the peak design efficiency, and policies impacting the load on the transformer, such as appliance-efficiency programmes and building performance regulations.

1.3 Energy and carbon savings potentials

There are no global savings potential estimates from the adoption of energy-efficient distribution transformers in the published literature, but some internal estimates have recently been derived by the United Nations Environment Programme (UNEP) and elaborated upon for the present study. This analysis shows that current policies, which are mostly minimum energy performance standards (MEPS) implemented since 2010, are on course to save 191 TWh of final electricity consumption in 2035 (Table 1-7) compared with what would have been otherwise expected to occur under a historic base-case scenario. Cumulatively from 2010 to 2035, these measures are projected to save 2289 TWh, some 1144 Mt of CO_2 emissions and energy worth US$229 billion at 2014 prices.

Although these savings estimates are very large, even greater savings are possible by broadening the number of countries with policies in place and through deepening existing policies (see the discussion on policy in Chapters 7–9). As an illustration of the magnitude of benefits that could be achieved, Table 1-7 indicates the annual savings in energy, CO_2 and energy costs that are projected with current policies relative to a 'historic base case' scenario, where it is imagined that no policies are implemented. The same table also indicates the savings that could be achieved if all economies were to install new or replacement transformers at SEAD Tiers 3, 4 or 5 (see section 7.4). To put these thresholds into context, Tier 1 is the efficiency of the least ambitious current MEPS, Tier 2 is the level of medium-ambition current MEPS, Tier 3 is the level of the most ambitious current MEPS (e.g. those set to come into effect for liquid-type distribution transformers in the USA from 2016) and Tier 5 is getting near to the level of the most advanced current transformer technology (the best available technology (BAT) level) (see section 7.4).

While current policies are projected to produce cumulative savings of 5992 TWh, 2996 $MtCO_2$ and US$599 billion of energy costs by 2050, universal adoption of SEAD Tier 3 transformers would be expected to produce cumulative savings of 8540 TWh, 4270 $MtCO_2$ and US$854 billion of energy costs over the same period. Universal adoption of SEAD Tier 4 transformers is projected to produce

Table 1-7. Projected annual global savings with higher-efficiency distribution transformers compared to the historic base-case scenario

Year	Current policies			Current policies plus all others to SEAD Tier 3			All to SEAD Tier 4			All to SEAD Tier 5		
	TWh	MtCO$_2$	US$, billions	TWh	MtCO$_2$	US$, billions	TWh	MtCO$_2$	US$, billions	TWh	MtCO$_2$	US$ billions
2010	3	2	0	3	2	0	3	1	0	3	2	0
2015	25	13	3	27	14	3	36	18	4	43	22	4
2020	60	30	6	75	38	8	113	57	11	135	67	14
2025	104	52	10	138	69	14	216	108	22	256	128	26
2030	154	77	15	213	107	21	339	169	34	402	201	40
2035	191	96	19	278	139	28	442	221	44	526	263	53
2040	230	115	23	336	168	34	534	267	53	636	318	64
2045	262	131	26	385	192	38	627	314	63	749	374	75
2050	282	141	28	423	211	42	697	348	70	833	416	83

cumulative savings of 13611 TWh, 6806 MtCO$_2$ and US$1361 billion of energy costs by 2050, and universal adoption of SEAD Tier 5 transformers is projected to produce cumulative savings of 16 210 TWh, 8105 MtCO$_2$ and US$1621 billion of energy costs.

An earlier Lawrence Berkeley National Laboratory (LBNL) analysis of savings potentials conducted for five major economies[7] found that additional savings of 44 TWh could be achieved in 2020 and 132 TWh in 2030 with the adoption of BAT (i.e. of the most efficient current transformer designs), thereby avoiding 84 Mt of CO$_2$ emissions in the same year (Letschert et al. 2012). The cost-effective savings potentials were estimated to be about 64% of the technical potential at 28 TWh in 2020 (16 MtCO$_2$) and 86 TWh in 2030 (46 MtCO$_2$). From the same analysis it was provisionally estimated that for the participating Clean Energy Ministerial (CEM) economies (which include Australia, Brazil, Canada, China, the EU, India, Indonesia, Japan, Mexico, Norway, Russia, Republic of Korea, South Africa, UAE and the USA), the adoption of the current most stringent standards for distribution transformers would result in final electricity savings of 75 TWh in 2030 and 30 Mt of CO$_2$ savings. These economies account for 79% of the world's electricity losses, so scaling on a pro rata basis would give a global savings potential of 95 TWh in 2030 with adoption of current most stringent MEPS. In fact, the savings potential should be greater than this because many of the CEM countries have already implemented MEPS for distribution transformers and hence have a lower remaining percentage of losses savings potential than would be the case for those countries that have not.

A more recent analysis by the same team considered the cost-effective savings potentials in 20 APEC economies (excluding China)[8] and found that in these economies it would be cost-effective to adopt MEPS which resulted in:

- 30 terawatt-hours (TWh) of electricity savings in 2030
- 19% reduction over the 157 TWh electricity distribution losses projected in 2030
- 17 million tonnes (Mt) of annual CO$_2$ emissions reductions by 2030
- 120 Mt of cumulative emissions savings between 2016 and 2030
- US$18.5 billion in cumulative consumer financial benefits (Letschert et al. 2013).

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[7] Canada, China, the EU, India and the USA.

[8] Australia, Brunei, Canada, Chile, Chinese Taipei, Hong Kong, Indonesia, Japan, Malaysia, Mexico, New Zealand, Papua New Guinea, Peru, Philippines, Russia, Singapore, South Korea, Thailand and the USA.

2. Technical aspects

Key messages

- While there are slight differences in the definition of a distribution transformer, most economies define them as transformers with a highest winding voltage at or below 36 kV.
- There are two main types of distribution transformer: liquid filled and dry types. The liquid-filled types dominate because they tend to be more efficient and compact; they are used in almost all distribution utility applications, but dry types are used by some commercial building and industrial customers, as well as electric utilities in areas where leaks would be more costly.
- Losses in transformers are split into load losses and no-load losses. No-load losses are independent of load, meaning they do not increase with the loading on the transformer. Load losses, sometimes referred to as 'winding losses', are lost in the transformer windings when it is under load.
- The combination of load and no-load losses means that each transformer has an optimum loading point when it is most efficient and the actual losses incurred will increase or decrease non-linearly as the load moves away from the optimum point.
- A number of energy performance metrics are in use for distribution transformers; however, it is important that regulators and private-sector procurement practice use metrics in their specifications that help minimise the losses over the way transformers are used in practice.
- When measuring transformer performance, most countries and economies around the world that are actively engaged in promoting more energy-efficient distribution transformers tend to use the test standard based on IEC 60076. For some markets, governments have made slight (local) modifications to the IEC standards on account of some specific or unique requirements; nonetheless, there are good prospects for global harmonisation around a common IEC test standard.

2.1 Basic principles of distribution transformers

Transformers are static devices operated between circuits in electrical T&D systems, converting voltages through electromagnetic induction. They are manufactured in a wide range of rated powers and voltages to meet the requirements of the network operator. Transformers are either single-phase or three-phase, and are designed for optimal performance at a specific frequency (usually 50 or 60 Hz). They tend to be loosely classified around their applications – such as generation, transmission and distribution transformers – but more precisely according to the different voltages, insulation type and number of phases.

Most countries define distribution transformers as those units with a highest winding voltage at or below 36 kV. Distribution transformers are installed in the distribution circuit of electricity networks, stepping down the voltage to service residential areas and commercial and industrial customers (see Figure 1-1).

Each manufactured transformer will have a specific rated power, measured in kilovolt-amperes (kVA), which represents its power-handling capability. Distribution transformers are typically rated between 5 and 3150 kVA, and include both single-phase and three-phase. These transformers are divided into two major categories according to the type of electrical insulation used in the unit – liquid-filled for those with core and windings immersed in liquid, and dry-type for those cooled by air or gas. The following subsections provide further detail on these two distribution transformer product classes (note: additional technical details are given in Appendix B).

2.1.1 Liquid-filled distribution transformers

Liquid-filled distribution transformers offer several performance advantages over dry-type transformers. They tend to be more energy efficient, are more compact for the same rated power and have a greater overload capability. Liquid-filled transformers also tend to have a long service life because they have low load factors and are able to readily reduce coil hot-spot temperatures. However, liquid-filled transformers are often filled with mineral oil,[9] which results in a higher flammability potential than found with dry types; local environmental laws may require containment troughs or other facilities to guard against insulating fluid leaks.

The liquid used in these transformers functions as both an electrical insulating fluid and a cooling medium. The windings of these transformers incorporate cooling ducts between the parts of the windings to enable fluid to flow through the windings and remove excess heat from the conductors. The core and coil (active part) assemblies of these transformers are installed in a tank that facilitates fluid circulation and then exhausts that excess heat to the environment through the tank walls, which may include cooling fins/tubes or active heat elimination systems (e.g. fans).

2.1.2 Dry-type distribution transformers

Dry-type transformers do not use mineral oil or other insulating liquid as a cooling medium. Rather, they use air as the basic medium for insulating and cooling the core and coil (active part) assemblies; however, air is not as efficient as oil in performing these functions. Thus, for the same voltage and rated power, dry-type transformers will tend to be larger than liquid-filled units. For these reasons, and on account of the inferior cooling capacity of air, dry-type transformers tend to have more losses than liquid-filled distribution transformers.[10] That said, dry-type transformers remain a very important part of the transformer market because they offer safety, environmental and application advantages, e.g. weight. For instance, dry-type transformers have a lower mass per unit capacity and therefore are often used instead of oil-filled transformers in the nacelle of wind-turbine masts.

Dry-type transformers are used by commercial building and industrial customers, as well as electric utilities. Generally, the location of the installation will have a significant impact on the insulation type of the transformer used. Higher-capacity transformers used outdoors will most often be liquid-filled, whereas lower-capacity indoor transformers are often dry-type. Part of the reason for this is because of the lower maintenance requirements of liquid-filled transformers, which do not require the same degree of cleaning to prevent surface tracking and flashover.

Dry-type transformers are typically housed in cabinet enclosures, with the windings insulated by varnish, vacuum pressure impregnated (VPI) varnish and epoxy cast resin. The insulated windings of dry-type transformers can offer excellent dielectric strength and offer a long, reliable service life.

2.2 Losses in transformers

Energy is lost by a working transformer as it converts the input voltage to the output voltage. This energy is manifested in the transformer as excess heat, which arises in the core or the windings of the transformer. The transformer must be designed to ensure the temperature rise at the rated

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[9] Another type of insulating liquid used in modern transformers are ester compounds, which have a much higher fire point and also self extinguish, and thus are able to offer similar (if not better) fire performance compared with some dry-type transformers.

[10] Compared to liquid-filled, MEPS for dry-type transformers around the world tend to have lower levels of ambition for the same kVA rating. Of course, it is possible to make a very efficient dry-type transformer, but that comes at a price premium which hitherto policymakers have not found to be cost-justified.

condition is not exceeded, to prevent damage to the transformer during operation. The upper limit of that designed temperature rise is based on industry or national standards; if this limit is exceeded (such as in an overload situation), the excess heat may degrade the winding insulation and shorten the transformer's service life.

The following subsections present the reasons why losses occur in distribution transformers and what can be done to minimise them, through better materials and good design.

2.2.1 No-load 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 load, meaning they do not increase with the loading on the transformer. No-load losses consist mainly of two components: hysteresis losses and eddy current losses. Hysteresis losses are created by the magnetic lag or reluctance of the molecules in the core material to reorient themselves 50 or 60 times a second (i.e. 50 Hz or 60 Hz frequency of the alternating current magnetic field). Eddy current losses in the core result from the electrical currents induced in the core material by the alternating magnetic field – the same way that the magnetic field induces current in the secondary winding. However, these circulating electrical currents do not leave the core; they simply circulate around within the material and become waste heat.

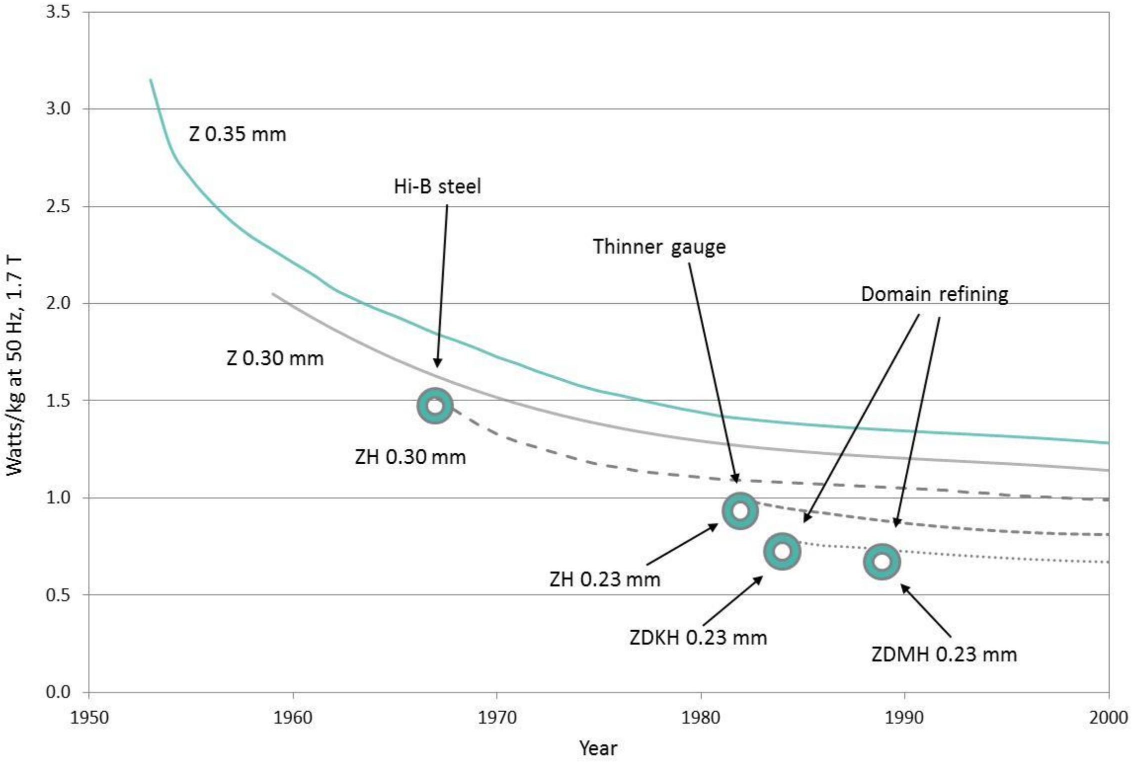
Over the last 70 years, there has been considerable investment and technology innovation to reduce the losses incurred in transformer cores. In the past, core material had relatively high losses, because of being produced from sheets of non-oriented, magnetic steels. Research investments made by core steel manufacturers have significantly reduced the losses, such that modern core steel now has 60–80% fewer losses than steel of the past. High-efficiency core steel incorporates low concentrations of silicon (approximately 2–3%) and trace amounts of other elements. The laminations are cold-rolled into very thin sheets and can also be grain-oriented or domain-refined (i.e. laser or mechanically scribed). Manufacturers of electrical core steel have also improved the insulation layers between the core laminations, electrically isolating the layers and thereby reducing eddy currents.

Generally, conventional grain-oriented (CGO) electrical steel is used for transformers with normal no-load loss characteristics, while transformers that require much lower no-load loss characteristics are built using higher-quality HiB steel (laser or mechanically scribed). The laminations used in these cores are 0.30, 0.27 or 0.23 mm thick and yield very low no-load losses. Using better-quality core steels also means that the saturation point of the flux in the steel is slightly higher. These higher flux densities increases losses of the steel on a watts per kilogram basis; however, a smaller core can be used, thereby leading to better overall loss performance.

Figure 2-1 depicts the losses per kilogram of electrical steel at a constant magnetic flux over time. This diagram illustrates some of the improvements and innovations in electrical steel that have been commercialised since 1950, with the trend toward fewer watts of no-load loss for the same quantity of steel at a constant magnetic flux.

In addition to using better-quality silicon core steel, core losses can also be reduced by using amorphous metal in place of CGO electrical steels. Amorphous metal is an iron alloy that usually incorporates boron, silicon and phosphorus. The metal is then produced in very thin (approximately 0.03 mm thick) sheets, which lowers eddy currents. The properties of amorphous metal give it high magnetic permeability, which helps to lower hysteresis losses. On the downside, amorphous cores have a lower magnetic saturation, which results in larger cores, and the technology cannot be used above around 2000 kVA, especially in applications where noise limits require the use of lower levels of magnetic induction. In addition, on the manufacturing side, amorphous material requires a specially adapted design, usually of the wound-core type, and specially adapted production lines.

Figure 2-1. Trend in no-load-loss reduction, 1950–2000.



However, those manufacturers that have made the production investment offer designers another option for building energy-efficient transformers.

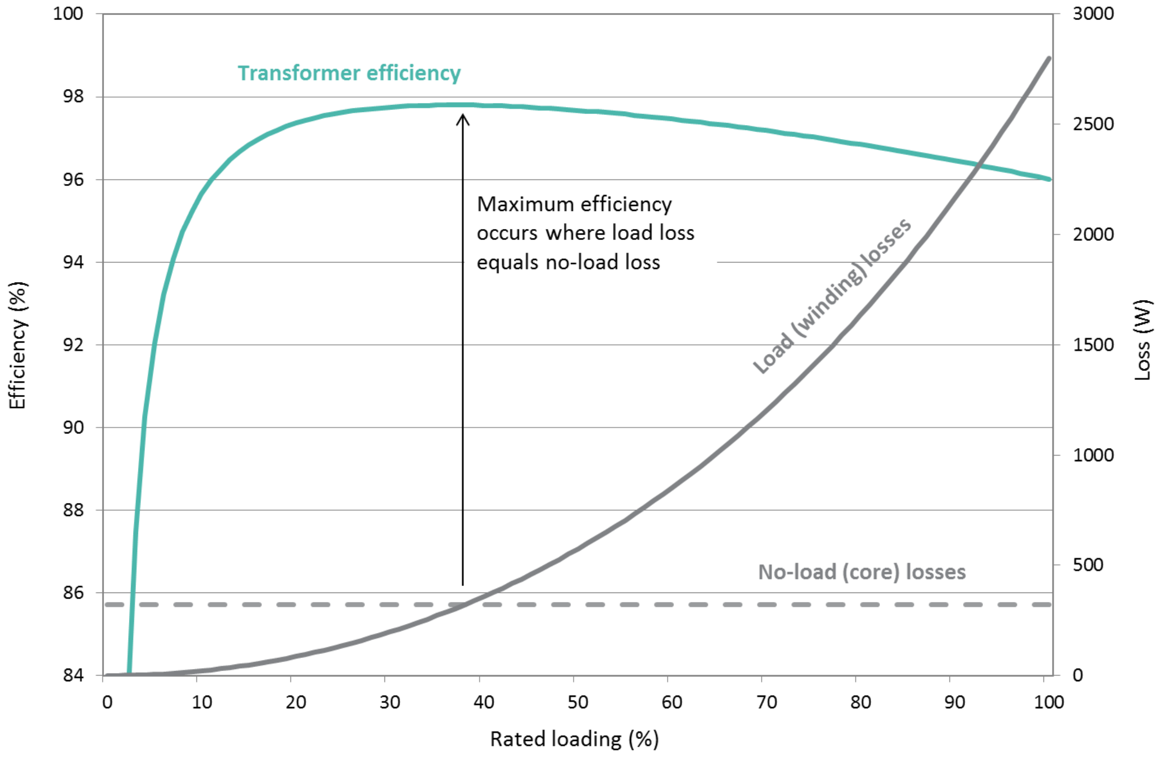
2.2.2 Load losses

Load losses, sometimes referred to as ‘winding losses’ or ‘copper losses’, comprise the energy that is lost in the transformer windings as a result of the load current flowing in the windings. Load losses are primarily caused by the electrical resistance of the windings, and the magnitude of these losses varies with the square of the current being carried in the windings. In addition, there are stray eddy losses in the conductor and in the core as a result of load loss. The resistive losses in the windings mean that as the loading on the transformer increases, the losses increase approximately to the square of the load. This impact is visible in Figure 2-2, which shows the no-load losses and load losses described over loading points from 0 to 100% of rated capacity transformer loading. Peak efficiency of the transformer occurs at the point where no-load losses are equal to load losses.

There are several approaches to reducing load losses in a transformer design, although some solutions may also increase losses incurred in the core of the transformer. One approach is simply to increase the cross-sectional area of the conductor, which will decrease the current density in the winding material and therefore reduce the losses because they are proportional to the square of the current. However, this technique also requires the transformer core to be made larger to accommodate the larger conductor volume, increasing no-load losses.

Another approach would be to use lower resistance materials in the windings. Today, both aluminium and copper are used in transformer designs and are widely available in standard wire sizes and sheets (called ‘foil’). When these two materials are used in exactly the same manner, copper offers an advantage because it offers electrical conductivity with around 40%-lower resistive losses than aluminium per unit volume. Aluminium conductors can experience lower resistive losses

Figure 2-2. Relationship between distribution transformer losses and efficiency (example of a 75 kVA, three-phase, dry-type).



if the conductor cross-sectional area is increased, but this approach requires larger cores, necessitated by the larger conductor, and thus tends to increase no-load losses.

2.3 Improving efficiency

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 distribution 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 2-1.

There are five approaches to reducing no-load losses shown in Table 2-1. One of these is a material-substitution option and four of them are transformer-design solutions. Each of these options is discussed briefly below.

1. The use of lower-loss core material will decrease the number of watts lost per kilogram of core, and very often it will have no impact on load losses. This can include, for example, using a laser-scribed M3 steel in place of an M6, or using amorphous metal in the core instead of silicon steel. In general, however, substituting with a lower-loss core material will result in an increase in price.
2. The use of better core-construction techniques can also reduce no-load losses. These can include, for example, using a distributed gap in a wound core or a 7-step mitre or cruciform core construction in a stacked core.The improvements can also include symmetrical triangular

Table 2-1. Loss-reduction interventions for distribution transformers

Objective	Approach	No-load losses	Load 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

cores.[11] These solutions, however, involve the use of sophisticated core-manufacturing equipment which may, in turn, lead to an increase in price.

3. 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 are used in the transformer, in both the core and the coil.
4. 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.
5. 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 2-1 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.

1. 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.

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[11] Wound triangular cores are made of three identical wound core rings arranged in a triangle for a three-phase transformer core. The electromagnetic properties are identical and a magnetically symmetrical configuration results. The symmetry of the core and lack of joints in the wound cores provide performance improvements over traditional stacked, planar cores (ABB 2013).

2. 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.
3. 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.
4. 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.
5. 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.

2.4 Defining energy performance of transformers

Many different metrics are used to assess the energy performance of a distribution transformer, each of which are described briefly below.

1. Maximum 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 for establishing mandatory requirements on transformer performance can be found in economies such as China and the EU.
2. 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 for establishing performance requirements on transformers can be found in countries such as Japan.
3. Percent efficiency at a defined loading point – this metric is also one unitless numerical value, percentage efficiency, representing the active power in watts delivered by the transformer to the load relative to the active power in watts drawn by it from the source. Percent efficiency must be declared at a specified loading point; as shown in Figure 2-2, it varies with load. This approach for establishing mandatory requirements on transformer performance can be found in economies such as Australia and the USA.
4. Peak efficiency index (PEI) – this is a new index that was developed by a technical working group supporting the European Commission's analysis of regulations for power transformers. The equation for peak efficiency determines the highest efficiency value of any transformer design, irrespective of a specified loading point. This approach for defining efficiency was included in the European ecodesign regulation for transformers (OJEU 2014) and an IEC committee draft of 60076-20.

Each of the above approaches offers certain strengths, but also has some weaknesses. A policymaker needs to decide which of these approaches offers the best approach for their specific economy, bearing in mind the various constraints and specific conditions of their market. To assist with that choice, the following subsections provide some more information on each of these four metrics.

2.4.1 Maximum no-load and load losses

Both the IEC 60076 and IEEE C57 test standard families base their energy-performance assessment of transformers on the measurement of no-load (with rated voltage to magnetise core but one circuit open) and load losses (at 100% of rated capacity). In this way, having two regulatory metrics that establish maximum no-load and load losses aligns very well with the test standard and offers policymakers a way to ensure that losses are limited, irrespective of usage. Using maximum watts of no-load and load loss is the regulatory approach followed in China and Europe and in the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) methodology, where maximum loss levels are provided in a table of different-sized transformers. A merit of this approach when used within regulatory or performance specification thresholds is that load and no-load losses are never greater than a certain value regardless of the loading applied, which is generally difficult to predict on average, on a daily, seasonal or life-cycle basis across the stock of identically rated transformers. This means that a minimum level of performance is assured whatever the level of loading applied to the transformer. However, it is also the case that once load and no-load loss requirements have been set, there is an implicit least-cost-of-manufacture optimum load point; regulators need to be mindful of this loading point to ensure that requirements do not encourage peak performance at a load point that is likely to be far from the typical values found in the economy. If this implied loading point does not match the load where the least-cost transformer is being installed, the least-cost transformer’s optimal performance point will not coincide with the installation loading, resulting in lost energy savings. Another drawback of specifying maximum no-load and load losses separately is that it reduces the designer’s flexibility of trading between no-load and load losses to arrive at the least-initial-cost design (as opposed to least life cycle cost design) by benefitting from relative material prices prevailing at the time. At extreme levels, this approach could also tend to favour specific core or conductor materials over others. This issue can, however, be mitigated if loss capitalisation is used in the transfomer tendering priocess, with the cost per kilowatt of iron and copper losses advised. This will result (where compatible with the regulatory limits) in an optimum balance beween load and no-load losses, while each component is less than the allowed maximum.

2.4.2 Maximum combined no-load and load losses

An alternative to separate requirements for maximum no-load and load losses would be to combine the total losses into one value. This combined value is still a measure of the watts of energy lost, but it is a ‘technology neutral’ metric because it allows manufacturers more flexibility with their designs, trading between no-load and load losses to develop the least-initial-cost design for their customers. This approach of using maximum combined no-load and load loss has been used in Japan in the Top Runner Program. On the negative side, this approach requires the regulator to select a loading point at which the loss measurement is made (e.g. 50%, 100%), and thus while the total combined losses are reported, it may not be at a level representative of the typical average over the lifetime of all distribution transformers. Similar to the maximum no-load and load loss set, there will be an implicit least-cost point of manufacture at that selected loading point, which may or may not be optimal for a given market. If this loading point does not match the load where the least-cost transformer is being installed, the least-cost transformer’s optimal performance point will not coincide with the installation loading, resulting in unrealised energy savings. Again, however, this issue can be mitigated if loss capitalisation is used in the transformer tendering process, with the cost per kilowatt of core and winding losses advised. This will result (where compatible with the regulatory limits) in an optimum balance beween load and no-load losses, while each component is less than the allowed maximum

2.4.3 Percentage efficiency

The option of using percentage efficiency is the regulatory approach followed in Australia, the Republic of Korea, the USA and elsewhere. This approach is similar to the combined no-load and load loss, as it is based on a single numerical requirement that combines the no-load and load loss values. The total loss is deducted from the power capacity of the transformer and the percentage efficiency is calculated as the power output divided by the power input. The advantage to using efficiency instead of maximum losses is that it is a 'technology neutral' metric, allowing for flexibility in the materials and the design methods employed in manufacturing a distribution transformer. This metric allows transformer design engineers to trade off no-load and load losses and produce an optimised transformer for a customer. On the downside, the percentage efficiency metric also has a drawback in that it must be defined at a specified loading point and, as discussed above, there is always uncertainty about how representative any specific loading point will be of future usage across the stock of distribution transformers. The point selected will not align with the average loading point at all installation sites.

It is important to appreciate that the annual energy loss in a particular transformer depends upon the shape of the load curve and not just a specific operating point or average load factor. For the same operating point or average load there can be an almost infinite set of load-curve shapes and therefore the cumulative energy loss in a transformer for each load curve will be different. Thus, while defining MEPS by this method is 'technology neutral' because it allows transformer manufacturers 'flexibility' in designing cost-optimised no-load and load loss combinations, customers may not always minimise life-cycle costs if the transformer is selected solely on the basis of energy efficiency at a specific load factor. As discussed above, if a transformer is purchased simply on a least-cost purchasing basis, its optimal loading point may not coincide with the average loading at all installation sites, resulting in lost energy savings. Thus, transformer procurement practices should always take into account the cost per kilowatt of core and winding losses to minimise the total cost of ownership over the lifetime of the transformer (see section 3.1 on life-cycle costing of transformers).

2.4.4 Peak efficiency index

The peak efficiency index (PEI) is a unitless index that was developed as a regulatory option for large power transformers in the European Ecodesign process. This index also combines no-load and load losses, but the equation is written in such a way that it does not require a specified loading point. Instead, the index finds the point where the no-load loss equals the load loss, and calculates the value. This approach has an advantage over other approaches in that it does not require a loading point to be specified or implied. However, it could also result in a mismatch of load and lost energy savings, if product designs are made at loading points that represent the lowest manufacturing cost but are not necessarily representative of actual loading levels experienced by transformers in the distribution network. Hence, the draft IEC and CENELEC standards (see section 7.4.2) advise that either the load factor or the cost per kilowatt of core and winding losses are also included in the tender process so that the core and winding losses that are combined to determine the PEI can be optimised for the proposed usage.

2.5 Transformer efficiency test standards

Transformer performance is measured through the use of test standards, which clearly delineate the test conditions to ensure that the measured energy performance of the transformers is accurate, consistent, reliable and repeatable. There are two major standards bodies around the world for the measurement of losses: the International Electrotechnical Commission (IEC) and the Institute of

Electrical and Electronics Engineers (IEEE). The IEC has developed, published and maintains approximately 19 standards in the IEC-60076 series, in addition to several standards on tap-changers, terminals and converter transformers. The IEEE, based in North America, has over 80 standards and guides covering transformers.

When measuring transformer performance, most countries and economies around the world that are actively engaged in promoting more energy efficient distribution transformers use a test standard based on IEC-60076. For some markets, governments have made slight (local) modifications to the IEC standards because of some specific or unique requirements. For the most part, however, the IEC standards are the most commonly used. For example, eonomies that use the IEC standards for energy-efficiency programmes and policies on transformers include Australia, Brazil, China, Europe, India, Israel, Japan, Mexico, New Zealand, the Republic of Korea and Vietnam. The IEEE standards, on the other hand, are used primarily in the USA and Canada.

Although these standards are managed by different institutions, they are not greatly dissimilar in the manner in which they measure and define transformer performance, thus there is a potential for the test standards to be harmonised in the future. To facilitate this, the IEC and IEEE have jointly created a 'Dual Logo' single-standard project addressing their standards on transformers and many other electrical products and equipment.[12] This cooperative effort applies to electric motors, instrumentation, nuclear power and so on. At the time of writing, there are already two transformer standards that were developed and agreed through this new 'Dual Logo' process (note: neither of these standards apply to distribution transformers):

- IEC 60076-21:2011 (E), Edn 1 (2011–12) (IEEE Std C57.15-2009): *Power Transformers – Part 21: Standard Requirements, Terminology, and Test Code for Step-Voltage Regulators*
- IEC 62032:2012, Edn. 2.0 (2012-06) (IEEE Std C57.135-2011): *Guide for the Application, Specification, and Testing of Phase-Shifting Transformers*.

In addition to these, there is a joint IEC/IEEE group on maintenance of IEC 60076-16, which covers transformers for wind turbine applications; this group is expected to produce a Committee Draft of the new standard sometime in 2015. It is hoped that in future, the IEC and IEEE will prioritise loss measurement of distribution transformers under the 'Dual Logo' scheme and accelerate harmonisation by standardising the definition of efficiency underpinning this equipment.

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[12] Information about this collaboration, including documents that outline the cooperation and licencing agreements, the procedures followed and the joint development agreement itself can be found at http://standards.ieee.org/develop/intl/iec.html

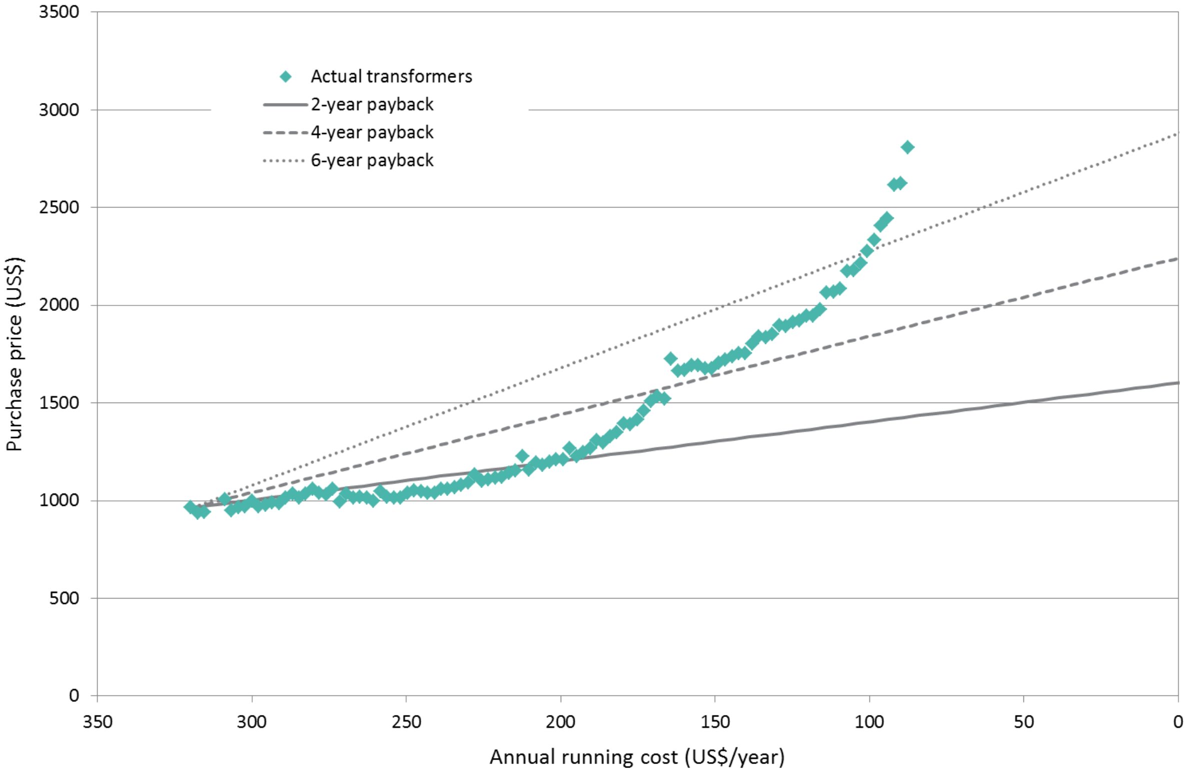
3. Economic aspects

Key messages

- Despite being highly cost-effective over the medium to long term, procurement practices that minimise the total cost of ownership (TCO; i.e. the purchase price, installation cost, and operation cost including energy and maintenance) are not used by all utilities.
- In part this is because many organisations separate the management of the capital expenditure budget from the management of the operations and maintenance budgets. This tends to weaken the economic incentive the procurement manager has to invest in products that minimise service-life cost and favours investment in equipment with the lowest price.
- In most cases, transformers with the lowest purchase price are also the ones with the highest losses. Since transformers have a long life span – typically greater than 30 years – the value of these extra losses can be several times the purchase price over the service life.
- Optimal procurement processes aim to minimise the TCO by reflecting the expected operational costs inherent in the transformer design and intended usage profile on the same basis as the purchase price in the procurement decision.
- The simple payback periods from investing in high-efficiency transformers are typically in the range of 2–5 years (UNEP 2011) for a product with an average service life of over 30 years, and hence for about 85% of the product service life there is a net profit on the investment.
- Payback calculations are affected by assumptions regarding the future costs of energy, interest rates, discount rates and load factors, and these need to be as fully informed as possible.
- At the economy level, the savings from investment in the most cost-effective transformers can be worth hundreds of millions of US dollars per annum. For example, the net discounted financial benefit of adopting cost-optimised MEPS in 20 APEC economies (excluding China) is estimated to be US$18.5 billion in 2030.
- Utilities and regulators need to use appropriate methodologies to estimate the true value of the cost of load losses in their network planning determinations. These need to be assessed using forward-looking, LRMC analysis that treats the load and no-load losses separately, and which evaluates the cost of losses at each point in the network.
- Furthermore, the value of these losses is usually greater than the LRMC of supply for all supply options except clean coal and renewables, which indicates that their reduction should receive precedence in investment planning compared to conventional supply options.
- Assessment of the best time to replace a distribution transformer will take into account not only the cost of energy losses, failure risk and maintenance, but also the investment cost, the residual value of the transformer when it is taken out of service and the value of functional changes if smart-grid capability is to be added.

If transformers were always procured and operated with the aim of minimising their life-cycle cost of operation, the market could be said to be working efficiently and there would be no need for any policy intervention unless to address hidden costs such as environmental externalities (see section 3.3). Although it would be an economically sound approach, procurement practices that truly minimise the total cost of ownership (TCO; i.e. the purchase price, installation cost, operation cost including energy, and maintenance) are not applied by all utilities, although they are more commonly applied by utilities than by other parts of the private sector.

Figure 3-1. Purchase price versus operating cost for 50 kVA, single-phase, rectangular-tank, liquid-filled distribution transformers.



In part this arises because many organisations separate the management of the capital expenditure budget from the management of the operations and maintenance budgets. This tends to weaken the economic incentive the procurement manager has to invest in products that minimise service life cost and favours investment in equipment with the lowest price. This focus on lowest price leads to suboptimal investments over the transformer's service life, because operating costs due to losses are significant and yet are undervalued in the procurement transaction. The principal manifestation of this practice in the case of transformers is a tendency to procure cheaper transformers that have higher operating costs due to their higher losses. As shown in Figure 3-1, in most cases, transformers with the lowest purchase price are also the ones with the highest losses. Since transformers have a long life span – typically greater than 30 years – the value of these extra losses can be several times the purchase price over the service life. Figure 3-1 shows the payback periods for a set of US Department of Energy (DOE) designs of a 50 kVA, single-phase, liquid-filled distribution transformer, assuming 50% average annual loading and US$0.10/kWh. All of these payback periods are significantly shorter than the anticipated service life.

3.1 Life-cycle costing

In principle, when comparing procurement options for competing transformers, the total cost during the lifespan of the transformer, i.e. the TCO, should be taken into account. An optimal procurement process would aim to minimise the TCO by reflecting the expected operational costs inherent in the transformer design and intended usage profile on the same basis as the purchase price in the procurement decision.

The TCO consists of several components, some of which have a degree of uncertainty in their estimation:

- purchase price
- installation cost
- value of the energy losses
- maintenance costs
- decommissioning costs
- residual value of materials (copper, steel, aluminium).

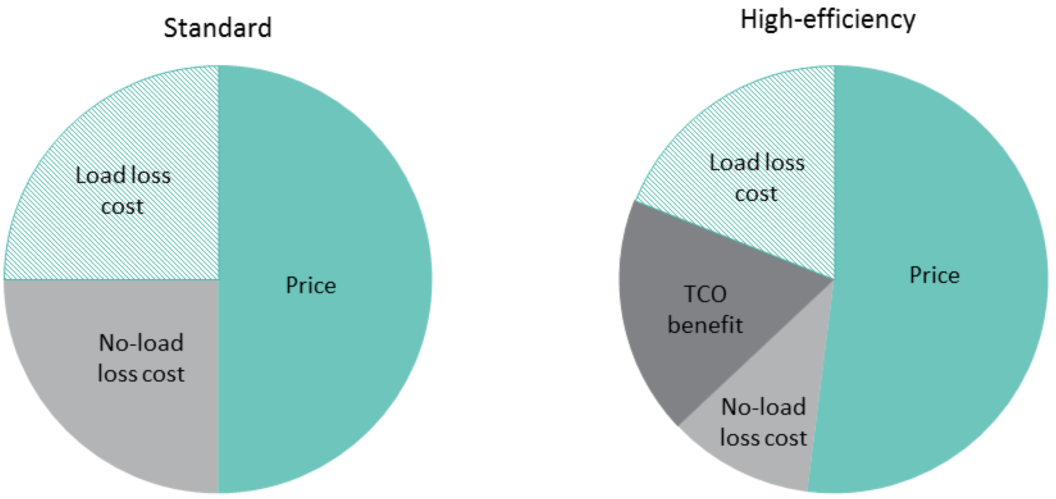
Except in the case of PCB-cooled transformers (see section 4.3), the last two elements are relatively insensitive to the type and design of the transformer and consequently are seldom taken into account. Purchase price and the value of energy losses are the two key factors that will affect the TCO. The installation cost will also become a factor, particularly for replacement units, if the transformer changes its physical dimensions or weight significantly.

It is worth considering just how important the value of the energy losses is to the TCO. Figure 3-2 illustrates that for a typical standard-efficiency silicon steel (SiFe) distribution transformer, the value of the losses is very similar to the purchase price. For an equivalent energy-efficient amorphous design the losses fall dramatically, giving TCO benefits of about 18%. The simple payback periods from investing in high-efficiency transformers are typically in the range of 2–5 years (UNEP 2011) for a product with an average service life of over 30 years, and hence for about 85% of the product service life there is a net profit on the investment (Figure 3-3). However, these figures are illustrative and actual TCO benefits from higher efficiency need to be assessed in the specific circumstances that apply to each procurement decision.

3.1.1 Calculating the total cost of ownership (TCO)

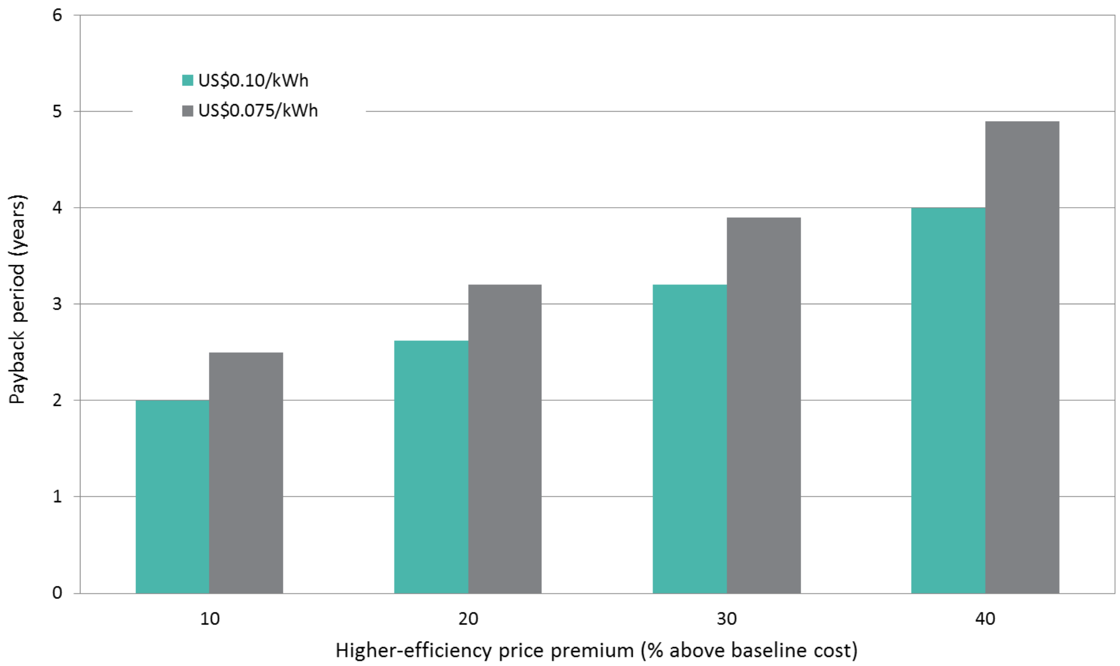
To include the total cost of losses in the purchase decision, a procurement manager calculates the annualised cost factors applied to the no-load loss and load losses (sometimes called the '*A* and *B* factors').

Figure 3-2. Distribution of total cost of ownership by key cost elements for a standard-efficiency distribution transformer and a high-efficiency distribution transformer.



Source: UNEP 2011.

Figure 3-3. Payback period for the purchase of high-efficiency amorphous distribution transformers compared to conventional technologies, as a function of electricity price.



Source: UNEP 2011.

These factors represent a discounted net present value (NPV) of future losses over the life of the transformer. They are multiplied by the tendered losses and added to the purchase price to yield the whole-life cost.

The NPV of losses (or total capitalised cost of the losses; TCC_{loss}) is calculated from the estimated average cost per kWh (C), interest rate (r) and the lifetime of the transformer in years (n), where E_{loss} is the total energy loss:

$$TCC_{loss} = E_{loss}\, C\, ((1 + r)^n - 1)/(r\, (1 + r)^n)$$

While the load profile over time and the future price evolution of energy is not known exactly, the use of trend-line values can give good estimates of the total cost of the losses.

When comparing similar technologies, the costs of installation, maintenance and decommissioning, for example, will not vary very much between different designs, so the equation can be simplified by leaving them out of the calculation. In this case the equation only includes the transformer purchase price and TCC_{loss}.

For such a simplified calculation of the TCO that takes into account only the purchase price and the cost of losses, one can use the base formula:

$$TCO = PP + A * P_0 + B * P_K$$

where:

- PP is the purchase price
- A is the assigned cost of no-load losses per watt
- P_0 is the rated no-load loss in watts
- B is the assigned cost of load losses per watt
- and P_k is the rated load loss in watts at full load.

P_0 and P_K are the transformer's rated no-load and load losses, respectively. The *A* and *B* factors vary according to a number of factors, including the expected loading of the transformer and energy prices. However, these factors both carry a degree of uncertainty, and interest rate and expected economic lifetime must also be taken into account. Thus, it becomes a challenging task to determine *A* and *B*. *A* will usually have a value of between €1.00 and €8.00 per watt and *B* will usually vary between €0.20 and €5.00 per watt.

Targosz et al. (2012) presented a reasonably straightforward way to calculate *A* and *B* for distribution transformers, using the formula:

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

for no-load loss capitalisation, and:

$$B = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \times C_{kWh} \times 8760 \times \left(\frac{I_l}{I_r}\right)^2$$

for load loss capitalisation, where:

- I = real interest rate (%/year), i.e. excluding inflation
- n = lifetime (years)
- C_{kWh} = value of the losses at mid life of the transformer (€/kWh), where inflation effects are not included, but non-inflation-related changes in price are accounted for
- 8760 = number of hours in a year (h/year)
- I_l = loading current (in amps)
- and I_r = rated current (in amps).

The assumption in these formulae is that both energy prices and loading remain static over the lifespan of the transformer and that the loss load factor is the load factor squared.

The transformer procurement manager must provide the *A* and *B* factors to the manufacturers when tendering the order. These factors will then influence the resulting transformer designs to offer the lowest TCO and optimum performance for that manager's network. The drawback of this process is the uncertainty around predicting the future load profile and electricity costs and tariffs. On the other hand, these optimisation efforts depend on material prices, particularly active materials, i.e. conductor and core material. Therefore, dynamic optimisation makes sense in the case of divergent price volatility of different materials such as aluminium and copper windings or high- and low-loss core material.

Targosz has proposed a schematic that can be used to more easily determine *A* and thereby make it easier to ascertain the TCO (Figure 3-4) (R. Targosz, personal communication, 2014).

A expresses the relation between the cost of no-load losses and:

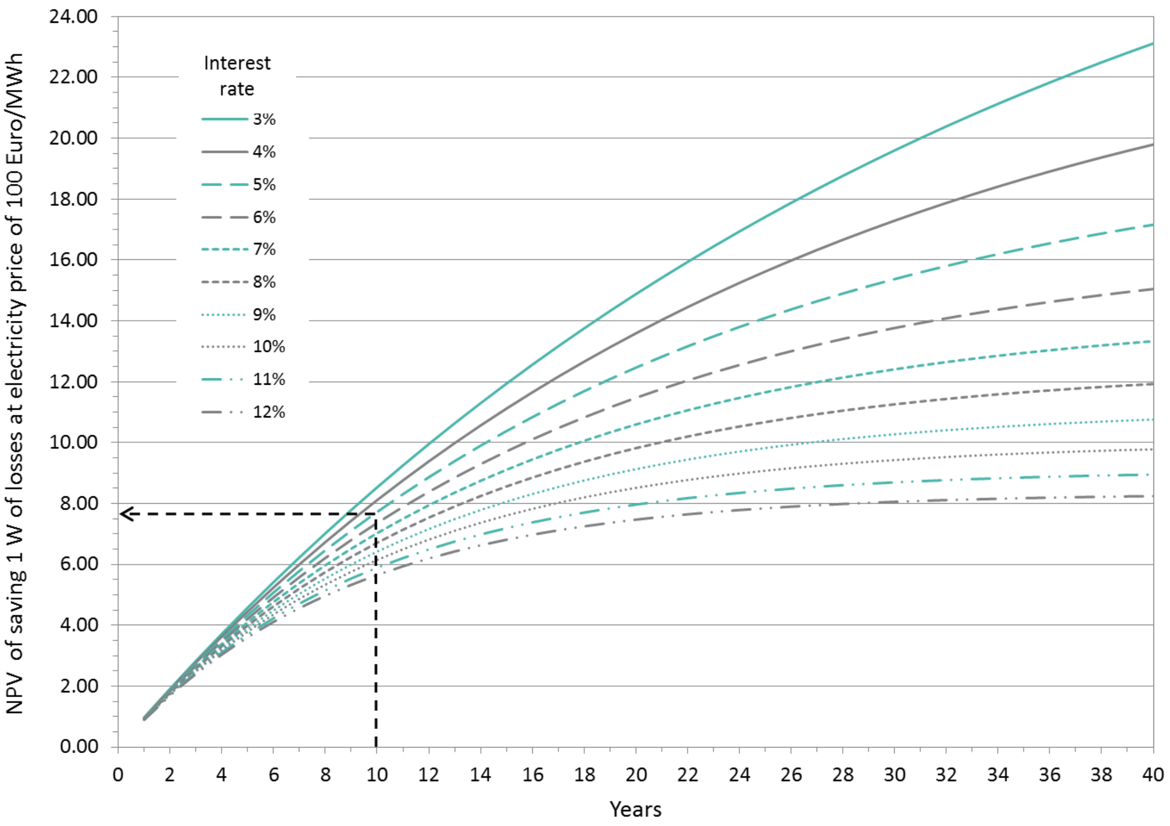
- electricity price
- discount rate, company interest rate or average cost of capital
- capitalisation period or expected lifetime of the transformer.

In Figure 3-4, with an interest rate of 5% and a capitalisation period of 10 years for an electricity price of €100/MWh, the NPV of the no-load losses (i.e. the '*A* factor') will be €6.75/watt.

Since *A* is directly proportional to electricity price, it can be scaled to account for changes in electricity price providing there are no changes in the interest rate or capitalisation period.

For small interest rates, however, the cost of losses will almost double with a doubling of the capitalisation period, whereas a low value of loss will result if the capital rate that is applied is too high (e.g. if risk provision is too high).

Figure 3-4. Simplified chart for calculation of *A* factor (€/watt).



Source: Kindly supplied by R. Targosz.

The '*B* factor' is calculated as the product of *A* and the square of the estimated loading factor, which represents the average load expected over the life of the transformer, possibly taking into account harmonics:

$B = A \times (\text{loading})^2$

The cost of losses also depends on voltage level and less strongly on rated power, location or transformer type. It should be noted that the NPV of losses may be higher if electricity prices are very high, interest rates are low and the lifetime is long.

Load losses depend on the load levels assumed. For distribution transformers this fraction is usually 15−20% of no-load loss costs (approximately 40% loading).

3.1.2 Determination of factors affecting the total cost of ownership

The TCO approach minimises the total investment over the lifetime of a transformer, enabling the utility or transformer procurer to maximise its energy savings at the lowest cost. However, the assessment will require a number of factors to be determined as a precursor to any tender specification, including the following.

1) At what cost should the lost energy be evaluated?

The utility must determine the opportunity cost ('cost of the foregone'), i.e. the value of the cost of supply (the cost of generation plus the cost of transmission losses to that point in the distribution network). This would yield a single value, but a more accurate assessment could be developed where a formula covers multiple costing or includes maximum demand charges. Similarly, separate costs could be attributed to the cost factors developed for no-load loss and load loss, respectively, to reflect the different costs associated with the generation mix for the two types of losses.

2) What is the load factor that should be applied?

The load factor used in the calculation will vary over time of day and time of year. It will also vary over the life of the transformer, with load growth or decline, depending on what is happening with the economy of the area being serviced. In general, transformer specifiers looking at distribution transformers will attempt to estimate the average load factor for the whole year and use that as the basis of their calculations. However, a more detailed analysis could be made in terms of monthly or even weekly loading if those data were available, to obtain a more accurate assessment.

3) What discount rate should be used for future investments?

The utility should use the same discount rate that it applies to all investment decisions it makes in its capital stock. Generally, the discount rate of a business tends to be higher than the social or societal discount rate. This is because a business includes the cost of raising the finance and also the opportunity costs of using these funds in other areas of the business that could yield a higher return. Accordingly, it is not uncommon, for a 20% discount rate (for example) to be used by a business, and yet the US DOE uses both a 3% societal discount rate and a higher 7% discount rate (representing typical business) when it assesses the impact of its regulatory measures on the national economy.

4) What interest rates should be applied to the capital purchase?

The interest rates used when financing a capital equipment acquisition should be linked to the interest rates paid on that capital, and typically the weighted-average cost of capital (WACC) is used as this represents the proportion and costs of equity and debt in the business. Depending on the status of the entity making the purchase, interest rates can be quite low, which would reflect a less risky investment.

Depending on the regulatory framework, the WACC to be applied by utilities may be determined by the regulator and is the return that the regulator will provide on an investment undertaken by the utility. However, when this parameter is unregulated it is likely that the level of interest rates assumed by utility capital expenditure managers will be different from those that a regulator might consider most appropriate.

3.2 Economic analysis of loss reduction

3.2.1 Rates of return on higher-efficiency transformers

Table 3-1 summarises losses, pricing, energy savings, payback periods and internal rate of return (IRR[13]) for a series of 400 kVA, three-phase, liquid-filled distribution transformer designs.

The details for the nine designs summarised in Table 3-1 were originally published in the *Final Report. Lot 2 – Distribution and Power Transformers, Tasks 1–7* (VITO 2011). The efficiency classes of the transformers range from a comparatively inefficient (i.e. 'baseline') design of DoCk to highly efficient designs that incorporate amorphous metal cores and low-loss copper windings.

The table shows that the payback period for purchasing a more-efficient transformer is considerably shorter than the expected transformer service life (usually greater than 30 years). If a customer decides to purchase an AoAk transformer in place of a DoCk unit, an IRR of 14% and a payback period of 7.8 years will be enjoyed. For the next 25+ years of service life, money will be saved.

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[13] IRR is defined as the discount factor at which present value of loss reduction over 25 years equals the investment premium in high-efficiency transformers.

Table 3-1. Energy savings and returns for high-efficiency 400 kVA, three-phase, liquid-filled transformers

Loss combination	No-load losses (W)	Load losses (W)[1]	Transformer price (€)	kWh used per year[2]	kWh savings per year	Value of savings[3] (€/year)	Payback period (years)	IRR (% over25 years)
DoCk	750	4600	6122	13 017				
CoCk	610	4600	6428	11 791	1226	86	3.6	39%
BoBk	520	3850	7285	9951	3066	215	5.4	22%
AoCk	430	4600	7102	10 214	2803	196	5.0	25%
AoAk	430	3250	8693	8322	4695	329	7.8	14%
ADMT-Ck[4]	196	4554	8632	8100	4918	344	7.3	15%
ADMT-Bk[4]	219	3898	10 040	7382	5635	394	9.9	10%
ADMT-Ak[4]	219	3324	10 714	6577	6440	451	10.2	10%
ADMT-Ak+[4]	216	2508	12 918	5407	7610	533	12.8	7%

Abbreviation: IRR = internal rate of return.

[1] Winding losses at 100% of rated capacity; [2] At 40% of rated load, assuming unit is loaded on average at 40% of rated capacity; [3] Based on the assumption of €0.07 per kilowatt-hour of electricity; [4] Design incorporating amorphous metal cores.

Source: Derived from VITO 2011.

It should be noted that even the most efficient design – which is twice as expensive on a first-cost basis – saves 7610 kWh per year and has a payback period of 12.8 years. The IRR for this unit is 7% and in fact the IRR is at least 7% for all the designs, achieving a maximum of 39%. Considering the relatively low risk of investing in an energy-efficient transformer, these economic facts should make efficiency attractive to commercial and industrial companies as well as utility grid operators. However, for some grid operators the rate structure may not provide an incentive to invest, as losses are most often simply passed through to the end user.

3.2.2 Economy-level economics

While minimising the TCO of a transformer should be the economic goal from the perspective of a utility or industrial purchaser, from a societal perspective other factors may need to be taken into account, such as the value of externalities. Furthermore, a longer-term perspective may be needed to assess the true economic value of the capital investment to society.

While the TCO is an appropriate metric for transformer procurers to use in assessing the procurement of individual transformers, at the national level it is appropriate to compare aggregate investment in transformer loss reduction to alternative electricity supply- and demand-side options. An economic analysis of transformer efficiency in APEC economies conducted by LBNL chose to use the cost of conserved energy (CCE) as its preferred metric because it allows easy identification of the largest energy savings that still provide a net savings to consumers (Letschert et al. 2013). The CCE represents how much an end user must pay in terms of annualised incremental equipment investment for each unit of energy saved through investment in higher-efficiency equipment. Calculation of the CCE first requires the definition of a baseline and target efficiency levels.

Calculating the cost of conserved energy

CCE divides annual incremental equipment cost by the energy saved in a year, which gives the investment needed per unit of energy savings (US$/kWh) as:

$\mathrm{CCE} = \Delta EC \times q / \Delta UEC$

where:

- ΔEC = incremental equipment cost between high-efficiency equipment and baseline technology (output from engineering analysis)
- ΔUEC = change in unit energy consumption (UEC), i.e. the annual energy savings kilowatt-hours.

The UEC is calculated from the load loss (LL), no-load loss (NLL) and transformer load β under field operating conditions (multiplied by the number of hours in a year) as follows:

- $UEC = (NLL + LL \times \beta^2) \times 8760$
- q = capital recovery factor, defined as:
- $q = d/(1 - (1 + d)^L)$

where:

- L = product lifetime, i.e. the average number of years that a product is used before failure and retirement (a constant lifetime of 32 years across all economies is used in the LBNL analysis)
- d = discount rate at which utility companies value their investments.

In the absence of country-specific data, the IEA's projected cost of energy generation discount rates of 5% and 10% (WEO 2010) were used for developed economies and economies in transition, respectively, in the LBNL analysis (Letschert et al. 2013).

Baseline efficiency definition

Derivation of the CCE requires knowledge of the 'baseline' efficiency of the typical technology that would be procured in the economy in question. If a country has mandatory MEPS in place (see Chapters 6 and 7), this can set the baseline efficiency level; however, if a country has never regulated distribution transformers, baseline efficiency information may be difficult to obtain. An analysis of the efficiency of distribution transformers in both China and the USA prior to their adoption of MEPS shows that the pre-programme baseline efficiencies for the two countries are very similar (Table 3-2) and hence these levels could serve as a reasonable first estimate for baseline efficiency levels in other countries that have not yet adopted MEPS and related policy measures.

Efficiency levels

The LBNL economic assessment of 20 APEC economies considers four distribution transformer types, known as 'design lines', that were originally defined in the US DOE's regulatory process as representative of the liquid-filled distribution transformer market (Letschert et al. 2013):

- DL 1: 50 kVA, single-phase, rectangular tank
- DL 2: 25 kVA, single-phase, round tank
- DL 4: 150 kVA, three-phase
- DL 5: 1500 kVA, three-phase.

Table 3-2. Estimated baseline efficiency in distribution transformers before first MEPS in China and the USA (at 50% load)

	Baseline efficiency			
	1-phase transformers		3-phase transformers	
	50 kVA	25 kVA	150 kVA	1500 kVA
China	98.5%	98.2%	98.5%	98.7%
USA	98.6%	98.2%	98.4%	98.9%

Source: Letschert et al. 2013.

Table 3-3. Distribution transformer efficiency level (EL) definitions by design line*

Efficiency level		DL1	DL2	DL4	DL5
EL0	Baseline	98.6%	98.2%	98.4%	98.9%
EL1	Intermediate level	98.82%	98.48%	98.74%	99.20%
EL2	US MEPS 2016	99.10%	98.95%	99.16%	99.48%
EL3	Intermediate level	99.30%	99.21%	99.38%	99.59%
EL4	Max. tech. 2013 rulemaking	99.50%	99.47%	99.60%	99.69%

* Design lines as per the US Department of Energy's regulatory process, representing liquid-filled distribution transformers: DL 1 = 50 kVA, single-phase, rectangular tank; DL 2 = 25 kVA, single-phase, round tank; DL 4 = 150 kVA, three-phase; DL 5 = 1500 kVA, three-phase.

Source: Letschert et al. 2013.

These transformer types are common around the world. A set of representative efficiency levels are defined as EL0 to EL4 (Table 3-3) for each of these design line types and are used to evaluate the potential for cost-effective savings in each economy and to facilitate comparison across economies.[14]

The findings of the LBNL analysis is summarised in Table 3-4. Collectively, the adoption of cost-effective distribution transformers triggered by the implementation of MEPS set at the most cost-effective efficiency level in terms of the CCE and endorsement labels would be expected to produce these outcomes:

- electricity consumption in 2011 = 8745 TWh
- T&D losses in 2011 = 601.0 TWh
- T&D losses = 6.9%
- distribution losses as a share of T&D losses = 26%
- distribution losses in 2030 = 158.9 TWh
- cost-effective electricity savings in 2030 through MEPS = 30.2 TWh
- electricity savings in 2030 through endorsement labels = 14.7 TWh
- average reduction in distribution losses = 26%
- cost-effective savings share of all distribution transformer losses = 28%.

The net discounted financial benefit of adopting such MEPS is US$18.5 billion in 2030 across these economies; however, this does not take account of the additional value of avoided CO_2 or other pollutant emissions.

3.2.3 Indonesia: a country case study

Indonesia was one of the economies assessed in this study and serves as a good example of the findings to be expected from such an aggregate national assessment. Table 3-5 summarises the input data developed for Indonesia. Table 3-6 presents the results for the four representative distribution transformer design lines considered. From this it can be seen that the average CCE through the adoption of efficient transformers is between US$0.05 and US$0.68 per kilowatt-hour, which is well below the US$0.12/kWh market price of electricity. The average efficiency of the cost-effective distribution transformers is between 0.7% and 1.5% higher than for the equivalent baseline model, which leads to energy losses of between roughly one-half and one-third of the baseline levels and a weighted-average reduction in losses of 63% for all the distribution transformer types (Table 3-7).

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[14] These efficiency levels correspond to the SEAD Tiers described in section 7.4.

Table 3-4. Estimated distribution losses and cost-effective savings potentials through the adoption of higher-efficiency distribution transformers in 20 APEC economies

	Annual impacts in 2030				Cumulative impacts 2016−30		Total net financial benefits (US$, millions)
	National distribution losses (GWh)	Energy savings (GWh)	Reduction	CO_2 emissions savings (Mt)	Energy savings (TWh)	CO_2 emissions savings (Mt)	
Australia	9402	2759	29%	2.3	21.5	18.1	1982
Brunei*	63	19	30%	0.0	0.1	0.1	43
Canada	10 058	1464	15%	0.3	11.4	2.1	463
Chile	3254	1248	38%	0.5	9.2	3.8	724
Hong Kong	586	95	16%	0.1	0.7	0.5	15
Indonesia*	7913	2361	30%	1.7	14.9	10.6	1634
Japan	15 492	2558	17%	1.1	20.5	8.6	1330
Malaysia	4516	1957	43%	1.4	14.7	10.7	2320
Mexico	6295	1434	23%	0.7	10.8	4.9	833
New Zealand	455	153	34%	0.0	0.3	0.2	152
Papua New Guinea*	156	47	30%	0.0	0.3	0.2	65
Peru	1646	392	24%	0.1	2.7	0.8	130
Philippines*	2230	665	30%	0.3	4.5	2.2	619
Russia*	22 031	6574	30%	4.2	47.2	30.1	3184
Singapore	814	243	30%	0.1	1.8	0.9	180
Republic of Korea	7354	1325	18%	0.7	10.0	5.4	514
Taipei*	4562	1183	26%	0.9	8.9	6.9	214
Thailand	4980	1491	30%	0.8	10.3	5.3	1066
USA	51 117	3138	6%	1.6	24.8	12.9	2604
Vietnam	4008	1107	28%	0.5	6.9	3.0	460
Total	**156 932**	**30 212**	**19%**	**17.3**	**221.5**	**127.3**	**18 532**

* Results subject to a sizeable uncertainty.

Source: Letschert et al. 2013.

Table 3-7 summarises the market shares and average market capacities used to scale the unit-level results to the national level. The table also includes the resulting scaled UEC and price inputs. When these savings are scaled up to the national level for Indonesia, the impacts shown in Table 3-8 in 2020 and 2030 are produced.

3.2.4 The real cost of transformer losses

Informative as CCE assessments are for national level assessments, they do not necessarily reflect the motivation and decision-making process of utility network businesses, the main procurers of distribution transformers. For these entities, the cost of losses may be a significant input for planning, design and operational activities, depending on how they are incentivised with respect to these losses. Even though the economic incentive to reduce the cost of losses is rarely sufficient to motivate a network augmentation project, it can change the relative ranking of alternatives. The cost of losses can also influence decisions on the timing of an augmentation project, if load growth is sufficiently moderate to permit this.

Table 3-5. Country-specific inputs summary for Indonesia in 2010

	Value
Total distributed electricity	160 TWh
Distribution transformer capacity	40 000 MVA
Stock	0.55 million
Average load factor	50%
Average capacity	73 kVA
Annual sales	17 400 units
Consumer discount rate	10%
National discount rate	5%
VAT	10%
Cost of electricity generation	US$0.12/kWh
CO_2 emission factor	0.709 kg/kWh
SO_2 emission factor	1.674 g/kWh
NOx emission factor	0.807 g/kWh
Labour cost	US$3/hour

Abbreviation: GDP = gross domestic product.

Source: Letschert et al. 2013.

Table 3-6. Cost-benefit analysis for representative design line units in Indonesia

	1-phase		3-phase	
	50 kA (DL 1)	25 kVA (DL 2)	150 kA (DL 4)	1500 kVA (DL5)
Efficiency rating (%)				
Baseline	98.5	98.0	98.3	99.0
Target	99.5	99.5	99.6	99.7
Losses (kWh/year)				
Baseline	3241	2225	11 292	69 046
Target	1139	911	4722	20 866
Price (US$)				
Baseline	776	419	1736	9988
Target	2001	1271	4882	34 164
CCE (US$)	0.061	0.068	0.050	0.053

Abbreviations: CCE = cost of conserved energy; DL = design line.

Source: Letschert et al. 2013.

As network infrastructure investment typically involves installation of new or replacement equipment with a lifespan of 30 years or greater, it is appropriate that the TCO of the investment is assessed over an equivalent period. From an economic perspective, the cost of the losses should be determined using the long-run marginal cost (LRMC) assessed over the period of investment analysis. It is important when deriving this to ensure that the losses associated with the operation of electrical equipment are considered separately for no-load losses and load losses. This is because no-load losses are relatively constant and independent of the loading on the equipment, whereas load loss varies as the square of current passing through the equipment (Colebourn 2011).

Table 3-7. Market shares and market average UEC and price for design lines (DL) in Indonesia*

	DL 1	DL 2	DL 4	DL 5
Market share (%)	24.9	68.3	4.6	22.0
Average capacity (kVA)	46	26	256	1451
Scaled UEC (kWh/year)				
Baseline	3053	2281	16 837	67 346
Target	1073	934	7040	20 353
Scaled price (US$)				
Baseline	731	430	2589	9742
Target	1885	1303	7279	33 323

Abbreviation: UEC = unit energy consumption.

* Design lines as per the US Department of Energy's regulatory process, representing liquid-filled distribution transformers: DL 1 = 50 kVA, single-phase, rectangular tank; DL 2 = 25 kVA, single-phase, round tank; DL 4 = 150 kVA, three-phase; DL 5 = 1500 kVA, three-phase.

Source: Letschert et al. 2013.

Table 3-8. National impacts analysis results for Indonesia in 2020 and 2030

	Year	MEPS scenario	Labelling programme scenario
Annual impacts			
Energy savings (GWh)	2020	454.0	181.6
	2030	2361.0	1104.0
CO_2 emissions savings (Mt)	2020	0.3	0.1
	2030	1.7	0.8
SO_2 emissions savings (kt)	2020	0.8	0.3
	2030	4.0	1.8
NOx emissions savings (kt)	2020	0.4	0.1
	2030	1.9	0.9
Cumulative impacts			
Energy savings (GWh)	Through 2020	1267.0	466.3
	Through 2030	14 917.0	6675.7
CO_2 emissions savings (Mt)	Through 2020	0.9	0.3
	Through 2030	10.6	4.7
SO_2 emissions savings (kt)	2020	2.1	0.8
	2030	25.0	11.2
NOx emissions savings (kt)	2020	1.0	0.4
	2030	12.0	5.4
Operating cost savings (US$, millions)		2186.8	1014.2
Equipment cost (US$, millions)		553.2	259
NPV (US$, millions)		1633.6	755.2

Abbreviations: MEPS = minimum energy performance standard; NPV = net present value.

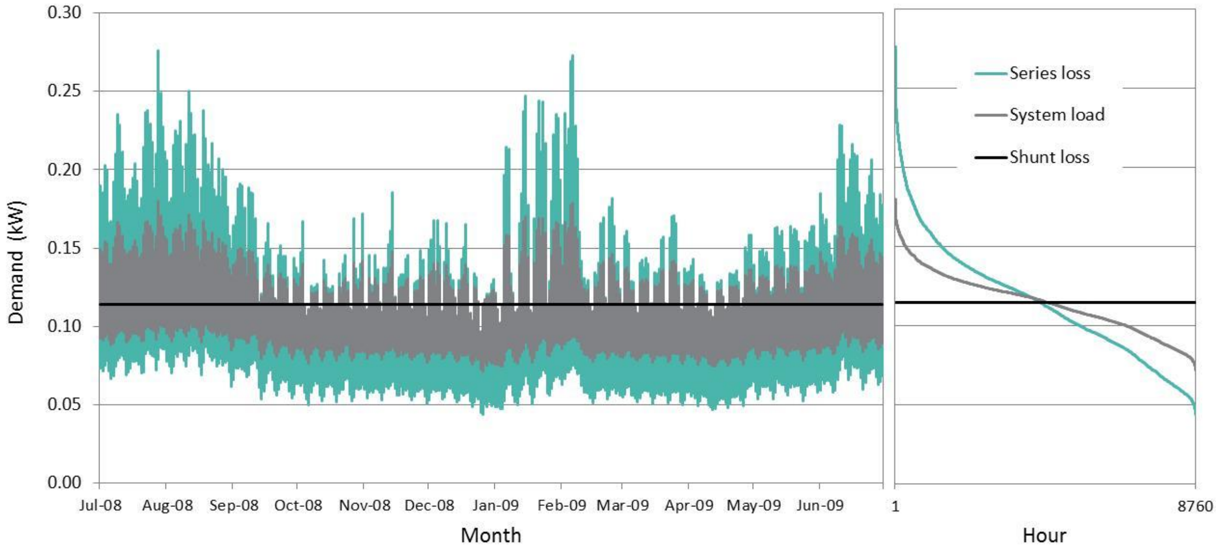
Source: Letschert et al. 2013.

An example is now presented for the electricity network of New South Wales, Australia, with the major components of the cost of losses being assessed on this basis. Figure 3-5 illustrates the half-hourly demand associated with load and no-load losses, compared with the demand profile of the average system load in the New South Wales region of the National Electricity Market for the year 2008/09. The three load and loss profiles are scaled for a normalised consumption of 1 MWh per annum. The blue trace represents the system load, the constant black trace the no-load-loss profile and the red trace the load-loss profile. This illustration serves to highlight how these very different load profiles affect the peak period demand, with a constant quantum of delivered energy. The annual load duration curves on the right-hand side of Figure 3-5 further highlight the comparison.

Considering the very different consumption profiles and influence on peak demand of the load and no-load losses shown in Figure 3-5, it is clear that the cost of both energy generation and network delivery are affected quite differently. Therefore, any credible LRMC assessment of their value will need to analyse them distinctly.

The cost of losses can and should be considered at different points in the network, but these also need to consider the future costs rather than those of the past. Colebourn presented the past (Table 3-9) and future costs (LRMC; Table 3-10) of losses at the generation (wholesale) level for the New South Wales electricity market. When these are compared with the forecast costs of losses

Figure 3-5. Profile of system demand and losses in the New South Wales region of the Australian National Electricity Market for 2008/09.[15]



Source: Colebourn 2011.

Table 3-9. Wholesale energy costs of supply (AU$/MWh) in New South Wales, Australia

Load profile	No-load loss	System load	Load loss
Wholesale cost of supply (2008/09)	$39.80	$43.80	$48.40
Forecast cost of supply (2020 forecast)	$80.80	$90.90	$92.40

Source: Colebourn 2011.

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[15] National Electricity Market consumption and price data are available from the AEMO website at http://www.aemo.com.au/Electricity/Data

over the long run (see Table 3-10) it is clear that the future value of the losses, which is the sensible basis on which to make an investment for capital equipment with a 30+ year lifespan, is projected to be more than double the recent historic costs.

Furthermore, the value of these losses is greater than the LRMC of supply for all supply options except clean coal and renewables, which indicates that their reduction should receive precedence in investment planning compared to conventional supply options (Table 3-11).

Table 3-10. Long-run marginal cost (LRMC) of new-generation technologies to be introduced in 2020 in New South Wales, Australia

Technology	Capacity factor	LRMC	
		Excluding CPRS (AU$/MWh generated)	Including CPRS (AU$/MWh generated)
CCGT	85%	57	74
PCGT	15%	156	183
Coal	85%	48	77
Geothermal	85%	78	78
Advanced coal[1]	85%	67	79
Nuclear	85%	98	98
Wind	30%	105	105
Biomass	85%	113	113
Large solar[2]	30%	268	268
Small solar photovoltaic[3]	20%	522	522

Abbreviations: CCGT = combined-cycle gas turbine; CPRS = Carbon Pollution Reduction Scheme; OCGT = open-cycle gas turbine; PCGT = pressurised-cycle gas turbine.

[1] Advanced coal = ultra-supercritical coal and integrated gasification combined cycle; [2] Large solar = solar collector or solar thermal; [3] Small solar = roof-top solar photovoltaic.

Source: Colebourn 2011.

Table 3-11. Long-run marginal cost (LRMC; AU$) of losses within networks in 2020 in New South Wales, Australia

Distributor	No-load loss	System load	Load loss
Market price	38.90	42.80	47.30
Generation LRMC	80.80	90.90	92.40
Metropolitan LRMC			
Transmission connection point	88.10	99.10	106.00
Subtransmission	103.00	116.00	133.00
High voltage	107.00	120.00	138.00
Low voltage	139.00	155.00	196.00
Regional LRMC			
Transmission connection point	94.40	106.00	117.00
Subtransmission	102.00	115.00	131.00
High voltage	135.00	151.00	190.00
Low voltage	172.00	193.00	259.00

Source: Colebourn 2011.

While Table 3-9 compares the value of losses experienced at the wholesale energy market level the value of the losses increases further down the electricity network as the magnitude of the losses increases. Table 3-11 illustrates how the cost (or value) of these losses increases when moving from the market price to LRMC at generation level, at metropolitan level and at regional network level.

The key lessons are that the cost of load losses needs to be determined using forward-looking LRMC analysis, that this needs to treat the load and no-load losses separately and that the cost of losses needs to be determined and evaluated at each point in the network in order to understand true values in network planning determinations.

3.3 Upgrading and adding value

Up to now the discussion on transformer economics in this report has focused on the process being followed during the procurement of a transformer, triggered either due to the addition of capacity in an existing system or because of the need to replace an old transformer. In fact, since transformers have no moving parts, their functional lifespans can be remarkably long. Nonetheless, transformers do fail, perhaps as a result of an external event such as a lightning strike or as a result of overloading or corrosion and chemical changes usually related to the insulation producing a short circuit. However, there are also cases where it makes economic sense to replace or upgrade an old transformer while it is still operational.

If reliability were the only criterion, then rewinding or repairs would be a viable option; however, economic and environmental best practice considers other criteria as well, of which energy efficiency is the most important. Traditionally there have been six reasons why early retirement of a transformer might be undertaken (based on De Wachter 2007):

- to improve energy efficiency
- to improve the reliability of supply (e.g. to prevent the failure of a poorly performing unit)
- in response to a change in the load profile
- in response to a change in voltage levels
- to comply with environmental or fire and safety regulatory requirements
- transformer nearing its end of life as a result of measured parameters (e.g. acidity of oil).

With the advent of smart grids, however, the need to upgrade equipment to allow for smart and more flexible operation of the electricity network can be added to this list and is also an opportunity to address transformer energy performance.

3.3.1 Best-practice replacement cycle

Financially speaking, the best time to replace a distribution transformer will take into account not only the cost of energy losses, failure risk and maintenance, but also the investment cost, the residual value of the transformer when it is taken out of service (assumed to be zero plus the scrap value of the material) and the value of functional changes if smart-grid capability is to be added. The optimal replacement cycle can be determined by calculating the equivalent annual cost (EAC) of the transformer and searching for the minimum.

For the EAC, all cost components are recalculated to the present monetary value, taking into account an annuity factor (AF), which should be based on a carefully chosen discount rate. This AF can then be calculated (De Wachter 2013):

$$AF\ (i,n) = \frac{1-\frac{1}{(1+i)^n}}{i}$$

where:

- *i* = annual discount rate
- *n* = number of years in the life cycle of the transformer.

The EAC of a transformer has two main terms.

(i) A cost term that decreases with increasing life cycle, namely:

$$\frac{(new\ tranformer\ investment\ cost)}{AF(i{,}n)*n}$$

The longer the replacement cycle, the more the investment can be spread over the entire period and the lower its influence on the annual cost will be.

(ii) A second cost term which increases with increasing life cycle, namely:

$$(average\ annual\ running\ cost) - \frac{(old\ transformer\ residual\ value)}{AF\ (i{,}n)*n}$$

Since the energy losses, maintenance costs and failure risks are likely to be higher for older transformers, the average annual running costs are likely to be higher. The residual value of the transformer appears as a negative cost and consequently also increases with age.

The minimum EAC for a transformer will occur at a life-cycle length *n* where the increasing and decreasing parts of the equation are equal to each other.

Transformer vendors and manufacturers will be more than willing to help calculate the transformer investment cost. Transformer manufacturers generally bid competitively for a contract, and these quotes can include the value of losses. If a repair scenario is being considered, the repair cost should be added to the investment cost.

The residual value of an old transformer is slightly more difficult to calculate. A precise calculation can be complex, but a good approximation can be made by multiplying the weights of copper and steel in the transformer with copper and steel prices. The price of copper is very unpredictable, making long-term predictions difficult, but it can be enough to make a reasonable 1-year prediction.

The most difficult term to estimate is the average annual running cost, the main components of which are energy losses, maintenance cost and reliability penalty.

3.3.2 Cost of energy losses

The annual cost of energy losses comprises (i) no-load losses and (ii) load losses.

The cost of annual no-load losses (also called 'iron losses') is the easiest to calculate. The power of these losses is listed in the transformer's data sheet and is multiplied by 8760 (the number of hours in a year) and by an average base generation electricity price to obtain the cost of energy losses.[16]

Load losses (also called 'copper losses') are more complicated, requiring an accurate estimate of the transformer's loading and loading time. It would be easier to calculate with an average load, but since load losses are not linear to the load and instead vary by the square of the load current, this is inadvisable. For example, in the case of a transformer with rated copper losses of 8 kW at nominal load, the figure is reduced to 0.25 × 8 kW = 2 kW at half the load. Consequently, 1 hour at full load and 1 hour at standstill results in 8 kWh of load losses, while 2 hours running at half the load results in only 4 kWh of losses.[17]

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[16] Some utilities may use fewer hours but concentrate on the losses incurred at peak times, when generation costs are high. The choice of average base generation electricity cost or peak lopping cost can have a very large impact on the calculation.

[17] This is also the reason why, during the design or purchase phase of the transformer, it is better to overestimate than to underestimate the load. For more on the energy efficiency of transformers, see Appendix 2.

Ideally, the exact load profile would be calculated over the entire year; however, in most cases this is difficult to predict. An acceptable alternative is to estimate the number of hours in a year that the transformer will work at or near a certain percentage of loading. For example:

- *A* hours unloaded
- *B* hours around 25% of the rated full load
- *C* hours around 50% of the rated full load
- *D* hours around 75% of the rated full load
- *E* hours at the rated full load.

The resultant calculated load losses should then be multiplied by the electricity cost, to give the annual cost of load losses.

While load losses are not always rated as such on the data sheet, the nominal power (e.g. 1000 kVA), no-load losses (e.g. 2 kW) and overall efficiency at nominal load (e.g. 98%) generally are. Load losses at nominal load can then be derived by first calculating the total losses at nominal load ([(1 − 0.98) × 1000 kVA] = 20 kVA) and then deducting the no-load losses (20 kVA − 2 kVA = 18 kVA) (De Wachter 2013).

The losses detailed on the transformer rating plate are valid at nominal frequency (50 or 60 Hz), but many loads draw 'harmonic currents' (small parts of the main current that have higher frequencies). Harmonic currents increase a transformer's load losses: a conservative estimate is to add 10% to the load losses for the average load mix in T&D networks, but the load losses can be much higher for transformers connecting premises with a high share of inductive loads.

3.3.3 Utility behaviour towards upgrades

Despite the existence of an economic incentive for some utilities to upgrade transformers, in practice this seldom happens without the additional motivation of the necessity to, for example, increase capacity or functionality. Transformer upgrades have been avoided by some utilities through the use of targeted demand-side management efforts (T. Kraft-Oliver, Chief Technology Innovation Officer at Bonneville Power Administration, personal communication 2011). Overall, the stance taken is to use capital elsewhere as long as the transformer is functioning. However, smart-grid features are becoming more important in transformer markets and regulatory developments sometimes motivate an upgrade; in China, for example, a regulation is being adopted for all transformers to be 'smart' after a certain date, i.e. a monitoring system (including sensors and protection) will be embedded in the transformer. This may create a driver for old transformers to be upgraded as well.

4. Environmental and social aspects

Key messages

- Avoiding pollution associated with power generation has a tangible value for the economy, and hence the value of environmental externalities should be factored into all infrastructure planning, including the electricity network.
- The average external cost for the world's generation mix has been estimated to be US$0.05/kWh. The projected losses in distribution transformers of 1050 TWh in 2035 would therefore represent additional externality costs of US$53 billion, which would add almost an additional 80% compared to the wholesale price value of the losses under 2011 prices.
- The EU has had an emissions cap and trade scheme, known as the EU Emissions Trading System (ETS), in place since 2005 that imposes emissions caps on major emitters including electricity generators; however, the emissions caps only apply to generators and hence do not reflect the CO_2 value of losses in the transmission and distribution of electricity.
- As a result of their high material value, there is a natural market in the recycling of transformers at their end of life. However, toxic polychlorinated biphenyls (PCBs) were used as a cooling fluid in electrical transformers for nearly 50 years and hence need to be actively eliminated through accelerated retirement, safe disposal and replacement of those old transformers containing PCBs.

4.1 The value of externalities

Sections 3.1 and 3.2 demonstrated that reducing transformer losses provides TCO benefits to the owner of the transformer and to the economy as a whole. However, the true cost of energy, and therefore the value of loss reduction, should take account of the cost of externalities such as pollutants and of the whole product life cycle, including its end-of-life treatment and its materials. Factoring these in can make a large difference to the assessment of the cost-effectiveness of different loss-reduction options.

These externalities principally originate from the various types of emissions resulting from the combustion of fossil fuel. Apart from CO_2, the main pollutants are SO_2 and NOx, which contribute to the acidification of the environment and poor air quality. The average external cost for the world's generation mix has been estimated to be US$0.05/kWh (UNEP 2011; Table 4-1).[18] Thus the projected losses in distribution transformers of 1050 TWh in 2035 (see Table 1-6) would represent additional externality costs of US$53 billion, which would add almost an additional 80% compared to the wholesale price value of the losses in 2011. A 30% saving in these losses through higher-efficiency distribution transformers would therefore bring a reduction of US$16 billion in environmental cost by 2035.

Colebourn (2011) analysed the expected impact that the value of the then proposed Australian Carbon Pollution Reduction Scheme (CPRS) would have on the forecast wholesale value of losses (Figure 4-1) and found that its inclusion combined with the future effects of the Mandatory Renewable Energy Target (MRET) and network upgrades roughly doubled the evaluated cost of the losses

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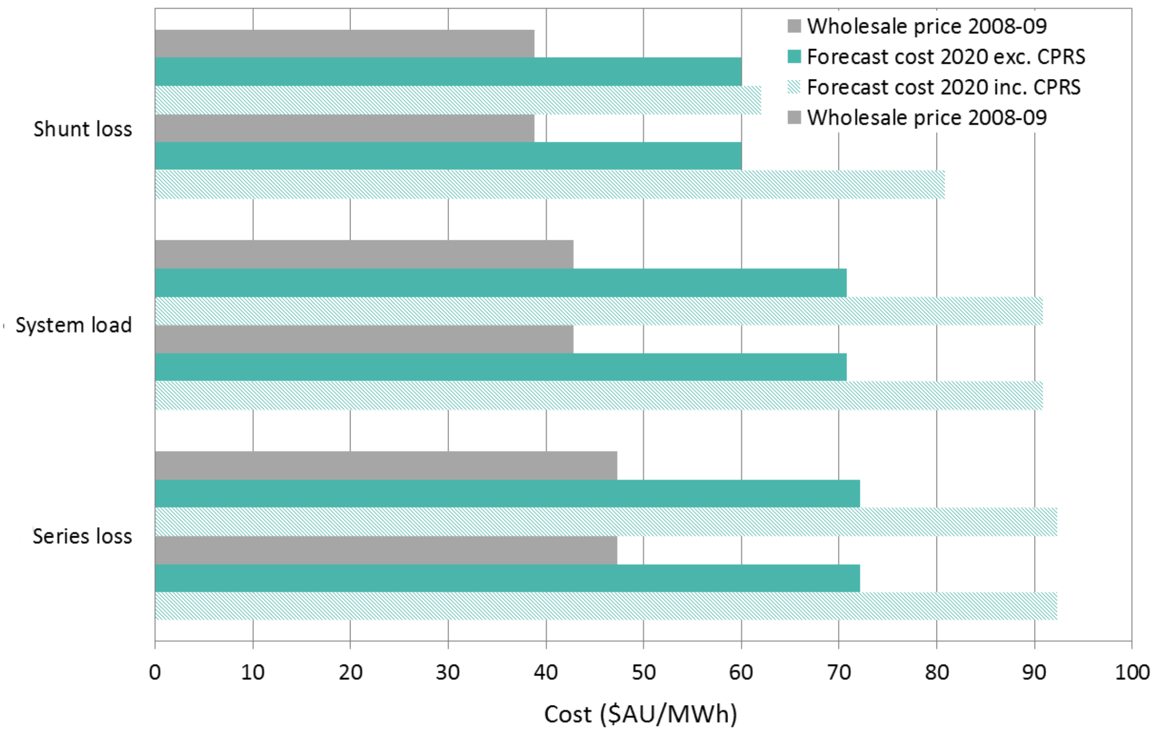
[18] There is a very wide range in estimates for external costs reflecting, for example, political preferences or the use of different technologies for power generation. For this reason, the use of external costs for energy policymaking has been limited so far.

Table 4-1. Cost of externalities from world electricity generation, based on 63 studies

Fuel	External cost (US$/kwh)	Part of generation (%)	Contribution (US$/kwh)
Coal	8.3	39	3.2
Oil	11.6	8	0.9
Gas	3.8	17	0.6
Nuclear	1.0	17	0.2
Hydro	0.3	17	0.1
Renewable	0.3–2.9	2	0.0
Total		100	5.0

Source: UNEP 2011.

Figure 4-1. Comparison of 2008/09 wholesale energy market costs with forecast costs (AU$).



Source: Colebourn 2011.

compared to the recent past. The inclusion of the CPRS alone added slightly less than half of the incremental cost.

While this scheme was not ultimately adopted in Australia, the EU has had a similar emissions cap and trade scheme, known as the EU Emissions Trading System (ETS), in place since 2005. This imposes emissions caps on major emitters; however, in the generation sector these caps only apply to generators and hence do not reflect the CO_2 value of losses in the T&D of electricity. In cases where specific regulatory investment approvals use cost/benefit assessments, the benefits of avoided CO_2 should be factored in to utility investment decisions. In cases where incentive-based mechanisms are applied by the regulator, the investment decision is made by the network planner, who should look at minimising total system costs, including loss-procurement costs (and thus also CO_2 costs). As a result, the EU ETS provides some, but not all, network operators additional incentive to reduce losses. When utilities are required to buy back losses from the market (as in France or Belgium), CO_2 costs will automatically be accounted for.

4.2 Overall environmental balance of distribution transformers

The environmental impact assessment carried out with the EcoReport tool for the EU Ecodesign ENTR Lot 2 study on transformers found that for each base-case model considered, the use phase is the life-cycle stage with by far the most impact in terms of energy consumption, water consumption, greenhouse gases emissions and acidification (VITO 2011). The production phase had a significant contribution to the generation of non-hazardous waste, volatile organic compounds, persistent organic pollutants, polycyclic aromatic hydrocarbons emissions and eutrophication.

The end-of-life phase had significant impacts for the generation of hazardous waste, particulate matter emissions and eutrophication, on account of either mineral oil or resin. Indeed, the end-of-life modelling used the same environmental data as for plastics incineration (environmental impacts and credits), yet burning mineral oil with energy recovery is expected to be more efficient than burning plastics with energy recovery. The Ecodesign assessment therefore concluded that analysis of the improvement potential should focus on technologies that reduce electricity losses during the use phase.

4.3 Materials and recycling

For power and distribution transformers, recycling has limited impact on overall environmental performance since electricity losses over the lifetime of the transformer represent over 99% of the product’s environmental impact. Nonetheless, recycling is important from a material resources availability perspective as the materials used in the transformer are quite energy and resource intensive to produce and have a high resale value. Given this, it is likely that almost 100% of transformers are recycled at their end of life.

A large portion of a transformer’s cost is comprised of its material costs, and hence transformers have significant scrap value. A large proportion of the materials recovered from transformers are copper, silicon steel, steel and oil; however, the scrap value of the transformer to the owner will be lower than the value of the secondary materials delivered to copper or steel plants on account of costs and mark-ups in the collection and recycling supply chain.

The safe disposal of PCBs during the recovery and recycling process is a key concern (section 4.4).

4.3.1 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.[19]

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[19] 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.

4.4 Non-technical losses

Technical losses can comprise up to 12% of system losses, but whenever the figures are higher they are invariably a result of non-technical losses and primarily theft (Smith 2004). Non-technical losses include:

- electricity theft
- invoicing errors
- bankruptcy of clients
- measurement errors.

Electricity theft is a social problem and is hard to solve, since it addresses a large portion of the population in certain countries. It is not the subject of the current report, which addresses technological solutions to increase efficiency, but care should be taken to distinguish between technical and non-technical losses when interpreting loss figures.

Electricity theft and inadequate billing are significant contributors to losses in the Indian subcontinent, some parts of Latin and Central America/the Caribbean, parts of the Balkans, Central Asian countries and some African and Middle Eastern countries (EIA 2014).

5. Business aspects

Key messages

- In the large majority of cases, energy-efficient transformers offer the customer a positive payback period of reasonable length, and cumulative net savings from investing in efficiency increase substantially with higher electricity prices.
- A worked example shows how a distribution network operator procuring 20 000 transformers would need to make a net investment for the first 2 years, but thereafter the savings from the installed units offset the capital required for the incremental investment in 500 more-efficient transformers. By 2025, the operator will have saved (cumulatively) over €10 million and will be actively lowering their total running costs overall, even though the efficient transformer is 64% more expensive than the baseline unit previously purchased.
- Good asset management practice also finds that in some cases it is less costly to replace an old, inefficient transformer than to continue to operate it. Therefore good asset management practice should actively evaluate the cost/benefit trade-offs from early retirement of outdated assets.
- Good asset management includes understanding and accurately forecasting load growth as well as monitoring it, so that the electricity network achieves its societal objective of being robust, reliable and efficient.

This chapter examines the business case for investing in energy-efficient transformers, focusing on the commercial and industrial markets – purchasers of both liquid-filled and dry-type distribution transformers.

5.1 Impact of purchasing energy-efficient transformers

The simplest way to look at investment in an energy-efficient transformer is to consider the payback period, which is defined in years and is calculated by dividing the transformer price premium by the value of annual energy savings. To start with a tangible example, consider the following example of a 150 kVA, three-phase, liquid-filled distribution transformer (Table 5-1). Payback periods are calculated for an installation with 50% of rated load on this transformer and €0.10 per kWh of electricity. The example considers the performance of a baseline transformer and five more energy

Table 5-1. Simple payback periods for SEAD Tiers 1–5, 150 kVA, liquid-filled, three-phase distribution transformers

Transformer	Efficiency (%)[1]	Price difference (€)	UEC (kWh/year)[2]	UEC savings (kWh/year)[2]	Savings value (€/year)[3]	Payback period (years)
Baseline	98.27		11 366			
SEAD Tier 1	98.77	639	8069	3297	330	1.9
SEAD Tier 2	98.97	1042	6780	4586	459	2.3
SEAD Tier 3	99.10	1461	5881	5485	548	2.7
SEAD Tier 4	99.25	2063	4942	6424	642	3.2
SEAD Tier 5	99.36	2681	4203	7163	716	3.7

Abbreviation: UEC = unit energy consumption.

[1] At 50% of the rated load; [2] UEC considers continuous, year-round operation; [3] Calculated on a basis of €0.10/kWh on the commercial- and industrial-customer side of the meter.

efficient alternatives, each meeting one of the five SEAD tiers (see Chapter 7). The difference in price between units is shown in the table, as are the annual energy savings, the value of the savings and the payback periods.

This table shows that for a market where transformers are neither evaluated nor regulated, and utilities are purchasing a 98.27%-efficient, 150 kVA, three-phase liquid-filled transformer, substantial energy savings and associated short pay-back periods may be achieved through adopting the SEAD tiers. In Tier 3, for example, the incrementally higher cost of €1461 relative to the baseline will yield €548 of annual operational savings, resulting in a payback period of 2.7 years. For a transformer that will last for more than 30 years in service, this offers an excellent investment option for businesses.

5.1.1 Payback time for a single transformer

To clearly illustrate the value proposition of investing in more energy efficient transformers, this subsection compares the TCO for 150 kVA, three-phase, liquid-filled distribution transformers at two levels of performance – baseline and SEAD Tier 3. Figures 5-1, 5-2 and 5-3 present the cumulative costs of these two transformers from 2015 to 2040, incorporating a 7% discount rate in the analysis and considering three different electricity cost scenarios:

- stable business, steady demand – purchase price of €0.05/kWh
- restricted supply, fully loaded network – purchase price of €0.15/kWh
- variable electricity pricing – high price of peak coincident demand, averaging €0.27/kWh.

Figure 5-1 presents the stable business scenario, where the customer purchasing and owning the distribution transformer pays €0.05 per kilowatt-hour. For this scenario, the purchase price differential of €1461 is paid back in Year 5 and from that point on a profit is earned. By 2025, the SEAD

Figure 5-1. Stable business scenario: total cost of ownership (TCO) for a SEAD Tier 3, 150 kVA, three-phase, liquid-filled transformer compared to baseline, from 2015 to 2040.

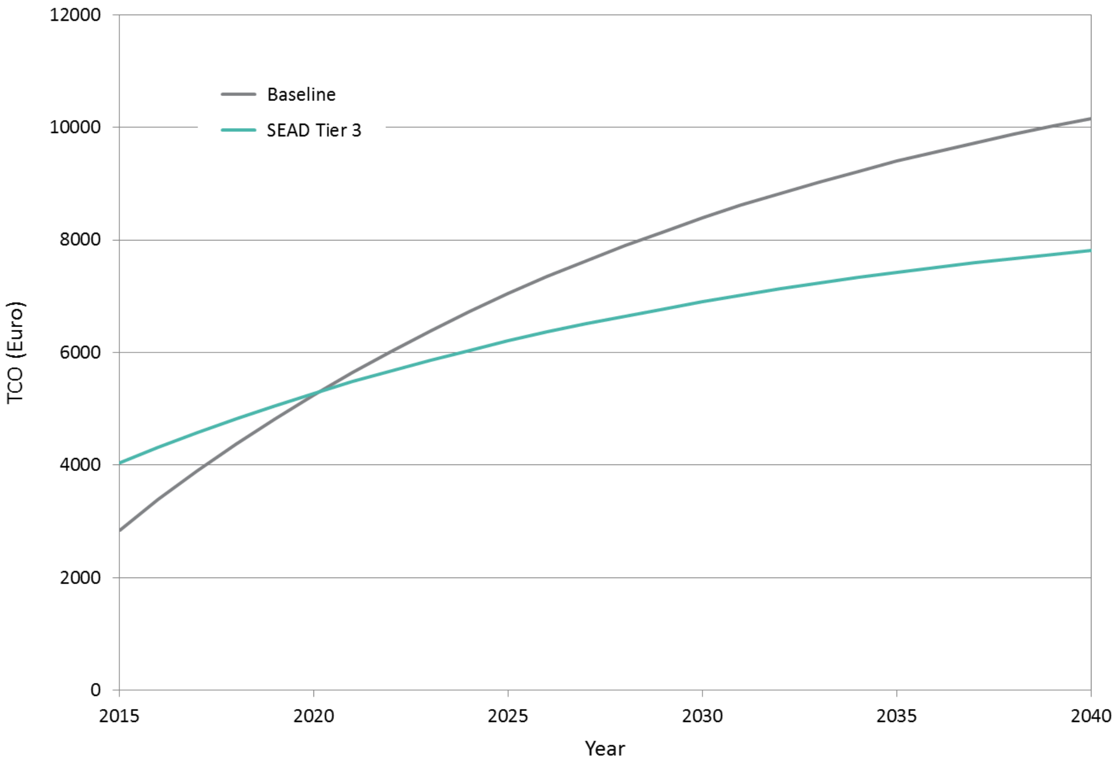
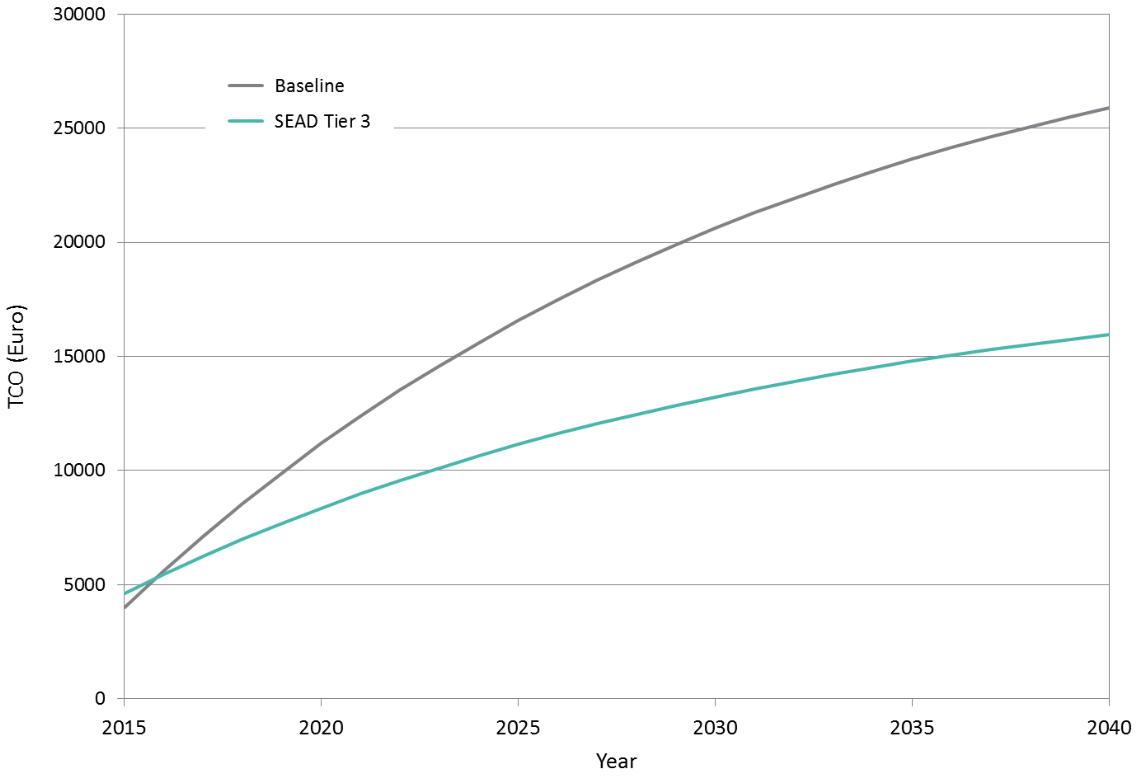


Figure 5-2. Restricted-supply scenario: total cost of ownership (TCO) for a SEAD Tier 3, 150 kVA, three-phase, liquid-filled transformer compared to baseline, from 2015 to 2040.



Tier 3 transformer has yielded a net discounted savings of €838 relative to baseline; savings continue to increase over the analysis period, reaching a discounted net saving of €2339 in 2040 – exceeding the initial incremental investment.

Figure 5-2 presents the restricted-supply scenario, where the customer purchasing and owning the distribution transformer pays €0.15 per kilowatt-hour. For this scenario, the purchase price differential of €1461 is paid back in Year 2 and from that point on a profit is earned. By 2025, the SEAD Tier 3 transformer has yielded a net discounted savings of €5435 relative to baseline; savings continue to increase over the analysis period, reaching a discounted net saving of €9939 in 2040 – more than five times the initial incremental investment.

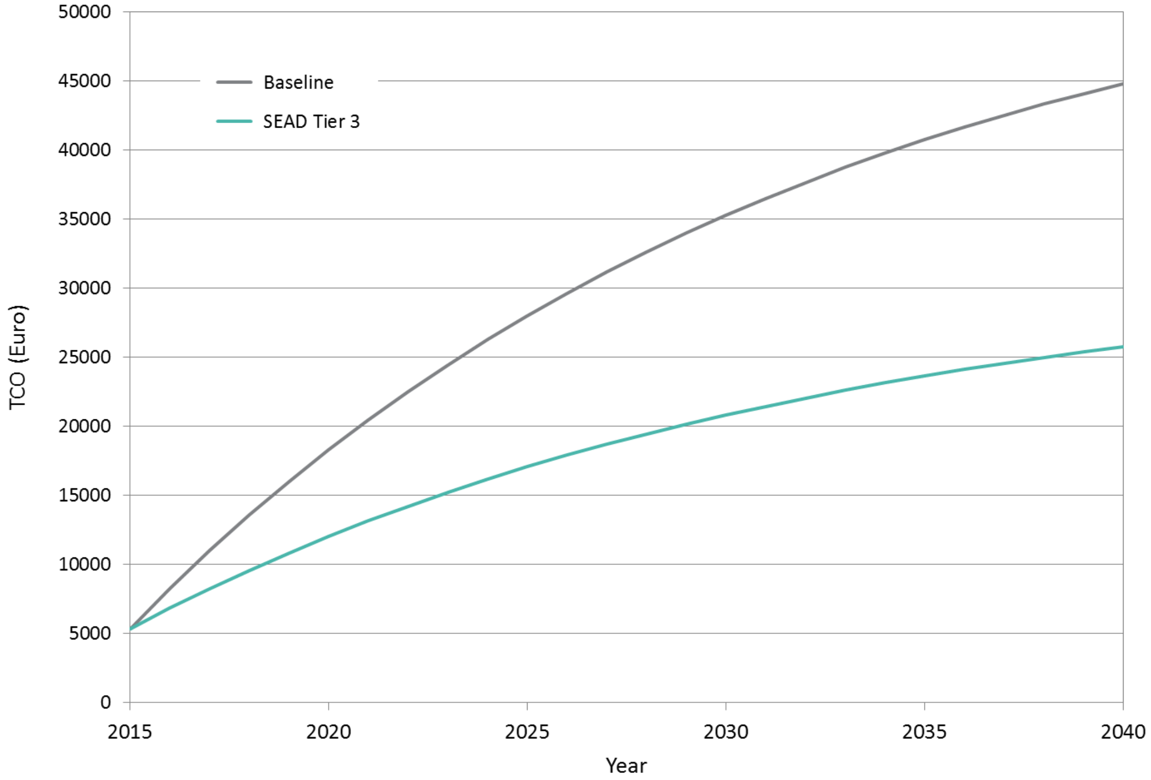
Figure 5-3 presents the variable electricity pricing scenario, where the customer purchasing and owning the distribution transformer pays €0.27 per kilowatt-hour. For this scenario, the purchase price differential of €1461 is paid back in the first year and from that point on a profit is earned. By 2025, the SEAD Tier 3 transformer has yielded a net discounted savings of €10 951 relative to baseline; savings continue to increase over the analysis period, reaching a discounted net saving of €19 059 in 2040 – more than ten times the initial incremental investment.

In all scenarios, the energy-efficient transformer offers the customer a positive payback period of reasonable length, and cumulative net savings from investing in efficiency increase substantially with higher electricity prices.

5.1.2 Business model for a distribution transformer network

A larger business model scenario is considered, considering cash flow of a company that manages 20 000 transformers. In this scenario, the company is paying €0.10/kWh and gradually replaces its existing stock of transformers with energy-efficient models over a period of 40 years (i.e. 500 units

Figure 5-3. Variable electricity pricing scenario: total cost of ownership (TCO) for a SEAD Tier 3, 150 kVA, three-phase, liquid-filled transformer compared to baseline, from 2015 to 2040.



purchased annually) as they reach their end of life. This calculation finds that the distribution network operator would need to make a net investment for the first 2 years, but from Year 3 the savings from the units installed offset the capital required for the incremental investment in 500 more-efficient transformers (SEAD Tier 3 in this case). By 2025, the operator will have saved (cumulatively) over €10 million and is thereby actively lowering the total running costs overall, even though the price for the SEAD Tier 3 transformer is 64% more expensive than the baseline unit previously purchased.

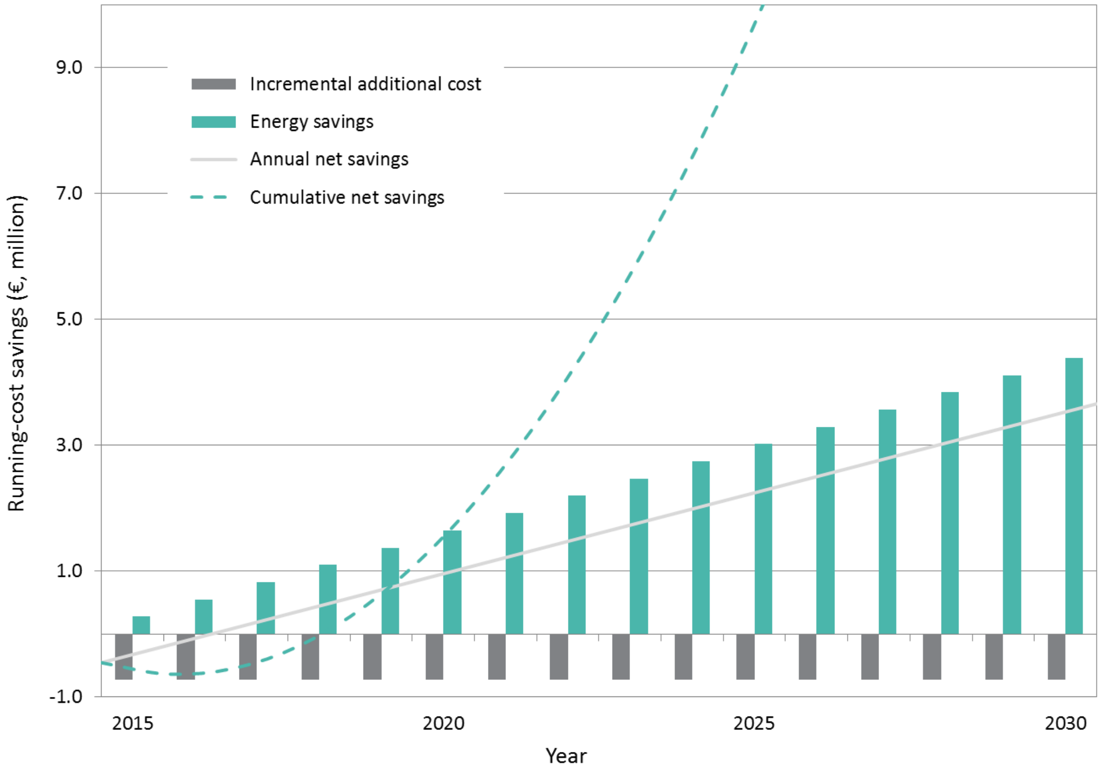
In Figure 5-4, the greybars represent the incremental additional expense (using nominal euros, i.e.not discounted) for the SEAD Tier 3 transformer (approximately €730 000/year). The turquoise bars represent the energy savings that offset those expenses, and the straight line shows the sum of the two. The exponential line shows the cumulative sum of all the costs, and thus the overall savings.

5.2 Asset management

Distribution transformers installed in today's electricity networks represent a relatively modest capital investment but play a crucial role in the reliability and availability of electric power. The individual or team responsible for maintaining these assets must look to safeguard reliability and control risks, but keeping the TCO as low as possible is not always an important objective. The common asset management instruments used to assess the performance of transformers in the network are monitoring, maintenance, refurbishment and replacement.

In the past, asset management was centred on a relatively simple objective of 'doing the best we can'. Today, asset management teams work to actively ensure that assets are performing optimally, taking into account cost and risk, and company business values. This new asset management focus has had an impact on the approach followed when taking replacement decisions. Risks such as failure

Figure 5-4. Running-cost savings for a business managing 20 000 units of 150 kVA, three-phase, liquid-filled transformers.



probability are identified and assessed on the basis of company business values, and decisions that are made weigh up the hazard risk score (i.e. urgency) and measure mitigating risk (i.e. effectiveness).

While careful consideration is often given to specific installation sites for large power transformers (due to the relatively high cost of replacement), the same consideration is often not afforded to distribution transformer installations. In general, distribution transformers are frequently regarded as commodities, as they are relatively inexpensive and can be delivered off the shelf. Thus, replacement units must be low cost, efficient and standardised. This situation may change as smart-grid technology rolls out and better monitoring of assets, even at the distribution transformer level, is afforded to the management team. This type of load growth and load-profile information is particularly important for installations that are experiencing steady growth and dynamic loads, to find the most efficient transformer for each installation on the network, and will be established from smart meter data.

Looking in detail at an example of a unit from De Wachter (2013), calculations are made to determine whether to replace a 1000 kVA transformer that has been operating for 20 years in the network. Should the unit be replaced this year, or would it be better to wait for another year or more? To make this decision, De Wachter presents the following assumptions:

- transformer purchase cost: €20 000
- transformer residual value (now and in one year): €2000
- discount rate: 8%
- annuity factor when keeping old transformer (life 21 years): 1.250
- annuity factor when replacing with new transformer (life 20 years): 1.249
- electricity cost: €0.10/kWh

- no-load losses, old transformer: 2 kW × 8760 h × €0.10/kWh = €1752
- no-load losses, new transformer: 1 kW × 8760 h × €0.10/kWh = €876
- load losses at nominal load, old transformer: 8 kW + 10% for harmonics = 8.8 kW
- load losses at nominal load, new transformer: 4 kW + 10% for harmonics = 4.4 kW.

Given these assumptions, the losses and cost of those losses are calculated for the load profile at this site, assuming 5% of the year at 100% load, 20% of the year at 75% load, 40% of the year at 50% load, 30% of the year at 25% load and 5% of the year at 0% load (Table 5-2).

Supplementing this calculation of the value of the losses, there are additional costs associated with maintaining this asset, specifically the maintenance cost and the risk of outage. De Wachter makes the following estimates for this installation:

- annual maintenance cost, old transformer: 4% of purchase cost = €800
- annual maintenance cost, new transformer: 1% of purchase cost = €200
- risk estimate of outage, old transformer: 1%
- risk estimate of outage, new transformer: 0%
- penalty for area with high risk of lightning strikes: 20% of outage risk, resulting in a total outage risk estimate of 1.2%
- cost of outage: €20/kVA
- total cost of failure risk, old transformer: 1000 kVA × €20/kVA × 0.012 = €240.

These assumptions then enable the calculation of the EAC of keeping the transformer for one more year versus replacing it with a more-efficient model. Table 5-3 provides the results of that calculation.

According to this analysis and the conclusions drawn, the author found that for this installation it would be appropriate to replace the transformer with a new one. The old transformer has an EAC that is nearly twice that of the new unit.

5.2.1 Operating transformers at efficiency-maximising utilisation rates

In many installations, distribution transformers are not optimally loaded, which can lead to unnecessarily high losses. For example, a study of the European (EU-27) electricity distribution companies found that the average loading on distribution transformers is 18.9% (SEEDT 2008). In some parts of the European network, this is because of a large installed stock of transformers either for system redundancy/reliability or because the network operators wish to avoid putting high loads on older units. By actively managing transformer loading through sectionalising the network to redistribute the loads on the transformers, the operational efficiency of the network can be increased (Papaefthymiou et al. 2013).

Table 5-2. Calculated losses for the example of a 1000 kVA transformer

Load (% of rated kVA)	Hours (per year)	Electricity cost (€/kWh)	Losses (kW)		Value (€)	
			Old transformer	New transformer	Old transformer	New transformer
100	438	0.10	8.80	4.40	385.44	192.72
75	1752	0.10	4.95	2.47	867.24	432.74
50	3504	0.10	2.20	1.10	770.88	385.44
25	2628	0.10	0.55	0.27	144.54	70.96
0	438	0.10	0.00	0.00	0.00	0.00
Total	8760				2168.10	1081.86

Source: De Wachter 2013.

Table 5-3. Calculation of the equivalent annual cost (EAC) of keeping a 1000 kVA transformer for a further year

	Keeping old transformer for 1 more year (€)	Replacing new transformers now (€)
Annual investment cost/AF	762.51	800.00
Annual rest value/AF	−76.25	−80.00
No-load losses	1752.00	876.00
Load losses	2168.10	1081.86
Maintenance cost	800.00	200.00
Reliability penalty	240.00	0.00
EAC	**5646.36**	**2877.86**

Abbreviation: AF = annuity factor.

Source: De Wachter 2013.

5.3 Demand-side considerations

When specifying a transformer for an installation, it is important for asset managers to take into account the dynamic nature of loads. Distribution transformers serving households in a network may be only lightly loaded (e.g. 20% on an annual basis), but there may be significant peaks in the morning and evening as high-power activities such as instant hot showers and cooking appliances are used. These household loads will also vary over time, as new appliances and equipment are added to the circuit.

Load growth can have a significant impact on transformer lifetime and should be taken into account when conducting an economic analysis for an installation. For example, a load growth rate of 2% per year will compound to change the average loading on a transformer by 49% after 20 years and 81% after 30 years. If the growth rate is higher, as can be found in some rapidly developing economies, the impact on distribution transformers can be so significant that it exceeds the rated capacity and causes premature failure.

Thus, asset management includes understanding and accurately forecasting load growth as well as monitoring it, so that the electricity network can achieve its societal objective of being robust, reliable and efficient.

6. Electric utility regulatory measures

Key messages

- It is widely accepted that the naturally monopolistic areas of electricity businesses (i.e. transmission and distribution (T&D)) need to be monitored and controlled by regulatory authorities to ensure that T&D companies do not exploit their market power by operating inefficiently and charging high prices and/or providing an inadequate quality of supply.
- In the case of network losses it is important for regulators to ensure utilities have an adequate incentive to reduce them rather than simply passing the costs on to a captive client base; however, that is an ongoing challenge.
- It is important to address whether T&D losses are measured, how they are measured and whether they are reported and used as a performance measure by utility regulators. All of these elements need to be adequately managed before incentives for loss reduction can be created.
- Means of ensuring losses that are costs to the utility and hence that they have an incentive to reduce them include (a) requiring the utility to buy losses from the market and (b) the regulator mandating that losses are included in any investment appraisal to be sanctioned by the regulator. This might be through an integrated resources planning regulatory framework or otherwise.
- Common regulatory models to incentivise reduction in technical losses include rate-of-return regulation, cap regulation and yardstick regulation; however, these need to be coupled with quality-of-supply requirements to ensure that this is not compromised as a result of loss-reduction incentives.
- Incentive regulation grants stronger incentives to reduce costs than does rate-of-return regulation. The longer the time between price reviews, the stronger the incentives to reduce costs. Depending on the regulations for benefit sharing, the time for which a company may completely retain the cost savings resulting from efficiency increases will vary.

6.1 Regulatory environment

Natural monopolies arise if duplication of an infrastructure or service provision is uneconomic, i.e. the character of the technology and demand dictate that the service is cheaper if the demand is met by a single firm rather than by competing firms (Petrov 2009). The naturally monopolistic areas of electricity businesses (i.e. T&D service access and provision) are controlled and monitored by regulatory authorities. One of the regulator’s tasks is to ensure that T&D companies do not exploit their market power by operating inefficiently and charging high prices and/or providing an inadequate quality of supply. In other words, a good regulatory regime provides companies with opportunities and incentives similar to those they would face in a competitive market. However, in mimicking market forces, regulators need to balance this responsibility with the need to ensure that network businesses earn a reasonable rate of return on their (efficiency incurred) investment (Scarsi and Petrov 2004; Petrov 2009). The utility regulatory regime has a large impact on the incentive a network utility has to minimise distribution losses. The costs associated with the losses occurring during the transport of power through a network are in principle recovered by the network operator through consumer tariffs. However, when losses can be fully passed through, any economic incentive for the network operator to reduce losses is removed. Putting a maximum amount on the costs associated with losses that can be recovered from the tariffs will create an incentive to prevent high losses. A fixed compensation for losses per network operator per year gives a direct incentive to reduce losses. Alternatively, the distribution network operating utility can be required to buy back the losses from the market, as is the case in France and Belgium, for example. Another potential route is via inclusion of losses within integrated resource planning. This measure is widely used by utilities, ministries and regulators to assess generation and other capital planning requirements and in principle should consider efficiency technologies on the same planning priority basis as generation measures. The way these technologies, transformers in particular, find their way into the plan can either come through direct regulatory advice or be based upon incentivised stakeholder engagement during the development of the integrated resource planning.

Before any of this can be acted upon it is important to address whether the T&D losses are measured or estimated, how they are measured or estimated and whether they are reported and used as a performance measure by utility regulators. All of these elements need to be adequately managed before incentives for loss reduction can be created.

In the EU, for example, a losses indicator is used as a revenue driver in 12 countries (Austria, the Czech Republic, France, Great Britain, Ireland, Italy, Norway, Poland, Portugal, Slovenia, Spain and The Netherlands) and for monitoring in six countries (the Czech Republic, Germany, Finland, Ireland, Norway and Sweden), and is under consideration as a revenue driver in Luxembourg and Lithuania and for monitoring in Luxembourg. This indicator can be determined for both distribution and transmission networks (CEER 2011).

The majority of countries report losses in T&D networks. However, the indicator is likely to be calculated in different ways in different countries; it is unclear to what extent this will impact on the results and the ability to compare.[20]

Losses need to be covered by additional generation, which in the case of a fossil-fuel generating plant will emit air pollutants that have a detrimental environmental impact. The objective of the regulatory treatment of losses therefore has a dual objective: to protect the interest of customers and to promote the efficiency of the network system.

Incentive mechanisms have been devised to reward (or penalise) network operators whenever losses are below (or above) a pre-set target level. To some extent network operators are able to control losses through, for example, network design, maintenance and investment decisions regarding the installation of grid elements that play a significant role in the determination of losses. If network operators have enough incentives, they will evaluate the costs and benefits of reducing losses and take action to optimise the level of losses in the most efficient way. Nonetheless, it should be recognised that a number of external factors can influence the level of losses significantly and may fall beyond the control of a distribution system operator (DSO), e.g. the geographical size of the market or the number of customers connected to a distribution network and the degree to which they are dispersed.

Other regulatory and operational issues, such as energy-efficiency schemes, infrastructure planning and network reconfiguration, also have an impact on the treatment of losses. Nonetheless, 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.

Depending on the mechanism for covering losses, the costs for technical losses must be covered by network customers with correctly metered consumption. Through the identification and reduction

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[20] An overview of methods for calculating losses as used in different countries is included in a European Regulators' Group for Electricity and Gas (ERGEG) consultation paper on losses (E08-ENM-04-03, July 2008) and its associated conclusions paper (E08-ENM-04-03c, February 2009). The reader is referred to those papers for more details on methods in use for calculating losses.

of non-technical losses and the installation of meters to all consumers, the actual level and costs of technical losses can be charged to the customers (or suppliers) in a cost-reflective and fair way.

An important issue is to reduce technical losses. The level of these losses can be affected by investments by network operators, and hence support for network operators in terms of incentive mechanisms has a significant role to play. However, the overall effects of such incentives must be positive, i.e. investments in networks to reduce losses must be less than the costs of the technical losses.

The impact of new distributed generation also needs to be considered as this can increase losses locally if the new distributed generation is not absorbed by local load. This can also affect the marginal costs of losses.

6.1.1 Common regulatory and incentive mechanisms addressing network losses

Current regulatory models may be classified as one of:

- rate-of-return regulation
- cap regulation
- yardstick regulation (Petrov 2009).

These are discussed in turn below.

Rate-of-return regulation

With rate-of-return, prices are set by the regulator in order that the utility’s costs of production are covered and there is a rate of return on capital that is at a level which provides an incentive for the investor to replace or expand company assets. This method of regulation is also called ‘cost of service’ or ‘cost plus’ regulation (‘plus’ equates with the allowed rate of return) and is common in the USA, whereas in Europe many regulators have implemented incentive regulation schemes.

A simplified formula for rate-of-return price control is:

$$R_t = TC_{t-1} + ROR \bullet RAB_{t-1}$$

where:

- R_t = allowed revenue in t
- TC_{t-1} = total cost in the previous year (inflated)
- ROR = (allowed) rate of return
- RAB_{t-1} = regulatory asset base.

Year t, which represents the allowed revenue in the year concerned, is set to equal the sum of the previous year’s total costs (operating and maintenance costs, and depreciation) plus an amount to provide a normal return on the capital invested. This total is used to determine tariffs that are set until review, usually every 1−2 years.

Since the regulator can choose which costs to include, it can determine matters such as service quality. Thereby, rate-of-return regulation is flexible. However, it does have the disadvantage of not providing any incentives to control or reduce costs, since the utility can cover increasing costs with an increased price the following year, and thus there is no consequence to being inefficient as long as prices are reset relatively frequently. In fact, if the utility does reduce costs, the prices set by the regulator will be lower, which provides no incentive to the utility as the benefits are gained by the consumer rather than the utility, and the rate of return on capital remains unchanged. An additional disadvantage is that the utility has an incentive to over-invest in capital equipment and plant (‘gold plating’) because an acceptable rate of return can be earned on that investment, especially in cases where the rate of return is higher than normal. It is difficult for the regulator to prevent this because inspection of investment plans may not reveal such over-investment.

In light of these failings of rate-of-return regulation, alternative methods that provide incentive-based price regulation and comparative benchmarking have been developed.

Cap regulation

First used on a large scale with respect to British Telecom in the UK in 1984, a ‘price cap’ or ‘revenue cap’ is an upper limit on prices or revenue and is intended to give utilities a strong incentive to reduce costs. This involves the setting of prices, or revenues, earned by a utility over a number of years (usually 3−5 years) regardless of the costs over the same period, and allows the utility to keep a percentage of the returns from efficiency improvements that extend beyond a certain level.

The period of set prices/revenue allows a utility to benefit from any savings in costs over the same period, but recalculations at regular intervals allows prices to be realigned with costs. Thus, while prices with the rate-of-return mechanism are set according to a company’s actual costs and provide no incentive to improve efficiency, this is not the case with cap regulation, with which costs and prices remain linked to a degree but not completely.

Inflation rates may fluctuate unpredictably, and in this case cap regulation allows for the adjustment of prices/revenues accordingly, with this inflation-adjusted price/revenue then being further adjusted by ‘the X factor’, which is a percentage that reflects a real change in costs that are deemed by the regulator to be acceptable. In the UK, the general prices index is called the ‘Retail Prices Index’ (RPI) and the X factor is the ‘RPI-X’.

Normally, however, so that the utility can earn a fair rate of return in any given period, the starting level and the development path of prices/revenue are fixed for several years. The price path is most easily calculated according to:

$P_t = P_{t-1}\,(1 + CPI - X)$

where:

- P = price
- CPI = inflation (consumer price index)
- X = productivity growth rate
- t = time index.

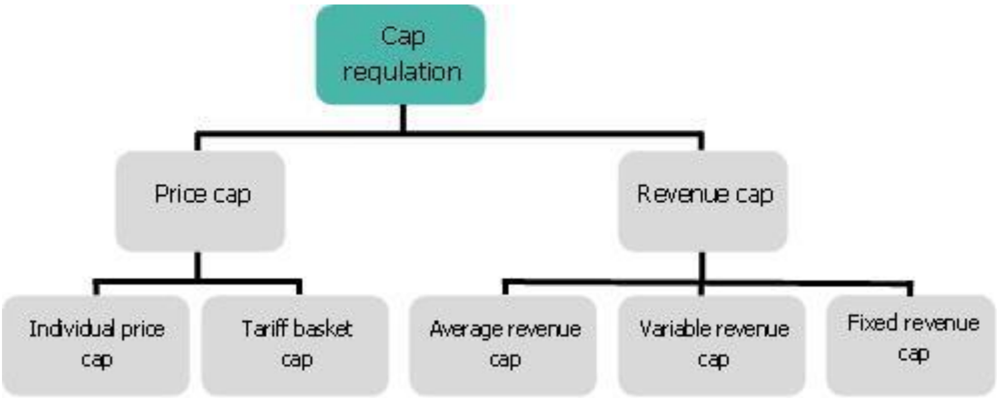
For a revenue cap, price (P) would be replaced with the revenue (R) of the company.

Types of cap regulation

(i) Price caps. The limit with price caps is applied to the actual price or an average of the actual prices charged:

  - ‘individual’ price caps are the most direct form of price control and the upper limit for each individual price is set by the regulator. It is used where the number of services provided is small and stable and where costs can be identified easily
  - ‘tariff baskets’ involve the grouping of prices into one or more baskets on the basis of the services to which they apply. A weighted-average price for the basket is calculated and then a cap or upper limit is applied to it. The cap increases over time according to an RPI-X formula (see above). Theoretically, this presents an incentive to implement, but in practice the tariff basket may be difficult to understand and to apply. The weights chosen in deriving the weighted-average price may be derived from a range of factors that are often based on either the revenue or quantity shares of each service in the basket. These weights may be fixed throughout the regulatory period or may be reset at appropriate intervals.

Figure 6-1. Types of cap regulation.



Source: Petrov 2009 (reproduced with permission).

(ii) Revenue caps. The limit with revenue caps is applied to the revenue earned:

- with 'fixed revenue' caps (also called a 'pure revenue' cap or 'fixed' cap), the upper limit of revenue is set as an absolute amount at the start of the control period and is adjusted annually for only general price inflation and the X factor. The allowed revenue does not normally vary automatically with a change in volume
- with a 'variable revenue' cap, allowed revenues are indexed (in addition to 'CPI-X) to some measure of change in one or more other cost drivers, such as units distributed or customer numbers. A variable revenue cap allows for automatic adjustment to some cost changes that cannot be controlled by the utility
- with an 'average (or unit) revenue' cap, sometimes also referred to as an 'average yield' cap or 'revenue yield' cap, an upper limit is placed on the average revenue per unit of throughput the business is permitted to earn in any year. The average revenue is then allowed to vary each year in accordance with an 'RPI-X' formula, where RPI is the retail price index and X is an efficiency factor.

Figure 6-1 illustrates the types of cap regulation.

Yardstick regulation

Yardstick regulation indexes prices/revenues to an industry performance average rather than to an individual utility's own performance, and compares prices and costs between companies. Utilities are not allowed to charge prices that are higher than the calculated average unless they have special operating conditions that warrant this. This is a transparent method of regulation that is not linked to price control.

The advantages of this method of regulation include that it is transparent, non-intrusive, completely unlinked from price control and brings a great incentive to perform better than the yardstick because this would lead to the generation of profits. At the same time, this would result in more-efficient operation, which would lower the yardstick and in the longer term result in lower prices for customers. On the other hand, frequent calculation tends to be required and companies have strong incentives to increase their volumes sold. The practical implementation of this regulation method has other disadvantages:

i) it can only be applied in cases where the number of comparative companies is great enough to allow a yardstick to be applied
ii) as a result of factors that cannot always be controlled by companies, companies are fundamentally different

iii) it is not at all common for companies to start from the same efficiency position
iv) companies could collude with one another
v) poor financial performance may be expected with the unlinking of costs and revenue.

Quality of supply

In general, utilities can define their own investments and levels of quality with rate-of-return regulation, and in this case incentives for oversized investments and quality are created. Consequently, regulators may work to concentrate attention on counteracting inefficiencies of this type as well as over-investment. Both a regulated company's costs and quality of supply may be lowered by reducing investment, maintenance or staffing levels when attempting to increase profits while operating under simple cap regulation. It seems that when quality measures are not included, incentive regulation eventually results in the deterioration of quality. Price and quality cannot be separated because higher quality requires higher cost, and so prices will be higher. Ideally, regulation would lead to an equal balance between the marginal benefits of quality and the marginal costs of delivering it.

6.1.2 European case studies on regulatory and incentive mechanisms addressing network losses

Table 6-1 summarises different approaches used to address network loss incentives in European countries, and illustrates the variety of regulatory or incentive mechanisms adopted to reduce power losses in EU transmission or distribution networks:

- no regulatory or incentive mechanism (this is common)
- regulatory model where the incentives for network losses are equal to the incentives for any other costs, i.e. incentive-based model
- allowed rate of losses to include in tariffs capped to a maximum value in percentage terms
- incentive mechanism allowing the network operator to be rewarded (or charged) if achieved global network losses are lower than (or above) a reference value.

Table 6-1. Examples of regulatory incentives applied to transmission system operators (TSOs)/ distribution system operators (DSOs) for network loss reduction in the EU

	Regulatory incentives	Incentive mechanism
Finland	None	None
Sweden	For distribution networks, standard losses are included in network performance assessment model	
Norway	Yardstick regulation. Costs related to network losses are treated as any other cost within the regulatory model	
France	TSO: none. DSO: incentive for theft reduction plus losses must be purchased	Losses must be purchased from the market
Austria	Allowed rate of losses to include in tariffs capped to a maximum value in % (only TSO)	
Czech Republic	Allowed rate of losses to include in tariffs capped to a maximum value in % (TSO and DSO)	An annual loss efficiency factor is in place (only for DSO)
Portugal	Total network losses should be below a specified value in %. An incentive mechanism exists to reduce losses in the distribution networks.	Tariff code includes an incentive mechanism to reduce losses in distribution networks allowing the DSO to be rewarded (or charged) if global distribution losses lower than (or above) a reference value set by the regulator, for each year, are achieved

Source: ERGEG 2008 (information has been updated for France).

It should be noted too that other jurisdictions apply operations and maintenance (Opex) and/or capital expenditure (Capex) plus Opex, i.e. Totex, benchmarks and incentives. These schemes are less precise in their incentives, but they give planners the freedom to decide which part of the costs should be reduced to arrive at least-cost service provision.

Germany

Germany's regulatory scheme includes a tariff structure and incentive regulation, both of which take energy efficiency into account. Grid operators calculate their own tariffs for both distribution and transmission according to a method specified by the Grid Tariff Regulation (StromNEV) (NETZ 2014), but these must then be approved centrally by the Regulatory Agency. The Grid Tariff Regulation has set a revenue cap for grid operators since 2009 that takes into account an increasing cost-efficiency factor (Papaefthymiou et al. 2013).

Grid tariffs are calculated according to all relevant operation costs of T&D (§17 StromNEV) (NETZ 2014). Any costs for purchasing energy to compensate for losses are taken into account when calculating the tariffs because these are considered to be relevant grid-operation costs (§10 StromNEV) (NETZ 2014). Consequently, these costs can be passed directly to consumers and grid operators have no incentive to keep losses to a minimum.

The Grid Tariff Regulation sets grid-operator annual revenue caps over a 5-year period. Costs that are relevant to setting revenue and cost-efficiency targets are calculated on a 5-yearly basis, and information regarding transmission and distribution must be provided to the regulator by the system operators. Costs comprise, on the one hand, those that system operators can influence, and on the other hand those that they cannot. These different categories of costs are included in the calculation in different ways. The regulatory agency determined that costs for purchasing energy to compensate for losses are volatile cost components and cannot be influenced (Bundesnetzagentur 2012a, 2012b). These costs do not have an increasing cost-efficiency factor applied to them within the regulation. The revenue cap is set according to:

$$EO_t = KA_{dnb,t} + (KA_{vnb,0} + (1 - V_t) * KA_{b,0}) * (VPI_t/VPI_0 - PF_t) * E_t + Q_t + (VK_t - VK_0) + S_t$$

where:

- *EO* = the revenue cap
- and *VK* denotes the volatile costs.

This formula shows that higher losses (i.e. higher volatile costs, *VK*) translate into a higher revenue cap.

Costs for losses can be calculated and benchmarked every year for distribution-system operators (Bundesnetzagentur 2010). However, the intention of the benchmark is to increase cost-efficiency and give grid operators incentives to purchase energy to compensate for losses cost-efficiently. There are no incentives for technical efficiency in grids. There is no incentive to reduce the level of losses, which is a fixed component for distribution-grid operators and is without any yearly adjustment. Overall, distribution-grid operators are not given any incentive to increase technical transmission or distribution efficiency, and hence there is no incentive to invest in a more-efficient grid infrastructure.

The UK

Electricity and gas distribution and transmission in the UK has a price cap regulation. The RIIO (Revenue = Incentives + Innovation + Outputs) mechanism has been developed from the previous scheme and was implemented from 2013 for transmission and will apply from 2015 for distribution; it increases the regulatory period from 5 years to 8, following which a new price development will be calculated (Papaefthymiou et al. 2013).

Electricity North West Ltd, UK: a case study of the impact of regulatory design on utility investment in efficient distribution transformers

How regulatory innovation has enabled more holistic investment planning

Electricity distribution in Great Britain is split into transmission and distribution activities. Distribution is organised into 14 regional networks (distribution network operators, or DNOs), operating from the 132 kV level down to low voltage in England and Wales and from 33 kV down to low voltage in Scotland (where the 132 kV network forms part of the transmission activity).

Since privatisation in 1990, the sector has been subject to price control regulation, administered by an economic regulator, Ofgem, in the form of successive 5-year price reviews. The fifth such period started in 2010 and completes on 31 March 2015. These controls are characterised as 'RPI-X' regulation, i.e. future revenues indexed by inflation (RPI) and reduced by an efficiency factor 'X', reflecting the focus on cost reduction at the time.

In 2008, Ofgem embarked on a wide consultation on the future form and structure of price controls for the gas and electricity transmission and distribution networks. This resulted in the 'RIIO[1]' model for future price controls, which enhanced the role of incentive-based regulation, established a clearer link between investment and the 'outputs[2]' it was intended to deliver and, most visibly, extended the price control period to 8 years.

The 14 distribution companies are in the process of completing the price review process with Ofgem that will set company revenues and outputs for the 2015–23 period. As part of this, companies have been exploring new ways of assessing asset life-cycle costs and evaluating the benefits of competing investments via a new approach, prescribed by the regulator, to cost–benefit analysis.

Historically, price controls treated capital and operating expenditure quite differently, leading to an inbuilt bias towards capital solutions to network issues. Capital solutions themselves were usually judged based on the lowest installation cost. Where the results of traditional whole-life cost analysis and asset management would point one way, regulatory incentives and value creation would often point the other. This would typically be to the detriment of 'within life' activities that would traditionally be defined as 'maintenance', and would focus DNOs on lowest initial cost solutions such as higher-loss transformers.

In the price control periods preceding RIIO,[3] Ofgem progressively broke down this distinction such that all interventions on the network were treated as having equal regulatory value. This enabled greater alignment of company forecasts with evolving asset-management best practice. Investment analysis, however, still only took account of the benefits that would accrue directly to the DNO (e.g. in the form of cost savings or incentive payments).

In the first RIIO price control for the electricity distribution networks (RIIO-ED1), this was taken a stage further through the introduction of cost–benefit analysis, which enabled investment decisions to take account of benefits that do not accrue directly to the network operator, but instead represent customer or societal benefits. This was particularly pertinent in the area of losses management where there would otherwise be no direct incentive on DNOs to manage network losses following the scrapping of the previous incentive scheme in December 2012 on account of data inaccuracies.[4]

By using a proxy cost for electrical losses linked to the government's standard valuation of the cost of carbon, higher-cost initiatives such as low-loss transformer installation could be evaluated alongside cheaper options on a more level playing field.[5]

In the case of Electricity North West,[6] this enabled the detailed evaluation of options for the early replacement of particularly high-loss units (that were otherwise fit for continued service), and the assessment of the incremental cost of lower-loss options (such as upsizing) for the routine replacement of cables and transformers.

As a result of the cost–benefit studies, Electricity North West gained approval for plans to replace 652 high-loss 800 and 1000 kVA, 11 kV units installed prior to 1990. This represents 7% of the population of transformers of this vintage and will complement their routine replacement programme, which will replace a further 15% over the RIIO-ED1 period (2015–23).

Case Study (continued)

Electricity North West has committed to an associated output in its RIIO-ED1 plan to reduce losses by 10 972 MWh by 2023. This represents approximately 3% of current distribution transformer losses.

Using the cost–benefit analysis approach, Electricity North West also justified the upsizing of high-voltage cables, 33 kV transformers and higher-capacity pole-mounted high-voltage transformers in its routine replacement activities, contributing to a total package of loss-reduction measures valued at £14 million over the RIIO-ED1 period.

This investment is part of a set of initiatives to manage future losses on the network in line with Electricity North West's losses strategy, the publication of which will be a formal requirement on all DNOs as a condition of the RIIO-ED1 settlement.

The RIIO approach and its associated tools allows network operators to conduct more holistic evaluations of investment benefits by quantifying external environmental and societal benefits, reflecting the continuing progressive evolution of network regulation in this sector.

Contributed by J. Booth, Head of Asset Management, Electricity North West, UK

[1] Revenue = Incentives + Innovation + Outputs.

[2] The Ofgem term that has a similar meaning to outcomes in this context.

[3] Distribution Price Control Review 4 (DPCR4) (2005–10) and DPCR5 (2010–15).

[4] The previous scheme measured total system losses but was reliant on settlements data from the suppliers that was hugely variable, leading to DNO windfall gains and losses outside their control. Identification of technical versus non-technical losses was believed to be very challenging under this scheme and hence very difficult for the DNOs to be incentivised on the impact of their direct actions.

[5] In principle, the same approach could be applied if the regulator simply applied a standard value of energy losses that reflects their true value to end-use customers, i.e. the applicability of the regulatory model is not contingent on carbon being valued, although this adds to the effect.

[5] Electricity North West is the DNO covering the north-west of England. Serving 2.4 million customers and a population of 5 million, its area ranges from the Greater Manchester conurbation to the Lake District. It delivers 23 GWh of electricity annually through a 57 000 km network.

The RIIO mechanism should give companies incentives to develop and submit reasonable business plans, with a focus on different aspects of T&D operation such as innovations or environmental issues. The methodology for calculating grid tariffs is set by the Balancing Service Incentive Scheme (BSIS) and is related to grid tariffs.

Grid users pay a charge to the grid operators that is part of the Balancing Use of System (BUoS) charge (National Grid 2010). The BSIS comprises a proportion of the BUoS charge and is made up of both internal (administration and staff expenditure) and external costs (incurred when operating the system, also called Incentivised Balancing Costs (IBC)). Both the BSIS and the IBC have target levels to be achieved by grid operators. Included in the IBC is a component that adjusts the BSIS incentive target if transmission losses fall below or rise above the agreed target, such that target costs are reduced when losses fall below the target and increased when losses rise above it. A reference price is applied to convert the loss volume into cost. The 2011–13 target developed by National Grid in conjunction with the Office of Gas and Electricity Markets (Ofgem) was 8.9 TWh ± 0.6 TWh (Ofgem 2011). There is no clear incentive for a reduction in losses.

The Common Distribution Charging Methodology (CDCM), which is approved by Ofgem, is applied to calculate Distribution Use of System (DUoS) charges. This methodology implies a cost component for losses but gives no incentives to grid operators to reduce losses (ENA 2012).

New incentives have been developed within the RIIO mechanism for TSOs. There are seven different categories for the output component of the RIIO mechanism (Ofgem 2012a). 'Environmental' outputs comprise transmission losses; this category sets incentives by publishing the overall strategy for transmission losses and annual progress in implementation and impact of transmission losses. Although there is a reputational incentive for transmission-loss reduction, no financial incentives are implied. Ofgem calculates distribution losses as an annual allowed loss percentage for each distribution company, who are rewarded or penalised according to their performance against the target (Ofgem 2012b). In 2009, the financial incentive for lowering transmission losses was £0.05/kWh (Sohn 2009).

Overall, there are no regulatory incentives to reduce losses in the UK. TSOs have only a reputational incentive, no financial one, but this could still have a worthwhile effect. DSOs have stronger incentives since the regulatory authority calculates allowed loss percentages on a yearly basis and DSOs are penalised or rewarded according to their performance with regard to losses, giving them strong financial incentives to improve distribution efficiency. Simultaneously, rewards are given for their announced capital costs and there are incentives to keep operational costs to a minimum. Hence this is a both an input- and output-based regulatory scheme.

6.1.3 The USA and China

Similar issues concerning the regulation of utilities to encourage cost-effective loss reduction are encountered elsewhere in the world. In the USA, as in Europe, sometimes the regulatory structure fails to incentivise the implementation of efficiency; however, in many cases it does. For example, Puget Sound Energy established an arrangement with the Washington Utility and Transmission Commission wherein they are granted a higher rate of return for energy-efficiency upgrades, facilitating more investment by Puget Sound into their own system.

Many US utilities do use 'total ownership cost' (TOC) evaluation formulae to value losses at US$X/watt for the core and US$Y/watt for the coil. These formulae take into account utility-specific variables such as the cost of capital, the LRMC of generation, and other key variables. However, many utilities are not thought to have updated their US$X/watt and US$Y/watt loss valuations for many years, and thus old evaluation formulae may not be selecting the most cost-optimised transformer designs. Generally, US utility purchases of transformers are done on a budget basis (i.e. using working capital), so the provision of low- or zero-interest loans to help defray the higher capital cost of higher-efficiency transformers is unlikely to be attractive. Thus, as in Europe, it is incumbent on the regulatory authorities to update and refresh the TOC/TCO formulae to ensure there is adequate incentive for network loss reduction.

While utility regulation is managed at state level in the USA, the Federal authorities do have the ability to oblige states to examine issues. Examples include legislation in 2007 that required states to look at smart grids, and earlier Public Utility Regulatory Policies Act (PURPA)[21] legislation that required them to look at power purchases. Thus, in principle, coordinated direction from the Federal authorities could occur if a Federal law were passed that requires state regulators to look into loss-evaluation formulae.

In China, existing power-sector reform efforts are based on international models of competitive generation markets and regulated grid companies (RAP 2008). Ownership reforms began in the mid-1980s, and subsequent restructuring has separated most generation assets from T&D. However, government institutions and capabilities are lagging behind. The State Electricity Regulatory Commission, a regulatory agency, was established in 2003, but its jurisdiction, capacity and resources are rather limited.

For the most part, power generation has been separated from the network business. The generation assets of the original, vertically integrated State Power Corporation were divided in 2002 into five

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[21] See http://en.wikipedia.org/wiki/Public_Utility_Regulatory_Policies_Act

new generation companies that are primarily state-owned. The reforms of 2002 put in place an industry structure that can be characterised as a single-buyer purchasing-agency model. In brief, provincial and municipal grid utilities are typically the sole purchasers of power from generators, and they re-sell to customers and distribution companies in their service areas. Transactions are closely choreographed by the government, generation is sold through long-term contracts generally set by the National Development and Reform Commission (NDRC)[22] and retail tariffs are set administratively.

As for bulk transmission, the system is organised into six regional grids, which are owned and operated by six regional state-owned grid companies. All bar one are subsidiaries of the State Grid Corporation. State Grid controls approximately 80% of the grid, serving 1 billion people, while Southern Grid covers the remaining 20% of the grid across the southern-most five provinces. Under the umbrella of each regional grid company, including Southern Grid, there are provincial- and municipal-level companies. Historically, these companies have been the backbone utilities in China's power industry. They typically own and operate the transmission network and all or most of the distribution network within the borders of the province. They are the sole buyers of electricity from generation companies and are responsible for re-sale to consumers and distribution companies within the franchised areas.

Transmission losses and congestion costs do not factor into dispatch in Hunan or Jiangsu. By contrast, losses do factor into dispatch in Liaoning. However, the loss calculation is based on average voltage-level loss estimates, rather than on-site and time-specific loss factors.

As China has MEPS and incentives for efficient transformers, this upgrade provision provides an infrastructure renewal opportunity where the selection of efficient transformers could be locked in. However, this is only likely to be effective to the extent that the strength of the policy signal is sufficient to require adoption of cost-optimised transformers over the next 30 years and hence is contingent on the design of the MEPS and incentives.

6.1.4 Conclusions

Incentive regulation grants stronger incentives to reduce costs than does rate-of-return regulation. The longer the time between price reviews, the stronger the incentives to reduce costs. Depending on the regulations for benefit sharing, the time for which a company may completely retain the cost savings resulting from efficiency increases will vary. It can be argued that the greater the share of benefits the regulated network businesses are allowed to retain, the greater their incentives will be to make cost savings, and hence the greater the extent of those savings that can eventually be passed on to consumers.

Conversely, incentive regulation could encourage regulated companies to reduce both their costs and quality of supply by curbing operating costs and investments in order to increase profits. Thus, incentive regulation without complementary quality service measures will eventually result in a reduction in service quality. If loss performance based incentive regulations are applied it is vital to also instigate a medium- to long-term system to regulate the quality of supply.

Ideally the regulatory regime should encourage the installation of loss-reduction equipment (such as efficient transformers) only if the investment in such equipment is economically feasible. Economically feasible investment means that the cumulative discounted social benefits from loss reduction over the asset lifetime is higher than the cumulative discounted social costs of the additional investment required for the efficient transformer (Papaefthymiou et al. 2013).

The regulator may allow the cost of loss-reduction equipment but should incorporate the expected loss reduction in the allowed cost of losses. On the one hand companies will be encouraged to invest

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[22] See http://en.wikipedia.org/wiki/National_Development_and_Reform_Commission

in loss-reduction equipment only if the regulator allows them to internalise the benefits resulting from those loss savings. On the other hand, most customers want to see the benefits in their electricity bill. In China, the government encourages customers to install smart meters and to transmit their end-use electricity data into the national and provincial information service networks to inform the design of demand-side management programmes. These initiatives will help to build trust and raise awareness between stakeholders, the power utility, energy service companies and customers.

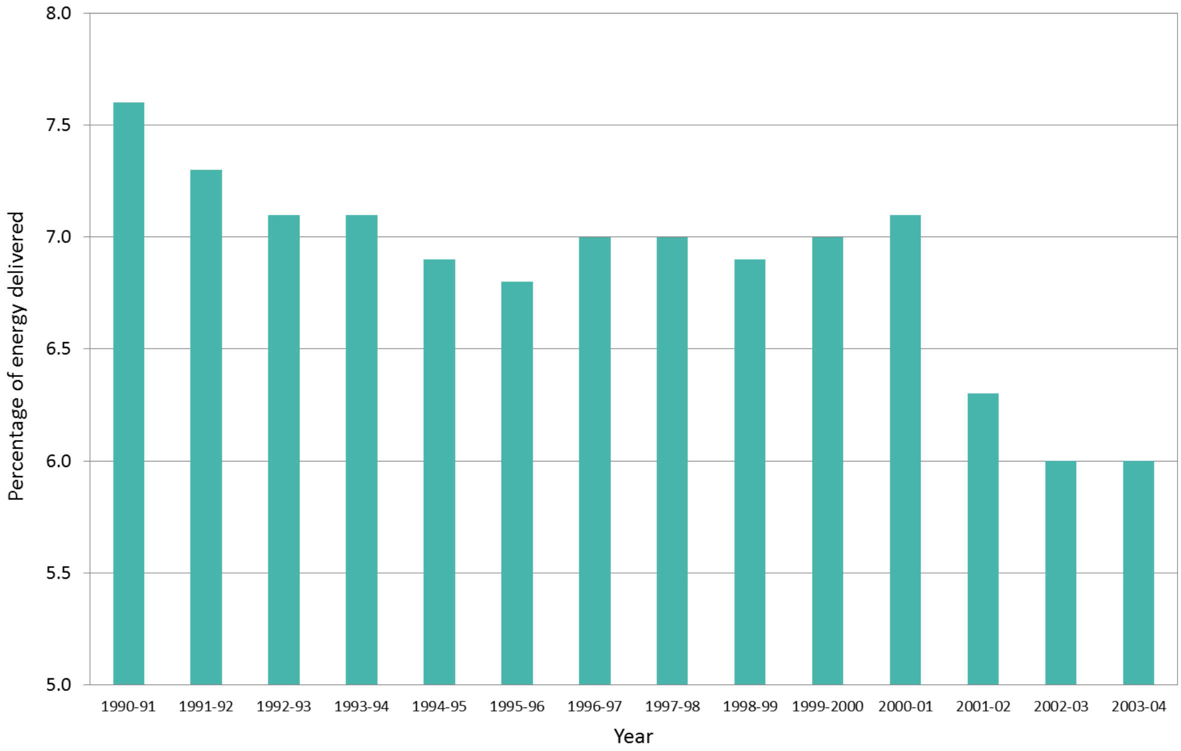
6.2 Liberalisation and network regulation

The conclusions drawn in the previous section with regard to the importance of regulation to incentivise losses illustrate that there need be little difference in the principles of how these operate for traditional, vertically integrated utilities or for liberalised utilities depending on the nature of regulation applied. This is because electricity network businesses still form natural monopolies and hence the same issues and regulatory principles apply to them as would apply to a vertically integrated monopoly utility, except that some provisions need to be factored in to take account of specific circumstances. Regulators determine the allowed cost recovery for distribution services; the cost of generation or wholesale power purchases and transmission is passed through according to rules that vary across regulatory regimes. Whenever a utility is able to simply pass on the network-loss costs to the customer without it affecting their profitability, there is a disincentive to invest in technical-loss reduction and hence in transformer loss reduction. Even in fully liberalised systems where customers have the freedom to choose from which DSO they purchase power, the same network hardware (lines and transformers/substations) are used to distribute the power to them and hence the same level of technical losses will be incurred. This means that competing DSOs have little opportunity to differentiate their service offer and hence compete on the basis of cost, where loss reductions play a role. This is the case unless they have been regulated in such a manner that they are measured and incentivised on the losses that are incurred in the parts of the network they directly manage. Section 6.1 provides examples of where this is the case in a liberalised market, e.g. in the UK, but incentives could also be applied for the T&D operations of a vertically integrated utility, when they are independent-investor owned. If they are state-owned and -regulated, the regulator still needs to approve investment decisions and hence in principle exactly the same type of determinations could apply.

Thus it needs to be recognised for liberalised utilities that regulation is also important in non-price areas, including network losses, reliability and standards for quality of service. If regulators fail to enforce penalties for the non-delivery of given standards, there may be incentives for services to deteriorate or fail to optimally improve the quality of the operation of the network. This is because distribution losses are paid for by retail customers, who must buy extra power to cover network losses. However, network losses in distribution networks are often assumed for charging purposes to be uniform and constant, so there is little advantage for competitive suppliers seeking to minimise losses, leading to a market failure. Distribution network losses in the UK did not change significantly over the first 10 years after liberalisation, yet when the regulator introduced a tougher financial penalty on network owners for distribution losses it reportedly led to a sharp and immediate cut in distribution losses (Figure 6-2) (Jamasb & Pollitt 2007; Pollitt 2007).

This tendency for the initial wave of liberalisation and deregulation to prompt short-term thinking, particularly in the area of capital expenditures, was confirmed by Frau (2004), who asserted that in European utilities there was a tendency at the decision-making level (as opposed to the advisory or engineering level) to purchase equipment at the lowest first cost. The capitalised cost of losses was often forgotten in the tender comparison procedure when purchasing transformers. The actual total cost of the transformer after a selected period of time (the total owning cost) was, therefore, not taken into consideration. The issue was not helped by the high uncertainty regarding the future price of electricity, which is itself increased by a lack of investment in interconnecting national/regional

Figure 6-2. Distribution losses in the UK as a percentage of energy delivered, 1990–2004.



Source: Jamasb & Pollitt 2007.

electricity markets. Therefore, liberalisation without improving transmission networks and interconnections (transnational bottlenecks) may discourage energy efficiency as a result of the uncertainty in electricity prices (IEA 2014a).

7. Policy

Key messages

- There are several barriers that lead to underinvestment in transformer efficiency. Most transformers operate at high efficiencies, so the seemingly small amount of losses is easily ignored. Furthermore, metering of individual transformers is usually not in place and so performance degradation is not always identified.
- At the network level, technical losses are often not distinguished from non-technical losses on account of the energy-flow metering systems used by utilities, so they are not always identified and acted upon.
- Regulators have a role to play in ensuring metering of energy flows is adequate to make technical network losses distinguishable from non-technical losses, and in ensuring their volumes are measured and reported.
- Some seven economies currently require transformer efficiency to be labelled in order to make it more visible in the market place.
- At the time of this report's publication, 13 economies around the world have adopted MEPS for distribution transformers.
- A number of voluntary programmatic schemes have also been adopted to promote transformer efficiency.
- The Clean Energy Ministerial, with the support of the International Partnership for Energy Efficiency Cooperation (IPEEC), established a programme called the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative, which has identified a set of energy-efficiency performance tiers for distribution transformers.

7.1 Market barriers and failures

It is well known that the energy efficiency of end uses is subject to a variety of market barriers and failures that hinder economically optimal investment in demand reduction. The transformer market is no exception. Table 7-1 summarises the generic barriers to energy efficiency that apply to all energy end uses as well as to transformers. As roughly 80% of distribution transformers are procured by network utilities, it is worth considering the specific barriers that apply to optimal procurement within these organisations. In principle, network utilities have capital to invest in maintaining and upgrading the network that they can procure at competitive market rates, and hence the same type of long-term capital investment process should apply as in other parts of the electricity system, such as generation investment. This should be favourable to transformer investment as the cost of capital will be relatively cheap; however, specific market failures and barriers remain to be addressed. The first and most important of these has already been addressed in Chapter 6 and concerns the degree to which a network utility has a sufficient incentive to invest capital in reducing network losses if the cost of those losses can simply be passed on to the end user and recovered through the tariff. Good-practice utility regulation seeks to compensate for this problem by creating incentives for network loss reduction that partially emulate a competitive market in this domain; however, it should be recognised that this is complex and that even with incentives in place there is a lack of clarity about the optimum design of incentives and how they can best be structured to factor long-term TCO planning into transformer and other loss-reduction investment decisions. Thus, while the creation of such incentives is essential to rectify market failures, it is likely to be a partial solution rather than necessarily sufficient in its own right.

Table 7-1. Barriers to and opportunities for energy-efficient transformers

	Barrier	Effect	Remedial policy tools
VISIBILITY	EE is not measured	EE is invisible and ignored	Test procedures/measurement protocols/efficiency metrics
	EE is not visible to end users & service procurers	EE is invisible and ignored	Ratings/labels/disclosure/benchmarking/audits/real-time measurement and reporting
PRIORITY	Low awareness of the value proposition among service procurers	EE is undervalued	Awareness-raising and communication efforts
	Energy expenditure is a low priority	EE is bundled in with more important capital decision factors	Regulation, mechanisms to decouple EE actions from other concerns
ECONOMY	Split incentives	EE is undervalued	Regulation, mechanisms to create EE financing incentives for those not paying all or any of the energy bill
	Scarce investment capital or competing capital needs	Underinvestment in EE	Stimulation of capital supply for EE investments, incubation and support of new EE business and financing models, incentives
	Energy consumption and supply subsidies	Unfavourable market conditions for EE	Removal of subsidies
	Unfavourable perception and treatment of risk	EE project financing cost is inflated, energy price risk under-estimated	Mechanisms to underwrite EE project risk, raise awareness of energy volatility risk, inform/train financial profession
CAPACITY	Limited know-how on implementing energy-saving measures	EE implementation is constrained	Capacity-building programmes
	Limited government resources to support implementation	Barriers addressed more slowly	Shift government resources toward efficiency goals
FRAGMENTATION	EE is more difficult to implement collectively	Energy consumption is split among many diverse end uses and users	Targeted regulations and other EE enhancement policies and measures
	Separation of energy supply and demand business models	Energy supply favoured over energy service	Favourable regulatory frameworks that reward energy service provision over supply
	Fragmented and under-developed supply chains	Availability of EE is limited and more difficult to implement	Market-transformation programmes

Abbreviation: EE = energy efficiency.

Source: Adapted from *World Energy Outlook 2012* © OECD/IEA, 2012; IEA 2012: Chapter 9, p. 280.

Furthermore, it only affects utilty procurement and usage of distribution transformers and hence has no influence over transformers deployed in the commercial and industrial sectors. The key issue for utility regulation, however, is to ensure that capitalised losses are included in all investment decisions.

Visibility, or the lack of it, remains a barrier for transformer efficiency. Most transformers operate at very high efficiencies, so the small amount of losses is easily ignored. Furthermore, metering of individual transformers is not usually in place and so performance degradation is not always identified. At the network level, the technical losses incurred are often not distinguished from the non-technical ones on account of the energy-flow metering systems used by utilities, so they are not always identified and acted upon. Again, regulators have a role to play in ensuring metering of energy flows is adequate to make technical network losses distinguishable from non-technical ones and their volumes measured and reported.

A low priority placed on technical-loss reduction can often be a result of low visibility. In recent years utility regulators have begun to place more emphasis on addressing technical-loss reduction, but efforts still need to be made to ensure appropriate corporate focus addresses this isssue.

Transformer investments compete with other utility investment and will only be countenanced when the rate of return on capital is competitive with other investments. Thus, regulators again need to create an investment environment that stimulates investment in loss reduction and which is reflective of society's broader long-term goals if short-termism is to be minimised. Among industrial users, the problem may be worse even if the benefits of lower TCO are fully accrued by the organisation. This is because transformers are far from being part of the core business for industrial end users, so they are likely to receive diluted attention and consideration compared with other operational concerns.

Split incentives often apply as a result of split or fragmented management of capital expenditure (Capex) and operational expenditure (Opex) budgets such that the manager of the Capex budget may not have an adequate incentive to make more expensive capital outlays to help minimise the Opex budget. This problem occurs in both the utility sector and the industrial transformer market.

The capacity to assess and implement optimised TCO investment in transformers is not universal. Many utility investors do not apply state of the art techniques to determine the optimum rate of return on their transformer investments; more needs to be done to facilitate and disseminate best practice.

For all these reasons, an increasing number of governments and regulators have found it appropriate to address these market failures through an array of policy measures. These are discussed in the following sections of this chapter.

7.2 Labelling

Labels are designed to provide information about the energy performance of a product to the buyer at the time of purchase. Labelling is particularly important in the consumer market, enabling a customer to learn about the energy performance of a product at the point of sale. In the commercial and professional market, labelling is not as common, but for certain products it can still play a key role in market transformation, particularly if coupled with other supporting policies.

In general, there are two broad categories of energy labels, both of which are designed to encourage the market to purchase more energy efficient products. These two categories are:

i) comparative energy labels – these labels offer information, often on a scale or similar ranking system, that enables users to compare the energy performance between different products. They are usually mandatory to ensure that poorly performing products are labelled too. An example of this label is India's five-star labelling system
ii) endorsement labels – these are usually voluntary schemes where only the best-performing products in the market are authorised to use the label. An example of this label is the 'Energy Star' label.[23]

Labels can be powerful tools in helping to facilitate change in markets, if the buyer is able to understand what the label means and to use the information when making a purchasing decision. Labelling can also be very effective when it is linked to other policies such as procurement specifications and financial subsidies.

In this section of the report, some of the energy labelling schemes in use around the world for distribution transformers are discussed, and the positive 'market pull' effect they have on the market is highlighted.

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[23] See http://www.energystar.gov/

Table 7-2. Summary of country labelling programmes for distribution transformers

Country	National programmes	National reference
Brazil	Mandatory scheme, covers liquid-filled	National Labelling No. 10.295/2001; Portaria Inmetro no. 378, 28/09/2010
Chile	Voluntary scheme; covers liquid-filled and dry-type	NCh3039, which is based on NEMA TP-3
China	China Quality Certification (CQC) Certification Mark; China Standard Certification Center (CSC) programme	http://www.cqc.com.cn/english/index.htm
India*	Labelling for three-phase, liquid-filled up to 200 kVA; procurement specification for three-star units*	IS 1180, based on IEC
Japan	Top Runner Program since 2002 for liquid-filled and dry-type; voluntary labelling scheme Energy Conservation Center, Japan (ECCJ)	JIS C4304, based on IEC
Republic of Korea	Mandatory labelling scheme	KS C IEC 60076, based on IEC
Vietnam	Proposed labelling scheme pending implementation in 2015	

* Likely to be extended up to 2500 kVA.

7.2.1 Labelling programmes for distribution transformers

To some extent, all distribution transformers have a label on the enclosure or tank in the form of a nameplate providing information about the manufacturer, kVA capacity, losses, voltages, impedance and other critical information about that unit. However, these data on the nameplate simply convey information about the performance of that specific unit and neither facilitate comparison between models nor identify units that are top performers with respect to energy efficiency. For this reason, several countries around the world wishing to promote more energy efficient transformers have developed labelling programmes for distribution transformers. Table 7-2 provides a list of these countries.

Looking at three of these schemes in more detail, the cases of Brazil, India and the Republic of Korea are considered. In Brazil, the government established minimum energy-performance levels, including specific standards and related regulation, to limit losses and encourage the specification and purchase of more energy efficient liquid-filled distribution transformers. This effort is being facilitated through the national energy conservation label (ENCE), in accordance with Brazilian law and the national policy on the conservation and efficient use of energy. The Brazilian label for distribution transformers (Figure 7-1) provides information about the manufacturer, model, type, kVA rating and voltage class. It also states the loss in watts at no load and full load, the design temperature rise and the basic impulse insulation level (BIL) of the transformer.

A new standard (ABNT NBR 5440) was developed in Brazil and published in 2013 in order to define different levels (A–E) and thereby promote comparison between different products on the market.

Figure 7-1. Brazilian liquid-filled distribution transformer label.

Energia (Elétrica)

TRANSFORMADOR EM LÍQUIDO ISOLANTE PARA REDE DE DISTRIBUIÇÃO

Fabricante	ABCDEF
Modelo	XYZ(Logo)
Tipo	ABC 1 2 3
Potência (kVA)	ABC 1 2 3
Classe de Tensão (kV)	ABC 1 2 3

Perdas máximas (tap nominal)
- Vazio (W)
- Totais (W)
Relação de Transformação

Perdas máximas (tap crítico)
- Vazio (W)
- Totais (W)
Relação de Transformação

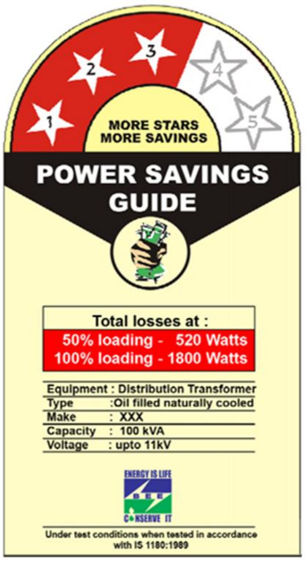
NBI (kV)

IMPORTANTE: NÃO SERÁ PERMITIDA A REMOÇÃO DESTA ETIQUETA EM DESACORDO COM PROGRAMA BRASILEIRO DE ETIQUETAGEM

The Indian government initiated its programme to promote energy-efficient distribution transformers through the use of its mandatory five-star label, which is also applied to other products and equipment sold in India (Figure 7-2). The highest loss designs (i.e. the least efficient) are defined as 1 Star and the lowest loss segment (i.e. the most efficient) designs are defined as 5 Star. The basis for the star ratings in India are:

- 1 Star – intended to represent the current purchasing practice in India, this is based on the maximum losses published in IS 1180 (part 1)
- 2 Star – intended to represent some of the utility purchase specifications such as Andhra Pradesh Central Power Distribution Company and North Delhi Power Limited
- 3 Star – intended to represent losses equivalent to a TCO design where the loss-evaluation formulae are moderate values per watt
- 4 Star – intended to represent losses equivalent to the lowest TCO design, with higher loss-evaluation formulae
- 5 Star – intended to represent a highly efficient design, the best available technology.

Figure 7-2. Indian liquid-filled distribution transformer label.



The label reports total losses (in watts) at both 50% and 100% loading; these values combine the measured no-load and load losses into one numerical value.

In an effort to build on the success of this labelling programme and to give a larger focus to energy efficiency, India recently updated the standard to include kVA ratings up to 2500 for three-phase, liquid-filled distribution transformers and from 6 kVA to 25 kVA for single-phase units. The new Indian standard defines three benchmark energy-efficiency levels for each distribution transformer rating.

In an official notification issued on 20 August 2010, the Central Electricity Authority (CEA) of India published a requirement for all utilities to procure at least a 3-Star distribution transformer.[24]

Figure 7-3. Korean liquid-filled distribution transformer label.

In the Republic of Korea, the government developed a mandatory label that would both facilitate the identification and selection of energy-efficient transformers and link with their MEPS to enable enforcement officers to more easily identify products that are compliant with the regulation. The label clearly shows the percentage efficiency of the unit (at 50% of rated nameplate) to one decimal place – this is consistent with the MEPS regulation for Korea. Beneath the percent efficiency value, the label presents the input and output voltage rating and the power handling capacity of the unit. The unit represented by Figure 7-3 is 98.9% efficient, with an input voltage of 22.9 kV and an output of 3.3 kV. The power rating of the transformer is 750 kVA. The label itself must be affixed to the transformer and should have a diameter of 7 cm.

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[24] Notification was issued by the Government of India vide No:2/11/(5)/03-BEE-3, Dtd: 05.03.2010 and the Central Electricity Authority Notification No: CEA/TETD/MP/R/01/2010 dt: 20.08.2010 under section 177 of Electricity Act 2003 on the Procurement of Star Rated Energy Efficient Distribution Transformer.

7.2.2 Labelling programme effectiveness

For the three countries identified in section 7.2.1, labelling plays an important role in the national energy-efficiency programmes, promoting transition to more energy efficient markets by combining labelling programmes with other policy measures such as procurement specifications or MEPS that ensure more-efficient models are purchased.

While labelling is a good idea in some markets, it may have a limited effect if applied solely on its own, because of the ways in which transformers are specified and purchased. In the utility sector, transformer procurement can very sophisticated and customers often do not view the physical units themselves during purchase, thus the label and the transformer being purchased through a sales contract are often completely independent of each other. In the commercial sector, the customer purchasing the transformer is often an electrical contractor bidding for a job to install the complete electrical system in a building. The electrical contractor, who will not be responsible for the cost of losses in the transformer, achieves a more competitive quote by selecting the least expensive (and least efficient) transformers. This situation is a classic example of the 'split incentive' whereby equipment is specified and installed by someone other than the party responsible for the future running costs. In the USA, the Environmental Protection Agency worked to promote the ENERGY STAR programme on low-voltage, dry-type distribution transformers, but it was found that the label alone was not enough to increase take-up of the more-efficient transformers. It was only when this programme was coupled with a utility incentive payment or similar supporting policy that the market started to change.

In December 2013, the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative published a review of the global transformer market and created five proposed levels that could be used by policymakers in developing an energy-efficient transformer programme. The SEAD efficiency levels offer five different equations that yield the percent efficiency for any kVA rating between 10 and 3150 kVA for liquid-filled and dry-type, single- and three-phase transformers. These different levels provide the flexibility to have both a MEPS level in the market (providing a push to a specific efficiency value) and a higher level that can be labelled and/or incentivised in some way, to pull the market toward higher efficiency.

7.3 Voluntary schemes

In addition to labelling, voluntary programmes seek to promote more energy efficient transformers. Although not mandatory, typically these programmes tend to be used by manufacturers producing premium, efficient products who wish to have this higher performance recognised in the market. A few voluntary schemes that are indicative (but not an exhaustive, global list) of the types of schemes in the market are discussed below.

7.3.1 National high energy performance specifications

Labelling can offer a longer-term view on the direction that policymakers want to take with respect to energy efficiency. In Australia and New Zealand, for example, when MEPS were adopted in 2004, 'HEPS' or 'high energy performance standards' were issued under their joint programme. The intention was that all products should meet MEPS, but should also be looking to the HEPS as a potential, future MEPS requirement. In this way, a signal is being sent to the market about the direction that should be followed in these two countries with regard to increasing the efficiency of distribution transformers.

Two other economies have also specified high-efficiency levels on a national basis. The Republic of Korea and Israel have both developed tables of performance that provide indicative levels reflecting their longer-term policy objectives. In Korea, the government has established MEPS levels and Target Energy Performance Standards (TEPS), and policymakers in Israel have published tables of both MEPS and high-efficiency performance levels (HEPL), each of which consists of maximum no-load and load loss at full load. HEPL are not mandatory but are used as a policy tool for recognition of highly efficient models.

7.3.2 NEMA premium

In the USA, the National Electrical Manufacturers Association (NEMA) first published a high-efficiency specification for transformers in 1996. This voluntary programme was published prior to the US DOE's regulatory work on distribution transformers, but was picked up by the US Environmental Protection Agency, and these NEMA TP-1 levels were adopted as ENERGY STAR. NEMA then updated the TP-1 requirements in 2001, providing some differentiation between insulation classes of medium-voltage dry-type transformers. The NEMA TP-1 programme was subsequently named the 'NEMA Premium Efficiency Transformers Program'[25] and requires 30% less loss than existing DOE regulations (10 CFR 431) for single-phase and three-phase, low-voltage, dry-type distribution transformers.

7.3.3 CEE efficient-transformers programme

The Commercial and Industrial Transformers Initiative of the Consortium for Energy Efficiency (CEE) manages a two-tiered premium-efficiency programme for distribution transformers. CEE's members and other participating organisations in the initiative include electric utilities and regional energy-efficiency organisations. CEE has harmonised its Tier 1 with the NEMA Premium levels and established Tier 2 for three-phase, low-voltage dry-type transformers only, with Tier 2 being more efficient than Tier 1.

7.4 Minimum energy performance standards

Minimum energy performance standards (MEPS) are one of the most powerful tools to ensure that energy-efficient transformers are taken up in the market. Fundamentally, these mandatory regulations require that customers purchase transformers that meet or exceed the specified performance requirements. MEPS can help to facilitate a shift to higher levels of efficiency, particularly when they are combined with supporting policies including financial incentives and communications programmes. Together with monitoring, verification and enforcement activities to ensure regulatory compliance, MEPS provide a foundational measure for policymakers to transform markets and ensure the realisation of national benefits from cost-effective energy savings. At the time of the current report being written, 13 countries around the world have adopted MEPS for their markets. Table 7-3 presents those countries, the distribution transformers covered by them, the metric used (see section 7.5) and the test standard (see section 2.5).

More detail is provided on individual country programmes in Chapter 8. In addition to these national/economy-based initiatives, there are a few international activities that are taking a regional or global perspective on distribution transformers, promoting greater uptake of energy-efficient designs.

7.5 The Clean Energy Ministerial's SEAD Initiative

The Clean Energy Ministerial, with the support of the International Partnership for Energy Efficiency Cooperation (IPEEC), established a programme called the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative. SEAD is a 5-year, US$20 million initiative designed to turn knowledge into action and accelerate the transition to a clean energy future through effective appliance and equipment programmes. SEAD is a multilateral, voluntary effort among Australia, Brazil, Canada, the European Commission, France, Germany, India, Japan, the Republic of Korea, Sweden, the United Arab

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[25] See https://www.nema.org/Technical/Pages/NEMA-Premium-Efficiency-Transformers-Program.aspx

Table 7-3. Summary of programmes in countries with minimum energy performance standards (MEPS) for distribution transformers

Country	National programmes	Metric	Test Standard
Australia	MEPS for liquid & dry-type; voluntary 'high efficiency' rating	% efficiency at 50% loading	AS/NZS 60076.1, based on IEC
Brazil	Liquid-filled	Maximum no-load and load losses	ABNT NBR 5440:2013, based on IEC
Canada	MEPS for dry-type; voluntary code for liquid-filled	% efficiency at 50% loading	CSA C802.2-12, based on IEEE/NEMA
China	MEPS for liquid-filled & dry-type, three grades of performance	Maximum no-load and load losses	GB 1094 series, based on IEC
Europe	MEPS for three-phase liquid-filled & dry-type (no single-phase regulations)	Maximum no-load and load losses	Will be based on IEC 60076 series
India	Labelling for three-phase, liquid-filled up to 200 kVA; procurement specification for 3-Star units	Maximum losses, combined, at 50% and 100%	IS 1180, based on IEC
Israel	MEPS for liquid-filled & dry-type; voluntary high-efficiency levels	Maximum no-load and load losses	IS 5484, based on IEC
Republic of Korea	MEPS for liquid-filled & dry-type; voluntary 'high efficiency' rating	% efficiency at 50% loading	KS C IEC 60076, based on IEC
Mexico	MEPS for liquid-filled units only (no regulation for dry-type)	% efficiency at 50% loading	NOM-002-SEDE-2010
New Zealand	MEPS for liquid-filled & dry-type; voluntary 'high efficiency' rating	% efficiency at 50% loading	AS/NZS 60076.1, based on IEC
Peru	Draft MEPS for liquid-filled, single- & three-phase	To be determined	To be determined
USA	MEPS for liquid-filled & dry-type, new MEPS in 2016; voluntary programmes	% efficiency at 50% loading	10 CFR 431, Subpart K, based on IEEE/NEMA
Vietnam	MEPS for liquid-filled	% efficiency at 50% loading	TCVN 6306-1, based on IEC

Emirates, the United Kingdom, and the USA.[26] The operating sgent for SEAD is CLASP, a non-profit organisation with deep experience in supporting international appliance-efficiency efforts.

SEAD initiated a study published in December 2013 that reviewed energy-efficiency policies and programmes for distribution transformers around the world. This study identified programmes in 13 countries and applied normalisation calculations to create an equivalent, comparative basis for the various programmes. It then developed a set of four 'best fit' curves that approximated the data points over the range of efficiency values used in these programmes, and developed Tier 5 which was meant to represent the best available technology.

Tables 7-4 and 7-5 present the equations developed for both liquid-filled and dry-type distribution transformers. When the user plugs in the kVA rating (either IEC kVA or the IEEE kVA rating) – represented by the letter '*S*' in the equations, the result is a percentage efficiency at 50% of rated load for 50 Hz operation. Of the five tiers, Tier 1 is the least efficient and Tier 5 is the most efficient.

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[26] For more information about SEAD, see www.superefficient.org

Table 7-4. Equations for determining SEAD efficiency Tiers 1–5 for distribution transformers operating at 50 Hz as a function of IEC/IEEE kVA ratings (*S*)*

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	$= 1 - \frac{0.0620}{S^{0.30}}$	$= 1 - \frac{0.0490}{S^{0.30}}$	$= 1 - \frac{0.0412}{S^{0.30}}$	$= 1 - \frac{0.0351}{S^{0.30}}$	$= 1 - \frac{0.0310}{S^{0.30}}$

* Equation outputs give the percentage efficiency at 50% of rated load.

Table 7-5. Equations for determining SEAD efficiency Tiers 1–5 for distribution transformers operating at 60 Hz as a function of IEC/IEEE kVA ratings (*S*)*

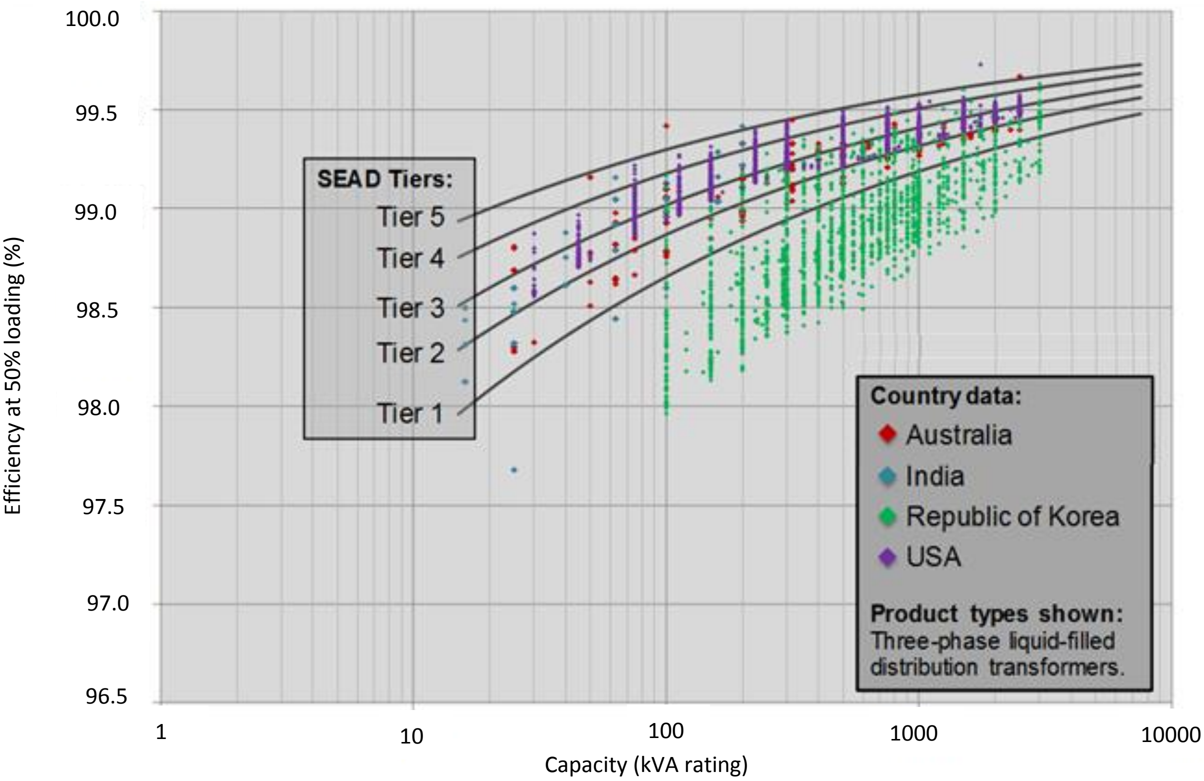
Type	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Liquid-filled three-phase	$= 1 - \frac{0.03584}{S^{0.227}}$	$= 1 - \frac{0.03019}{S^{0.227}}$	$= 1 - \frac{0.02627}{S^{0.227}}$	$= 1 - \frac{0.02203}{S^{0.227}}$	$= 1 - \frac{0.01851}{S^{0.227}}$
Liquid-filled single-phase	$= 1 - \frac{0.0346}{S^{0.227}}$	$= 1 - \frac{0.02899}{S^{0.227}}$	$= 1 - \frac{0.02476}{S^{0.227}}$	$= 1 - \frac{0.02031}{S^{0.227}}$	$= 1 - \frac{0.01649}{S^{0.227}}$
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	$= 1 - \frac{0.04044}{S^{0.30}}$	$= 1 - \frac{0.03132}{S^{0.30}}$	$= 1 - \frac{0.02585}{S^{0.30}}$	$= 1 - \frac{0.02169}{S^{0.30}}$	$= 1 - \frac{0.01896}{S^{0.30}}$

* Equation outputs give the percentage efficiency at 50% of rated load.

The SEAD levels were then applied in an IEA 4E Mapping and Benchmarking study that looked at actual market data from five countries: Australia, Canada, India, the Republic of Korea and the USA (IEA 2014b). The five SEAD tiers were superimposed over a scatter plot of data for the models on the market in these five countries, as shown in Figure 7-4.

The Republic of Korea (green dots) has comparatively low MEPS levels that were not considered by SEAD when setting the recommended tiers. While Korea does have several modelsbelow the Tier 1 line, it also has many models within the range of efficiencies shown for models in the other economies reviewed, including Australia, India and the USA. The Mapping and Benchmarking study found that, with the exception of some lower-performing units in Korea, there is reasonably good correspondence between the market data and the SEAD tiers.

Figure 7-4. Comparison of SEAD tiers with IEA 4E mapping and benchmarking market data.



7.6 IEC and CENELEC Committee Draft

An IEC Technical Committee is developing a set of energy-performance standards to recommend as a global standard. In December 2013, this Technical Committee prepared and issued a Committee Draft (CD) of IEC 60076-20, entitled ‘Power transformers – Part 20: Energy efficiency’, which covers two efficiency levels that were copied from the draft European regulatory requirements, and includes a table of efficiency requirements from the USA. Work on this document is ongoing, and the IEC Technical Committee is now looking at the results of the SEAD report and the feedback it received on the CD. The output of this process may be a technical guidance note, rather than a full international standard.

7.7 APEC Efficient Transformer Initiative

In the Asia–Pacific region, the APEC economies have been working together to harmonise and coordinate their efforts on energy-efficiency standards and labelling programmes for a number of products. Recently, policymakers from the APEC economies have begun to turn their attention to distribution transformers, for which a number of studies have been produced. One report prepared by Lawrence Berkeley National Laboratory looked to increase awareness among APEC policymakers of the cost-effective potential to establish or increase efficiency requirements for distribution transformers. This study looked across 20 APEC economies, large and small, and conducted individual country-level economic analyses of MEPS for distribution transformers (Letschert et al. 2013). A second report was prepared by ECONOLER and performed three key tasks: (1) analysed enablers for and barriers to introducing MEPS or increasing ambition in individual APEC countries; (2) reviewed the APEC experience, successes and failures of energy-efficiency standards and labelling programmes for distribution transformers and identified best practices; and (3) provided a strategic framework for developing national roadmaps for introducing or raising mandatory MEPS for distribution transformers (ECONOLER 2013). These two studies have provided current and compelling evidence to the APEC economies and their findings are currently under consideration.

7.8 The Integrated Policy Approach

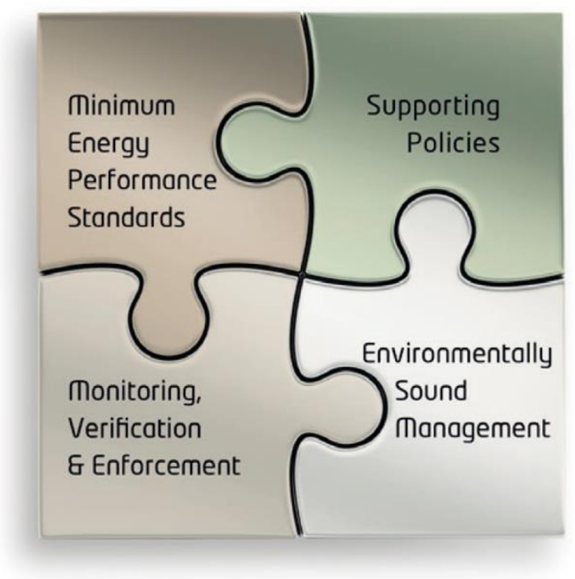
Product market-transformation strategies need to be designed for the long-term, sustained phasing-out of inefficient products from the market while ensuring an environmentally sound management system to collect and recycle decommissioned transformers. To address these issues and guarantee a robust market transition, UNEP's en.lighten initiative developed a concept called the 'Integrated Policy Approach' (IPA).

The IPA has four core elements, shown in Figure 7-5. This process highlights the importance of a multi-stakeholder consensus process, incorporating the needs and priorities of public- and private-sector partners, non-governmental organisations, civil society and financing institutions. This integrated approach helps to ensure that the resulting market transformation is both successful and sustainable.

Minimum energy performance standards

MEPS are regulatory measures specifying minimum efficiency or maximum losses that must be met or exceeded for distribution transformers sold in a particular country. In a MEPS policy measure, countries will define the parameters, stringency and implementation (i.e. phase-in) period for the regulation. Many countries choose to review existing measures in major markets to learn from that best practice and apply it to their own market. A schedule of future performance standards may require greater stringency as more-efficient technology becomes available, e.g. Europe recently established a Tier 1 that takes effect in 2015 and a more stringent Tier 2 that will become effective in 2021. In addition to energy-performance standards, regulations can stipulate other requirements such as maximum noise levels.

Figure 7-5. Integrated Policy Approach for a rapid transition to energy-efficient distribution transformers.



Source: UNEP 2012 (reproduced with permission).

Supporting policies

Supporting policies ensure that the objectives of the MEPS are met by enabling all market players to make an effective transition to higher-efficiency technologies and practices. Examples of supporting policies include energy labelling, directives, executive orders, laws and implementation regulations that require products or system designs to improve energy efficiency. There are also economic and market-based instruments, including market mechanisms, that are often initiated and promoted by regulatory incentives but which can also contain elements of voluntary action or participation. Other strong, supporting policy measures are fiscal instruments and incentives, including subsidies and tax breaks aimed at reducing energy consumption, or financial incentives to overcome initial cost differences. Finally, information and voluntary action are a key supporting policy, providing communications and outreach that persuades users to change or modify their behaviour by providing relevant information and examples of successful implementation.

Monitoring, verification and enforcement

To ensure compliance with MEPS and labelling requirements, there must be a robust, functional system of monitoring, controlling and testing facilities capable of ensuring enforcement and full compliance with standards. Unless effective and timely market surveillance systems are enforced, substandard products could enter markets in increasing numbers, reducing energy and financial savings.

Compliance activities have multiple purposes that seek to protect transformer buyers (particularly commercial and industrial customers) from products that do not perform as declared. Compliance activities are undertaken in three parts: (1) monitoring is a measurement process to verify product efficiency; (2) verification is the process through which declarations of compliance are confirmed by transformer suppliers, testing laboratories or third-party services; and (3) enforcment is the system of action taken by programme administrators or other responsible parties against suppliers of non-compliant (including counterfeit) products. In addition to this, compliance benefits can also be derived by enhancing the capacity of various countries, and the sharing of information and skills between countries and across regions provides an effective means through which to promote best practice, quickly and thoroughly.

It should be noted that compliance testing of transformers by market surveillance agencies can be difficult, on account of the size and cost of transformers and the equipment necessary to conduct the tests. For these products, review of test reports and other compliance paperwork may prove to be a more practical alternative to testing. However, it is clear that product compliance can be assured only through testing.

Environmentally sound management

Environmentally sound management encompasses all phases of the life cycle for transformers, including materials used in manufacture, the manufacturing processes, distribution, use, collection and recycling. The purpose of this part of the IPA is to ensure that environmental issues are taken into account and that there is compliance with regulatory requirements encompassing hazardous waste and health and safety. Examples of environmentally sound management include: (1) development of a legal framework for environmentally sound end-of-life activities, making this a high national priority and ensuring coordinated law enforcement; (2) each country’s environmentally sound management plan giving consideration to the concept of extended producer responsibility; and (3) drafting and implementation of policy and legislation before formal collection channels and recycling facilities are established.

8. Ongoing initiatives

8.1 Global policy overview

Over the last decade, many new national efforts have been initiated to accelerate the market transition to energy-efficient distribution transformers. Figure 8-1 provides a snapshot of the countries that are covered under these programmes, representing 60% of the world's population and 75% of global electricity consumption.

This section of the report provides a summary of the programmes and initiatives being established by policymakers in these countries to support the take-up of energy-efficient distribution transformers. While these countries represent a large share of the population and demand in 2014, the growth projections in terms of both population and electricity demand in other countries that do not yet have programmes is substantial. According to forecast estimates by the Energy Information Administration, for example, 73% of new electricity growth between now and 2030 will occur in countries that currently have no programmes for distribution transformers.

8.2 Country profiles

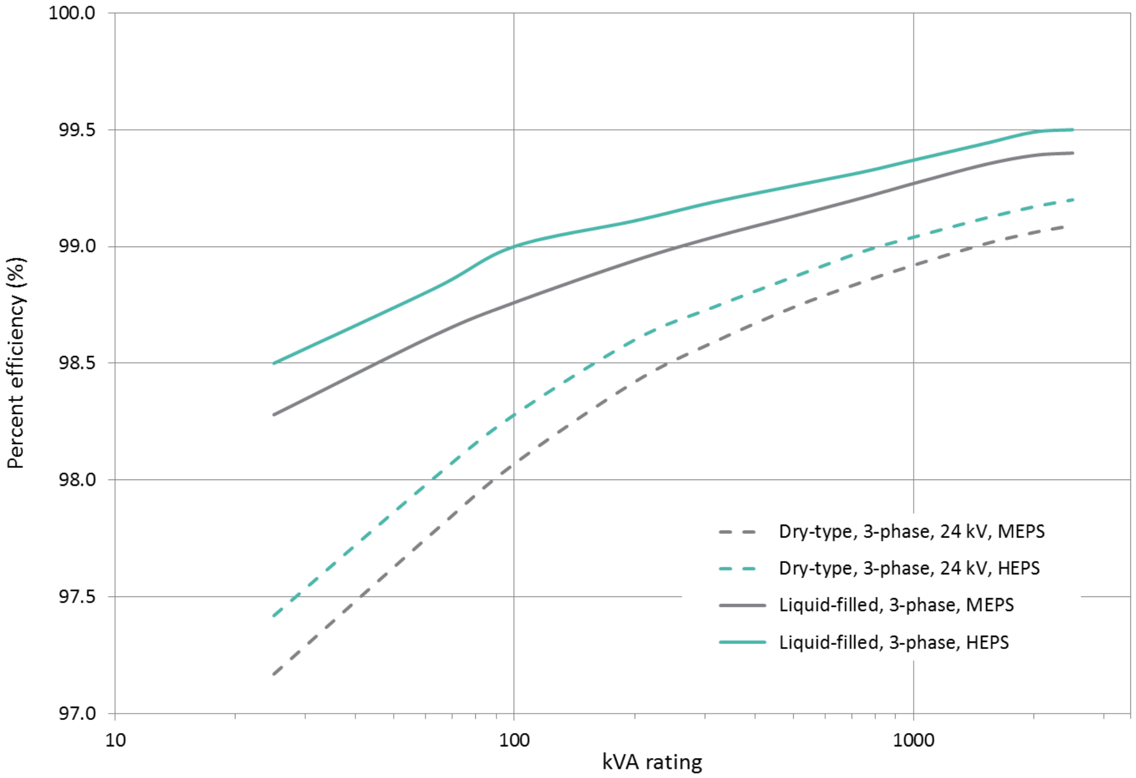
Thirteen economies around the world currently have MEPS and other national programmes in place to promote energy-efficient transformers: Australia, Brazil, Canada, China, Europe, India, Israel, Japan, the Republic of Korea, Mexico, New Zealand, USA and Vietnam. All of the country information in the following sections is adapted from Part 4 of the *SEAD Distribution Transformers Report* (SEAD 2013).

8.2.1 Australia and New Zealand

Australia and New Zealand have one of the longest-running energy-efficiency MEPS programmes for distribution transformers in the world, having adopted minimum efficiency requirements for both

Figure 8-1. Countries with national policies promoting energy-efficient distribution transformers.

Figure 8-2. Australia and New Zealand minimum energy performance standards (MEPS) and high energy performanc standards (HEPS) for three-phase distribution transformers.



liquid-filled and dry types in 2004. The liquid-filled regulations apply to single- and three-phase 10–2500 kVA units, and the dry-type regulations apply to single- and three-phase 15–2500 kVA units. In both instances, the requirements are prescribed at 50% of rated capacity.

In addition to MEPS, Australia and New Zealand have harmonised high energy performance standards (HEPS), which have the same scope of coverage as the mandatory requirements and represent an aspirational, voluntary level that is indicative of a possible future MEPS level. Manufacturers are allowed to promote any of their products that meet or exceed these levels.

Figure 8-2 illustrates the MEPS and HEPS that were adopted in 2004 for three-phase dry-type and liquid-filled distribution transformers. A review of the regulations is currently being performed and the 2004 levels may be updated in the near future.

8.2.2 Brazil

Brazil’s market-transformation work on distribution transformers was initiated through an energy-efficiency label, including MEPS based on Inmetro regulation 378/2010.

The Brazilian labelling scheme provides information such as the manufacturer, model, type and kVA rating. Total loss at no load and full load (in watts) is stated, together with the temperature rise and basic impulse insulation level (BIL) at the nominal tap and the furthest from nominal. The label was developed in accordance with Brazilian national law No. 10.295/2001, concerning national policy for the conservation and rational use of energy.

Brazil adopted MEPS for liquid-filled distribution transformers in 2010. These MEPS apply to single- and three-phase transformers from 5 to 100 kVA and 15 to 300 kVA, respectively, and voltage classes of 15, 24.2 and 36.2 kV. The regulation sets maximum levels of watts permitted for no-load and load losses separately, for both three-phase (Table 8-1) and single-phase (Table 8-2), liquid-filled transformers.

Table 8-1. MEPS for three-phase, liquid-filled distribution transformers in Brazil

kVA rating	15 kV units		24.2 kV units		36.2 kV units	
	No-load loss (watts)	Load loss (watts)	No-load loss (watts)	Load loss (watts)	No-load loss (watts)	Load loss (watts)
15	85	410	95	470	100	460
30	150	695	160	790	165	775
45	195	945	215	1055	230	1075
75	295	1395	315	1550	320	1580
112.5	390	1890	425	2085	440	2055
150	485	2335	520	2610	540	2640
225	650	3260	725	3605	750	3600
300	810	4060	850	4400	900	4450

Table 8-2. MEPS for single-phase, liquid-filled distribution transformers in Brazil

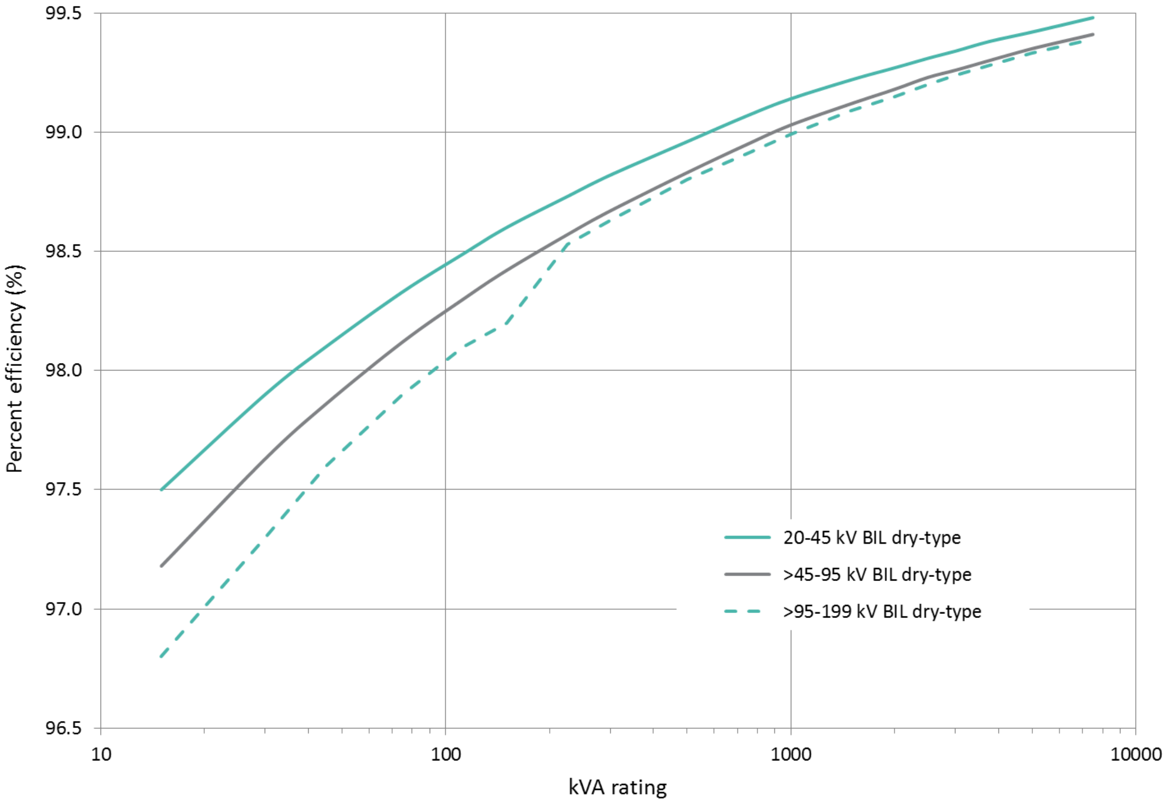
kVA rating	15 kV units		24.2 kV units		36.2 kV units	
	No-load loss (watts)	Load loss (watts)	No-load loss (watts)	Load loss (watts)	No-load loss (watts)	Load loss (watts)
5	35	140	40	155	45	160
10	50	245	55	265	60	270
15	65	330	75	365	80	380
25	90	480	100	520	105	545
37.5	135	665	145	740	150	740
50	165	780	190	925	200	935
75	205	1110	225	1210	240	1225
100	255	1445	275	1495	280	1480

8.2.3 Canada

In Canada, the main policy instruments promoting energy-efficient distribution transformers is a MEPS scheme for low- and medium-voltage dry types and a voluntary standard for liquid-filled types. MEPS for dry-type distribution transformers became effective in April 2012, harmonising with US MEPS and replacing the previous Canadian standards that had been in place since 2005. The Canadian MEPS apply to single-phase, 15–833 kVA, and three-phase, 15–7500 kVA dry-type transformers of 35 kV or less, with performance requirements being set out separately for single- and three-phase (Figure 8-3) units, and for low- and medium-voltage units, at 50% of the rated load. These dry-type regulations establish different requirements based on the insulation rating of the transformer winding, also called the basic impulse insulation level (BIL). As a transformer achieves a higher BIL rating, it becomes more difficult to achieve high efficiency because of the additional distance the magnetic flux must travel because of the extra insulation.

For liquid-filled transformers, Canada has published voluntary efficiency levels through the Canadian Standards Association under CSA C802.1-2000. These voluntary levels apply to all liquid-filled, single- (10–833 kVA) and three-phase (15–3000 kVA), 60 Hz distribution transformers, with a primary voltage of 34.5 kV or less. These standards are followed by utilities and the transformer industry, and are referenced in the Canadian Electrical Code. The Canadian Electricity Association monitored

Figure 8-3. Minimum efficiency for three-phase, dry-type distribution transformers in Canada (BIL = basic impulse insulation level).



liquid-filled transformer sales in Canada between 2000 and 2004 and found compliance levels with this voluntary specification were more than 99%.

8.2.4 China

China first adopted MEPS for distribution transformers in 2006, covering three-phase liquid-filled (30−1600 kVA capacity) and dry types (30−2500 kVA capacity) and extending coverage to large power transformers. These standards were updated in June 2013 by the China National Institute of Standardization (CNIS), which issued national standard GB 20052-2013 on ‘Minimum allowable values of energy efficiency and energy efficiency grades for three-phase distribution transformers’, specifying the maximum allowable no-load and load losses. Liquid-filled units have a Grade 3 level, based on conventional silicone steel (cold-rolled grain-oriented, or CRGO, steel), as well as Grade 2 and 1 levels, which include maximum losses for both CRGO steel and an amorphous metal distribution transformer (AMDT) design; Table 8-3 presents the maximum losses permitted.

China is also one of the few countries in the world to set regulations on large power transformers (which are outside of the scope of this report). The national standard GB 24790-2009 prescribes minimum permitted energy-efficiency levels, which apply to three-phase, oil-filled types with a rated working frequency of 50 Hz, voltage level of 35–220 kV and rated power of 3150 kVA and above.

China also has an industry standard document (JB/T 10317-02) that applies to single-phase, liquid-filled transformers rated between 5 and 160 kVA.

Table 8-3. MEPS for three-phase, liquid-filled distribution transformers in China (GB 20052-2013)

kVA rating	Level 3		Level 2				Level 1			
	CRGO		CRGO-DT		AMDT		CRGO-DT		AMDT	
	No-load loss (W)	Load loss (W)	No-load loss (W)	Load loss (W)	No-load loss (W)	Load loss (W)	No-load loss (W)	Load loss (W)	No-load loss (W)	Load loss (W)
30	100	600	80	600	33	600	80	480	33	540
50	130	870	100	870	43	870	100	695	43	785
63	150	1040	110	1040	50	1040	110	830	50	935
80	180	1250	130	1250	60	1250	130	1000	60	1125
100	200	1500	150	1500	75	1500	150	1200	75	1350
125	240	1800	170	1800	85	1800	170	1440	85	1620
160	280	2200	200	2200	100	2200	200	1760	100	1980
200	340	2600	240	2600	120	2600	240	2080	120	2340
250	400	3050	290	3050	140	3050	290	2440	140	2745
315	480	3650	340	3650	170	3650	340	2920	170	3285
400	570	4300	410	4300	200	4300	410	3440	200	3870
500	680	5150	480	5150	240	5150	480	4120	240	4635
630	810	6200	570	6200	320	6200	570	4960	320	5580
800	980	7500	700	7500	380	7500	700	6000	380	6750
1000	1150	10 300	830	10 300	450	10 300	830	8240	450	9270
1250	1360	12 000	970	12 000	530	12 000	970	9600	530	10 800
1600	1640	14 500	1170	14 500	630	14 500	1170	11 600	630	13 050

Abbreviations: AMDT = amorphous metal distribution transformers; CRGO-DT = cold-rolled grain-oriented steel distribution transformers.

8.2.5 Europe

Europe originally initiated a voluntary effort to promote energy-efficient transformers through the European norm 50464-1, which covers the same liquid-filled units that were previously included in the Harmonised Document HD 428. For dry-type transformers, the European norm was EN 50541-1, which was based on HD 538. In these voluntary standards, maximum loss levels were associated with ratings of A, B and C, using subscripts ‘o’ for no-load losses and ‘k’ for load losses. This approach was meant to facilitate transformer specification, such that customers could choose a combination of no-load and load losses, such as ‘AoBk’.

In May 2014, the European Commission published MEPS for ‘small, medium and large power transformers’ under the Ecodesign Directive. This comprehensive regulation covers transformers used in 50 Hz electricity T&D networks and in commercial and industrial installations, with a minimum rating of 1 kVA. The regulations establish maximum load and no-load losses for three-phase liquid-filled and dry-type transformers. As yet, there are no requirements on single-phase transformers in Europe, nor are there any labelling requirements, as only Ireland and the UK use such units.

Table 8-4 sets out the MEPS for three-phase, liquid-filled, medium power transformers in Europe (OJEU 2014). The first set of requirements will take effect on 1 July 2015 and the second (more stringent) tier will take effect on 1 July 2021. There are other tables in the EU regulation which provide the maximum losses for dry-type as well as larger-capacity transformers. Large power transformers have a PEI requirement (see section 2.4.4).

Table 8-4. MEPS for three-phase, liquid-filled, medium power transformers (≤3150 kVA) in Europe

kVA rating	Tier 1 (from 1 July 2015)		Tier 2 (from 1 July 2021)	
	Maximum no-load losses (Po; W)*	Maximum load losses (Pk; W)*	Maximum no-load losses (Po; W)*	Maximum load losses (Pk; W)*
≤25	70	900	63	600
50	90	1100	81	750
100	145	1750	130	1250
160	210	2350	189	1750
250	300	3250	270	2350
315	360	3900	324	2800
400	430	4600	387	3250
500	510	5500	459	3900
630	600	6500	540	4600
800	650	8400	585	6000
1000	770	10 500	693	7600
1250	950	11 000	855	9500
1600	1200	14 000	1080	12 000
2000	1450	18 000	1305	15 000
2500	1750	22 000	1575	18 500
3150	2200	27 500	1980	23 000

* Maximum losses for kVA ratings that fall between the ratings given in this table shall be obtained by linear interpolation.

In addition to distribution transformers, the recent European regulation establishes requirements for transformers with rated power >3150 kVA expressed as minimum PEI values for liquid-filled and dry-type transformers. The EU regulation also establishes requirements for pole-mounted transformers; these requirements are less stringent than those for pole-mounted transformers in other economies around the world.

8.2.6 India

In January 2010, India established a mandatory energy labelling scheme for certain three-phase, liquid-filled distribution transformers that are naturally air-cooled. These requirements apply to models covered under the Bureau of Energy Efficiency (BEE) labelling programme (some of which are also covered by the Indian Standard IS 1180 (Part I)) with power capacity ratings of 16, 25, 63, 100, 160 and 200 kVA. The label is based on a five-star rating system, ranging from one star (least efficient) to five stars (most efficient). The scale enables users to easily differentiate between transformers with the same kVA rating.

In August 2010, India’s CEA issued a requirement for all utilities to procure at least a 3-Star distribution transformer; this functions effectively as a MEPS for the electric utility sector (the largest consumer of distribution transformers in India). Table 8-5 presents the maximum losses associated with the Star levels. Maximum losses are defined at 50% and 100% of rated load and, as for Japan, are combined (i.e. the losses are the sum of no-load and load losses at the defined loading points).

At the time of writing, India is actively working on a review of the scope of the label coverage, through the Bureau of Indian Standards (BIS) and BEE. In June 2013, BIS issued document number ETD 16(6648), entitled ‘Outdoor type oil immersed distribution transformers up to and including 2500 kVA, 33 kV [Fourth Revision of IS 1180 (Part 1)]’, to all members of Technical Committee ET 16,

Table 8-5. Maximum losses (in watts) at 50% and 100% of rated load for three-phase, liquid-filled distribution transformers, according to the 5-star rating system, in India

kVA rating	1 Star		2 Star		3 Star		4 Star		5 Star	
	50%	100%	50%	100%	50%	100%	50%	100%	50%	100%
16	200	555	165	520	150	480	135	440	120	400
25	290	785	235	740	210	695	190	635	175	595
63	490	1415	430	1335	380	1250	340	1140	300	1050
100	700	2020	610	1910	520	1800	475	1650	435	1500
160	1000	2800	880	2550	770	2200	670	1950	570	1700
200	1130	3300	1010	3000	890	2700	780	2300	670	2100

Table 8-6. Indian Standard IS 1180: maximum permitted losses (in watts) at 50% and 100% of rated load for three-phase, liquid-filled distribution transformers up to 11 kV

kVA rating	Impedance (%)	Energy efficiency level 1		Energy efficiency level 2		Energy efficiency level 3	
		50%	100%	50%	100%	50%	100%
16	4.5	150	480	135	440	120	400
25	4.5	210	695	190	635	175	595
63	4.5	380	1250	340	1140	300	1050
100	4.5	520	1800	475	1650	435	1500
160	4.5	770	2200	670	1950	570	1700
200	4.5	890	2700	780	2300	670	2100

the Electrotechnical Division Council and other interested parties. In this document, BIS and BEE propose to extend the coverage of the national standard up to and including 2500 kVA and 33 kVA.This standard is now published and defines the maximum total loss levels not only for 16–200 kVA transformers covered by the original standard, but also for liquid-filled transformers of the same voltage class (11 kV) from 250 to 2500 kVA. In addition, a new table of energy-efficiency losses has been added for single-phase, liquid-filled transformers from 5 to 25 kVA. Each of the tables now has three levels of energy efficiency, Level 1 being the lowest efficiency and Level 3 the highest. Table 8-6 is indicative of the new tables of combined maximum losses contained in IS 1180. Other tables can be viewed at the BIS website: http://www.standardsbis.in/

8.2.7 Israel

Israel adopted national regulatory requirements establishing maximum no-load and load losses for distribution transformers with nominal input voltage of 22 kV or 33 kV and a nominal output voltage of 400 V, with power ratings up to 2500 kVA. The referenced national standard is Israeli Standard (IS) 5484, 'Distribution transformers − energy efficiency requirements and marking', and establishes requirements regarding losses and labelling.

IS 5484 contains six tables of maximum no-load and load losses for liquid-filled and dry-type (cast resin coil) distribution transformers. It exempts special-purpose transformers such as metering transformers, testing transformers, welding transformers, starter transformers and others. The requirements establish maximum no-load loss and load losses at 100% of rated capacity. Israel's regulation is similar to the Australia/NZ regulation, in that they have published both a MEPS level and a high-efficiency performance level (HEPL). Table 8-7 presents the maximum permitted losses for the MEPS and HEPL specified in IS 5484 for three-phase, liquid-filled distribution transformers.

Table 8-7. Maximum losses for three-phase, liquid-filled distribution transformers (22 kV) in Israel

kVA rating	Minimum energy performance standard (MEPS)		High-efficiency performance level (HEPL)	
	No-load loss (Po; W)	Load loss (Pk; W)	No-load loss (Po; W)	Load loss (Pk; W)
100	550	1700	300	1700
160	750	2300	390	2300
250	1020	3300	550	3000
400	1380	4800	870	4700
630	1900	6930	1100	6300
800	2250	7800	1400	7500
1000	2650	9100	1550	8700
1250	3050	11 000	2000	10 600
1600	3600	13 500	2250	13 000
2000	4620	14 500	2950	12 500
2500	5750	17 000	3400	14 000

8.2.8 Japan

The Japanese government works, in part, to promote energy-efficient transformers through its Top Runner Program. This is slightly different from MEPS programmes found in other countries, in that rather than establishing a minimum requirement for each individual distribution transformer, the Top Runner Program establishes an average value that must be achieved across a production run – in other words, the average of the population has to meet or exceed the Top Runner value, with individual units falling above or below the requirement.

The Top Runner Program applies to both liquid-filled and dry-type, 50 and 60 Hz units (both types of electrical distribution systems exist in Japan), with requirements for both single-phase (rated between 5 and 500 kVA) and three-phase (rated between 10 and 2000 kVA) units. The Top Runner Program issued an update to its requirements in October 2013. Performance is determined by establishing a maximum level of energy consumption (in watts) at 40% loading for ≤500 kVA and 50% loading for >500 kVA. The maximum loss levels allowed under the scheme are calculated from an equation based on the kVA rating of the transformer.

Table 8-8 presents the Japanese Top Runner Program equations, covering both liquid-filled and dry-type (‘encapsulated windings’), single- and three-phase distribution transformers, at 50 Hz and 60 Hz frequency.

The test methods used for measuring losses are those given in Japanese Industrial Standards JIS C4304-2013 (6 kV liquid-filled distribution transformers) and JIS C4306-2013 (6 kV encapsulated-winding distribution transformers). Tolerances of maximum losses for individual transformers are specified as 10% in both of these standards.

8.2.9 Republic of Korea

In 2012, the Korean government, like Australia/NZ and Israel, adopted a two-tier system for promoting energy-efficiency requirements – a set of mandatory efficiency requirements for liquid-filled and dry-type distribution transformers, and a set of Target Energy Performance Standards (TEPS). The scope of coverage in Korea includes the main types of distribution transformers used there: dry-type, single-phase and three-phase from 50 to 3000kVA; and liquid-filled, single-phase and three-phase from 10 to 3000 kVA. The requirements set a minimum efficiency requirement at 50% rated load. Although the Korean MEPS have been found to be not particularly ambitious when

Table 8-8. Top Runner Program for distribution transformers in Japan, 2013

Category				Top Runner target standard value (maximum watts)
Type	Phase	Frequency	Capacity	
Liquid-filled	Single	50 Hz	≤500 kVA	E = 11.2 × *S*^0.732
		60 Hz	≤500 kVA	E = 11.1 × *S*^0.725
	Three	50 Hz	≤500 kVA	E = 16.6 × *S*^0.696
			>500 kVA	E = 11.1 × *S*^0.809
		60 Hz	≤500 kVA	E = 17.3 × *S*^0.678
			>500 kVA	E = 11.7 × *S*^0.790
Encapsulated winding	Single	50 Hz	≤500 kVA	E = 16.9 × *S*^0.674
		60 Hz	≤500 kVA	E = 15.2 × *S*^0.691
	Three	50 Hz	≤500 kVA	E = 23.9 × *S*^0.659
			>500 kVA	E = 22.7 × *S*^0.718
		60 Hz	≤500 kVA	E = 22.3 × *S*^0.674
			>500 kVA	E = 19.4 × *S*^0.737

Abbreviation: S = rated capacity (kVA).

compared to the requirements of other markets (SEAD 2013), the market purchases distribution transformers that exceed the minimum efficiency levels (IEA 2014b). Korea is studying its current MEPS levels with a view to possibly updating them in the near future. Figure 8-4 illustrates the MEPS and TEPS for three-phase liquid-filled and dry-type distribution transformers in Korea.

Figure 8-4. Efficiency requirements for three-phase distribution transformers in Korea (MEPS = minimum energy performance standards; TEPS = Target Energy Performance Standards).

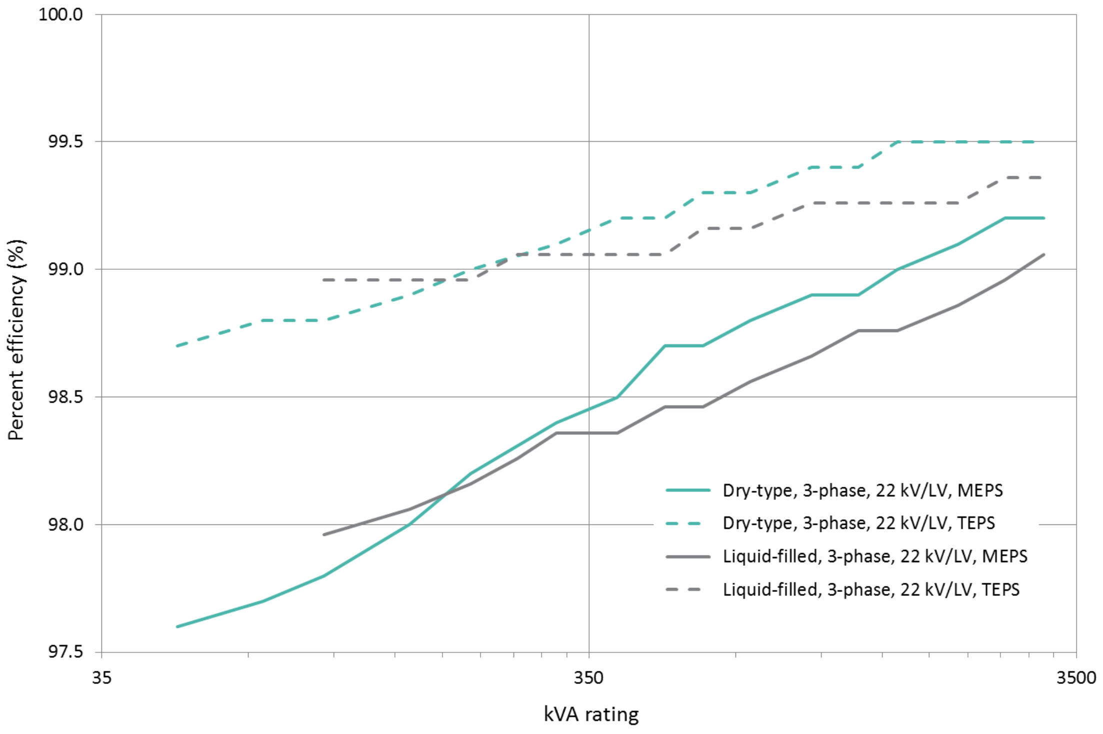


Table 8-9. Minimum energy performance standards for three-phase, liquid-filled distribution transformers in Mexico, 2012

kVA rating	Up to 95 BIL (15 kV)		Up to 150 BIL (18–25 kV)		Up to 200 BIL (34.5 kV)	
	Minimum efficiency (%)	Maximum loss (watts)	Minimum efficiency (%)	Maximum loss (watts)	Minimum efficiency (%)	Maximum loss (watts)
15	98.32	205	98.18	222	98.03	241
30	98.62	336	98.50	365	98.35	403
45	98.72	467	98.60	511	98.48	556
75	98.86	692	98.75	759	98.64	827
112.5	98.95	955	98.85	1047	98.76	1130
150	99.03	1175	98.94	1286	98.86	1384
225	99.06	1708	98.96	1892	98.87	2057
300	99.11	2155	99.02	2375	98.92	2620
500	99.20	3226	99.11	3592	99.03	3918

Abbreviation: BIL = basic impulse insulation level.

8.2.10 Mexico

Mexico has a long tradition of energy-efficiency standards through regulation. Current regulations cover both single- and three-phase liquid-filled distribution transformers with a primary voltage of 34 500 kV or below and a secondary voltage of 15 000 kV or below. These regulations apply to 5−167 kVA capacity for single-phase units and 15−500 kVA capacity for three-phase units, and apply to pad, pole, substation and submersible transformer installations and to newly purchased as well as repaired/refurbished units.

Although dry-type distribution transformers are used in Mexico, no mandatory regulatory standards have yet been adopted.

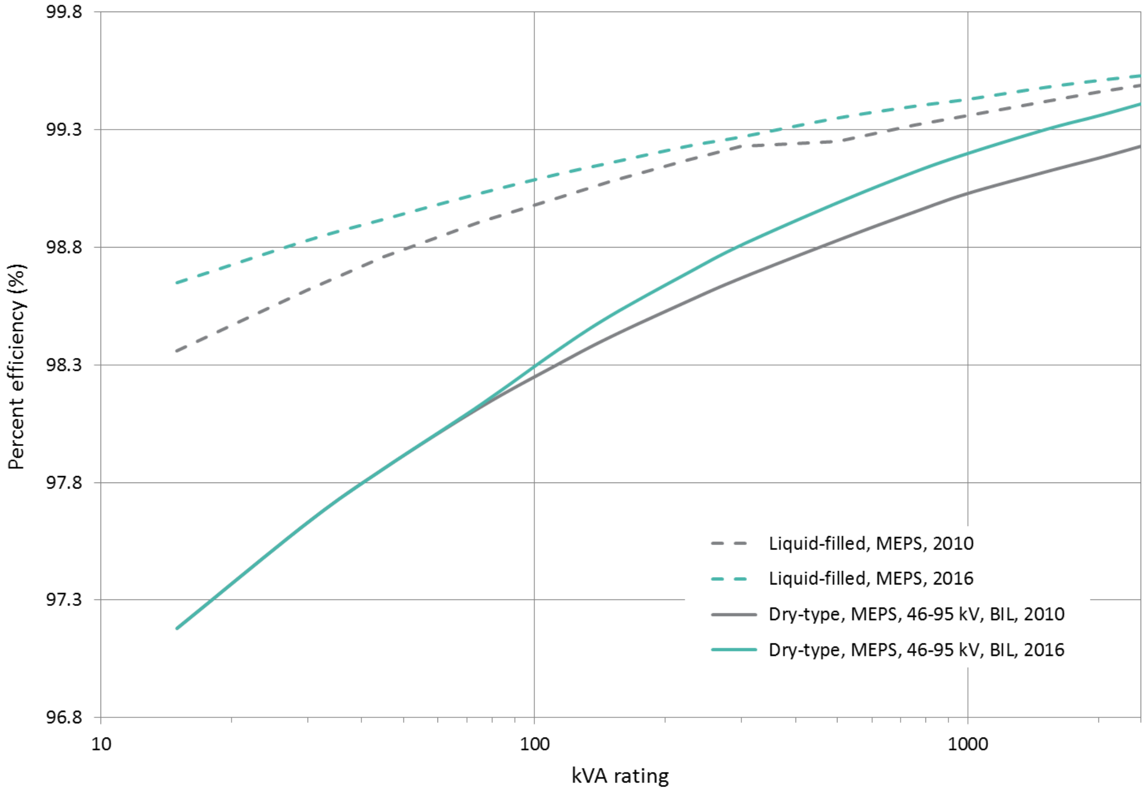
The Mexican government reviewed and updated its national regulation, NOM-002-SEDE/ENER-2012, in August 2012. Table 8-9 presents the requirements and the proposed new requirements for three-phase, liquid-filled distribution transformers, with three groups based on the primary voltage and with respect to both percentage efficiency and maximum loss. For both metrics, transformer performance is measured at 80% of rated output.

8.2.11 The USA

The USA has had a policy focus on energy-efficient distribution transformers for over 20 years, starting with the Energy Policy Act of 1992, when the US DOE initiated a process to develop efficiency standards for these units. US MEPS on distribution transformers covers both liquid-filled and dry-type, single-phase and three-phase rated with a 60 Hz frequency and a primary voltage of 34 500 V or less. The power ratings are from 10 to 2500 kVA for liquid-filled units and from 15 to 2500 kVA for dry-type units.

In October 2007, the DOE published its MEPS in Part 431 of Title 10 of the Code of Federal Regulations (10 CFR Part 431). The regulation required all liquid-filled and medium-voltage, dry-type distribution transformers manufactured or imported into the US after 1 January 2010 to have efficiencies that are no less than the specified efficiency values at 50% of rated load. In parallel with the DOE developing these regulations, the US Congress passed the Energy Policy Act of 2005, which specified a minimum efficiency level for all low-voltage, dry-type transformers from 1 January 2007.

Figure 8-5. Minimum energy performance standards (MEPS) for three-phase distribution transformers in the USA: current regulations and reviewed regulations to take effect 1 January 2016 (BIL = basic impulse insulation level).



In 2011, the DOE began to review its regulations with regard to all three groups: liquid-filled, low-voltage dry-type and medium-voltage dry-type transformers. The process was completed and published in April 2013 and the new efficiency requirements will take effect on 1 January 2016. These new regulations measure the percentage efficiency of medium-voltage dry-type transformers at 50% load, while the low-voltage dry-type transformers are measured at 35% of load. Figure 8-5 presents both the 2010 regulation (currently applicable) and the upcoming MEPS that will take effect in 2016 for three-phase liquid-filled and dry-type distribution transformers. In the case of dry-type transformers, MEPS for the 46-95 kV BIL group are presented.

8.2.12 Vietnam

Vietnam has a national programme that promotes energy efficiency across a range of appliances and equipment. Some aspects of this programme are mandatory and others are voluntary. Distribution transformers are included, with minimum efficiency levels that were published in 2011 and became mandatory in 2013 (Table 8-10). The level of ambition associated with the Vietnamese requirements is harmonised with the Australian/NZ MEPS.

Performance levels are published in the Vietnamese National Standard, TCVN 8525:2010, 'Distribution transformers – minimum energy performance and method for determination of energy efficiency'. Vietnam's programme applies to three-phase, 50 Hz, liquid-filled transformers with a nominal capacity of 25–2500 kVA and nominal voltage up to 35 kV. The requirements do not apply to special-purpose transformers such as mobile units or traction transformers.

Table 8-10. Minimum energy performance standards (MEPS) for three-phase, liquid-filled, 50 Hz, distribution transformers (0.4−35 kV) in Vietnam

kVA rating	MEPS (% efficiency)	kVA	MEPS (% efficiency)
25	98.28	500	99.13
32	98.34	630	99.17
50	98.50	750	99.21
63	98.62	800	99.22
100	98.76	1000	99.27
125	98.80	1250	99.31
160	98.87	1500	99.35
200	98.94	1600	99.36
250	98.98	2000	99.39
315	99.04	2500	99.40
400	99.08		

9. Conclusions and recommendations

The opportunity costs from a failure to access distribution transformer savings potentials through a more coherent policy framework are of such a scale that they would incur significant economic costs, lower competitiveness and substantial environmental damage. Thus, bolstering measures in this domain belong to a clear set of win–win policies that both improve the economy and support environmental sustainability objectives. While there are savings opportunities in other end uses that may produce equal or in a few cases larger savings in the 2020 or 2030 timeframe, transformers belong to a class of long-term capital infrastructure with a very slow turnover period, so decisions regarding their level of efficiency in the near term will have consequences for many decades to come. This 'lock in' effect increases the importance of ensuring that procurement decisions are not made for short-term reasons and adequately reflect longer-term value propositions. This aspect also makes transformers an appropriate target for climate change negotiations, because it will be prohibitively expensive to reverse procurement decisions made in the next decade and their consequences regarding greenhouse gas emissions will be felt for many decades afterwards.

It is not surprising then that there is a growing international appreciation of the need to set remedial public-policy frameworks to overcome the market failures and barriers that inhibit the optimal reduction of losses in electricity networks and distribution transformers. This has triggered many policy developments that are contributing to improvements in the efficiency of the transformers that are procured and used.

At the product level, there has been a growth in the adoption of MEPS and energy labels to prevent less-efficient designs from being sold into the market and to make the relative energy performance of transformers more fully visible within it. These efforts are supported through the technical standardisation process and further efforts are to be hoped for to develop a fully internationally harmonised test procedure. This will bring IEC and IEEE standards into full alignment, coupled with the adoption of a common set of energy-performance tiers that will enable the efficiency of all transformers to be classified on a common basis but allow each economy and transformer procurer to set policy and/or purchase products at energy-efficiency performance levels that meet their needs. The pathway has been paved with the recent revision of IEC test procedures for power transformers and the publishing of joint harmonised IEC/IEEE test procedures. It is hoped that in the future, the IEC and IEEE will prioritise the measurement of distribution transformer losses under their 'Dual Logo' scheme and accelerate the harmonisation of the test methods and energy-efficiency schemes underpinning this equipment.

At the network utility level, regulators are increasingly adopting performance-based regulation for network loss production, underpinned by quality-of-service standards to encourage reliable but more-efficient network operation.

The objective of public policy with respect to the transformer market should be to create a policy framework which ensures that the practice of procurement and operation of transformers produces outcomes that minimise their economic and environmental impacts over their service life. To help attain this goal, the following recommendations are made.

9.1 Measures aimed at the product offer

Ensure a minimum level of energy performance is assured

While ensuring the provision of information is an important first step to help address barriers to energy efficiency in the transformer market, many economies have found it beneficial to adopt MEPS to set a legal floor on how large transformer losses can be. This can be one of the surest ways of addressing the barriers to energy efficiency and, if properly specified and implemented, will ensure a good proportion of the cost-effective savings potential is realised at a modest programmatic cost. It is therefore recommended that economies should develop MEPS for distribution transformers and that these should be informed by efforts in peer economies to ensure they are designed and implemented to produce the most feasible savings at least cost.

Ensure declared transformer energy performance is reliable

There is a need to ensure that each economy, their end users and regulators have access to transformer energy performance testing facilities. As these can be expensive to develop, it is recommended that economies look to institute regional cooperative arrangements to establish suitable testing capability that can be accessed on acceptable terms by all regional players as appropriate. These facilities will need to be accredited by competent accreditation agencies and ideally offer independent third-party testing to support public-policy and commercial-user requirements; note that there are very few third-party laboratories testing transformer performance currently, thus viable solutions need to be found. As with other equipment energy performance schemes, there is a need for public-policy bodies to conduct market monitoring and test performance verification efforts to ensure that self-declared performance is being supplied. Suitable legal provisions need to be established to deter false declarations or failure to respect legal provisions concerning MEPS, rating and labelling, and the acceptable magnitude of tolerances also needs to be addressed for these three aspects. In the case of utility or industrial-user tender specifications, it is recommended that these consider specifying zero tolerances to ensure they receive performance levels fully commensurate with the levels assumed in their TCO valuations.

Ensure transformer energy performance is visible in the market

Measures should be put in place to ensure that transformer energy performance is known and visible in the marketplace. First, this entails ensuring that a reproducible, repeatable and representative energy-performance test procedure is adopted (ideally aligned with the international test procedure to facilitate comparability and technology transfer). Second, it is necessary to ensure that the energy-performance information is communicated to the marketplace in a consistent manner across suppliers. This can be achieved through specifications concerning the type of energy-performance information and presentational format that suppliers are required to provide when placing their products on the market. It could be complemented by a graded energy label that indicates the efficiency ranking of the transformer relative to its peers and thus simplifies a first-order efficiency comparison.

In order to facilitate the development of a true global marketplace for transformers, it would be beneficial to have an internationally harmonised approach to setting performance tiers that can be used in labelling/disclosure rating requirements. Such a scheme could build upon SEAD Tiers 1–5 and if adopted would lower testing and conformity costs, minimise redundancy in design types that add to overall market costs, facilitate technology transfer and enable direct benchmarking of policy measures between peer economies. Similar international cooperative initiatives have already been successfully developed for electric motors and external power supplies and thus transformers would be a natural extension of this.

Establish a research and development fund to support investment in energy-efficient transformers

Governments may look at the potential to establish a research and development fund that specifically targets innovation and improvements in materials and construction techniques to reduce losses and improve the reliability and performance of transformers. This type of initiative would help get manufacturers to invest in and develop new technologies that could further improve the efficiency of transformers, developing the next generation of products for the market.

9.2 Measures aimed at the utility sector

Ensure network utilities have a full incentive to provide least life cycle cost network losses from the final customer perspective

Network utilities account for 80% of global transformer acquisitions, yet as discussed in Chapter 5 they often do not adequate incentive to reduce network losses that are commensurate with the least-cost energy service to final customers. Appropriate utility regulation has been identified as an essential measure to help address this. It is therefore recommended that utility regulators should:

- ensure technical losses are measured and accounted for at an adequate level of resolution within the network so informed loss-reduction measures can be considered by the utility, auditor and regulator
- ensure the cost of load losses are determined using forward-looking LRMC analysis, that this treats load and no-load losses separately and that the cost of losses is determined and evaluated at each point in the network in order to understand their true value in network planning determinations
- review the adequacy of current incentives for loss reduction among network operators and introduce performance-based incentive regulation as appropriate to ensure the long-term cost of losses is minimised
- ensure the enactment of loss-reduction incentives does not stimulate loss-reduction measures at the expense of investment in network reliability by taking steps to tie loss-reduction performance incentives to satisfaction of quality-of-service requirements
- ensure smart-grid development and investments are also a trigger for loss reduction in network transformers, both by ensuring improved loading, operation and maintenance on the transformer stock and by ensuring any transformer replacements or additions triggered through the need to improve the intelligence of the network are consistent with minimising the TCO of the new transformers
- ensure distribution-utility technical losses are measured and accounted for at an adequate level of resolution within the network, so that informed loss-reduction measures can be considered by the utility, auditor and regulator
- consider requiring or encouraging utility companies to review their transformer procurement specifications to ensure that downstream losses are adequately valued in their procurement tender specifications.

9.3 Measures aimed at the broader market

Raise awareness of the opportunities among key stakeholders

Awareness regarding the opportunity for cost-effective savings through transformer-loss reduction is underdeveloped and therefore efforts are needed to promote understanding of the principal value proposition among key influencers. It is therefore recommended that promotion and dissemination activities be developed that are aimed at senior utility management, industrial end users, equipment procurers, utility regulators, product policymakers and industrial policymakers. This should build upon existing efforts and could include:

- continuation and expansion of the International Copper Association's annual energy-efficient transformers conference (last held in Seoul in 2011, Beijing in 2012 and Bangkok in 2013)
- staging of side events on network loss reduction and transformers at leading utility regulator conferences
- targeted presentations and side events at leading utility conferences
- submission of articles to the principal utility and industry trade journals
- promotion of the transformers clearing house proposed on page 91.

Implement measures to overcome split incentives

Split incentives exist in two major ways in the transformer market. First, many network utilities are regulated in such a way that they have no financial incentive to invest in loss reduction. Second, in both utilities and industry/commerce it is common practice to separately manage the Capex and Opex budgets which, unless remedied through other means, creates an incentive for the Capex budget to be minimised at the expense of ongoing Opex costs. The first split incentive needs to be addressed primarily through appropriate utility regulation but also by requiring utility companies to review their transformer procurement specifications to ensure that downstream losses are adequately valued. The second split incentive can be addressed through education and awareness-raising (see page 89) among senior management and the creation of first-cost incentives (see below), as well as through the creation of innovative finance or business models. Business models, such as energy service companies (ESCOs) or energy-efficiency/green revolving funds, create upstream financing to pay for a share of the downstream energy savings and hence help to overcome incremental first-cost barriers. These kinds of instruments need to be promoted and applied to the transformer sector to internalise the future value of avoided losses within TCO procurement decisions. In non-utility markets (i.e. the industrial and commercial sectors) they can be linked to the broader energy management framework and hence transformers could be just one of many energy transformative equipment types that benefit the creation of such mechanisms.

Establish programmes to look at early retirement and upgrading of stock

Some of the installed stock of transformers around the world have been in service for over five decades. These transformers are still working, but their performance is far less efficient than models produced today with improved materials and manufacturing techniques. This early retirement and replacement programme would establish an initiative between governments and T&D grid operators to incentivise investment in the network to reduce losses, improve reliability and install smart-grid operating functions. Upgrading of these electricity networks would ensure lower operating costs, while also allowing for proactive maintenance by having more real-time information on loading and network performance.

Consider introduction of financial incentives and fiscal measures

Since overcoming incremental first costs is one of the principal barriers needing to be addressed to promote the adoption of transformers with the lowest TCO, policymakers should consider the development of carefully designed and targeted incentives. These could be financial or fiscal in nature and could take the form of net subsidies or be managed through innovative financial instruments. Simple financial incentives have been effectively applied to overcome first-cost barriers for many energy-efficiency fields. Interestingly, these include utility-financed energy-efficiency incentives[27] and it may not be unreasonable where these mechanisms exist to consider adjusting the rules to allow a certain proportion to be invested in loss-reduction measures for distribution transformers, whether these are within a distribution network or among industrial/commercial operators. Incentives can also be managed centrally by the state (e.g. the German kfW bank provides soft loans for energy-efficiency investments, and China has incentives for the procurement of energy-efficient equipment). Fiscal incentives can include tax breaks on energy-efficient investments, such as the UK's Enhanced Capital Allowance Scheme,[28] or can even take the form of differentiated taxation that can be either beneficial or punitive according to the level of efficiency procured. This may be structured to be net fiscally neutral and/or designed to take account of the value of externalities. Examples, applied to equipment types other than transformers, include the

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[27] E.g. operated as utility energy-efficiency obligation or portfolio schemes, or when energy-efficiency measures are permitted to be bid into forward capacity markets.

[28] For more information, see https://etl.decc.gov.uk/etl/site/about.html

French bonus-malus scheme or the Californian ‘feebates’. Whatever incentives are applied, it is important that they are sufficient to affect a transformation in the market but not so large or long-standing as to become a continuous transfer of value from one sector to another, i.e. a long-standing cross subsidy. Incentives have often been applied in other product policy sectors as a transitory measure to help prepare a market for a transformation that is then locked in by regulation, e.g. MEPS.

Build capacity on best-practice procurement and operation of transformers

The capacity to procure and operate transformers in line with best practice is currently constrained and needs to be strengthened. This can be facilitated by the development and dissemination of best-practice information and training targeted to the specific needs of the principal market segments. Information can be developed in the form of brochures, guides, case studies and reports targeted to the needs of specific market actors with influence on the procurement and operation processes of transformers. These can be complemented by analytical tools that can be made available in a central repository or clearing house accessible over the internet. Toolkits may include programmes to help buyers determine loss valuation and apply TCO/life-cycle cost into their transformer procurement practices. Courses, training and other capacity-building activities need to be developed and offered. As much material is already available through the Leonardo Energy website and elsewhere, it is proposed that this body of work is elaborated upon and gaps filled to provide a comprehensive resource that meets the needs of each national/regional transformer-user community. In principle this could be managed through the creation of a centralised repository or social network site for energy efficiency in transformers. *In situ* capacity-building efforts would require a different level of resources and this is probably best managed through a cooperative venture of government, utility regulators, transformer suppliers and transformer procurers/user industries.

Phase-out of PCBs

The Stockholm Convention on Persistent Organic Pollutants is an international environmental treaty, signed in 2001 and effective from May 2004, that aims to eliminate or restrict the production and use of persistent organic pollutants. Most countries in the world are signatories and have agreed to implement measures to phase out the use of prescribed substances. These include PCBs, which were commonly used in transformer insulation until relatively recently. It is therefore recommended that signatory countries initiate or continue to take measures to eradicate PCBs within the existing transformer stock. This may entail early retirement and controlled end-of-life management and recycling of PCB-containing transformers.

Ensure environmental costs are fully internalised in the transformer procurement process

When public policy places a value on pollutants, as expressed by pollutant externality cost valuations, policymakers should ensure these are reflected in TCO valuations applied during the procurement process. This could be done at the macro level by:

- ensuring that any carbon/pollutant cap and trade scheme or tax applies to network operators and other major transformer users and not just to energy suppliers
- ensuring that life-cycle cost valuations used to set MEPS include the value of externalities (as is currently done in the US DOE rulemaking process)
- ensuring that the environmental impacts associated with transformer losses are accounted for and included in corporate sustainability reports.

At the micro level, this could be supported through setting requirements on the procurement process or by providing financial/fiscal incentives that are contingent on the value of the avoided environmental impacts.

9.4 Share the load through cooperative work with international partners

Given the global scale of the potential for cost-effective, long-term savings in distribution transformers, the common nature of the problems faced and the body of previous and existent efforts to address the barriers to higher energy efficiency, it is recommended that stakeholders seek to work cooperatively in the field to combine and leverage their resources for greater benefits at lower cost. Such cooperation expedites knowledge transfer, minimises duplicative effort and unnecessary fragmentation, and generally accelerates progress. Some existing efforts that can be built upon include:

- IEC/IEEE cooperative efforts in standardisation
- the SEAD Initiative on energy-efficiency tiers
- the Leonardo Energy and IEA 4E best-practice dissemination efforts.

Thus far, most of this international cooperative effort has focused elements linked to product policy, standardisation and awareness-raising. In the future this could be extended to include greater communication on utility regulation and energy-management best practice. In general, it is recommended that the scale of such cooperation be increased to foster more rapid spread of best practice.

Appendix A: Types of transformers

The IEC defines a transformer as an ‘electric energy converter without moving parts that changes voltages and currents associated with electric energy without change of frequency’. This is a general, all-encompassing definition for transformers. There are, as the IEC then goes on to define, many different types of transformers that are used in different applications or which have special features making them uniquely suited for specific installations. In this Appendix, a few of the important transformer types are defined and some context provided for how they are used.

A.1 Power transformers

The terms ‘power transformer’ and ‘large power transformer’ are generally used to refer to those transformers installed between the generator and the distribution circuits. These transformers tend to use high voltages, usually greater than 36 kV and often in the hundreds of kilovolts, and they tend to have larger kVA ratings, such as 10 000 kVA and above. Electrical power networks typically consist of a large number of generation locations, distribution points and interconnections within the system or nearby systems. System complexity leads to a variety of different voltages, and power transformers must be installed at each interconnection where there is a transition between voltage levels.

A.2 Distribution transformers

Distribution transformers take a voltage from a primary distribution circuit and ‘step it down’ or reduce it to a secondary distribution circuit or a consumer’s service circuit. Although not uniform around the world, distribution transformers tend to have a highest voltage (i.e. the input or primary voltage) at or below 36 kV. Although some industry standards tend to try to define distribution transformers by their kVA rating (e.g. 5−2500 kVA), distribution transformers can have ratings of 5000 kVA or even higher, depending on the circuit they are servicing.

A.3 Liquid-filled transformers

Liquid-filled transformers are those in which the core and coil assembly are immersed in a liquid. The liquid serves as both an insulating material and a means of collecting and removing waste heat from the core and coil assembly. The fluid used is usually, but not exclusively, mineral oil. However, oil is becoming scarcer and more expensive and alternatives such as ester compounds are becoming much more prevalent for new equipment globally. These fluids have higher flash-point temperatures, making them safe to use indoors in certain countries where they conform to the electrical code.

A.4 Dry-type transformers

Dry-type transformers are those in which the insulating medium surrounding the winding assembly is a gaseous or dry compound. There are several different types of dry-type transformers, including single- and three-phase, ventilated and non-ventilated/sealed. These transformers can have a range of different voltages, including low-voltage models with primary voltages of 600V and below, all the way up to large power units working in a utility network at more than 36 kV. The fundamental principles of dry-type transformers are no different from those encountered in liquid-filled designs in terms of design aspects such as temperature rise, insulation rating and tolerance of harmonics.

A.5 Rectifier transformer/converter transformers

Transformers that convert alternating current (AC) to direct current (DC) and *vice versa* are called ‘rectifier transformers’ by the IEEE and ‘converter transformers’ by the IEC. These transformers service rectifier circuits (AC to DC) and inverter circuits (DC to AC). A transformer that has one of its windings connected to a rectifier or inverter circuit, as a dedicated transformer, is also called a ‘rectifier transformer’ (IEEE) or a ‘converter transformer’ (IEC).

A.6 Instrument transformers

An instrument transformer is used to supply an information signal to measurement equipment, including instruments, meters, relays and other protective or control devices or similar apparatus. They provide isolation between the main primary circuit and the secondary control and measuring devices. Isolation is achieved by magnetically coupling the two circuits. There are two categories of instrument transformers: voltage transformers (VT) and current transformers (CT). The primary winding of the VT is connected in parallel with the monitored circuit, while the primary winding of the CT is connected in series. The secondary windings proportionally transform the primary levels to typical values of 120 V and 5 A. Monitoring devices such as watt meters, power-factor meters, voltmeters and ammeters are often connected to these secondary circuits.

A.7 Constant-voltage transformers

Constant-voltage transformers (CVTs) are designed to maintain a constant output voltage in situations where the transformer may be exposed to over- or undervoltages. CVT units are being applied as a voltage-sag protection device for industrial and commercial facilities. The CVT consists of three or four windings and a high-reliability capacitor,which makes it relatively impervious to continuous short circuits (whether turned on into a short circuit or from full load).

Appendix B: Technical issues

B.1 Size and weight

Policymakers should be aware that increases in transformer efficiency are normally also subject to increases in transformer weight and size. This occurs because of an increase in the quantity of material used in the design, to reduce either core or coil losses. Thus, when upgrading an installation to a more energy-efficient transformer, the capacity of the existing pole or pad should be taken into consideration.

Performance and dimensional data from ABB are provided in Table B.1, illustrating changes in size and weight. Percentages have been calculated to show how loss reduction translates into changes in physical characteristics.

Table B.1. Illustration of size and weight differences between standard and efficient 100 kVA and 400 kVA distribution transformers

	100 kVA			400 kVA		
	Standard design	Efficient design		Standard design	Efficient design	
		Low no-load losses	Low load losses		Low no-load losses	Low load losses
No-load loss (W)	240	180	200	720	530	460
Load (W)	1680	1720	1200	4100	4100	3200
Total watts	1920	1900	1400	4820	4630	3660
Weight (kg)	585	585	800	1355	1520	2000
Width (mm)	870	870	1000	1085	1210	1200
Depth (mm)	670	670	650	900	850	750
Height (mm)	1200	1200	1400	1445	1480	1780
Volume (m^3)	0.70	0.70	0.91	1.41	1.52	1.60
Change in total watts of loss	N/A	−1%	−27%	N/A	−4%	−24%
Change in weight	N/A	0%	37%	N/A	12%	48%
Change in volume	N/A	0%	30%	N/A	8%	14%

Source: ABB Global Website.

B.2 Harmonic loads

Policymakers also need to be aware of the importance of reliability and how that can be affected by harmonic loads in the network. Harmonic loads can cause an increase in temperature that degrades the insulation, creating hot spots and ultimately shortening transformer lifetime. Thus, particular care should be taken when specifying transformers that supply non-linear loads such as variable-speed motors, computers and uninterruptable power supplies which draw non-linear currents from the supply, creating substantial currents at harmonic frequencies. Losses arising from a current at the third harmonic is nine times higher than load losses due to a current of the same magnitude at the fundamental. Thus, in an actual installation, load losses in transformers servicing non-linear loads can be twice the rated (fundamental frequency) losses.

Because distribution transformers operate close to the load, they are affected by harmonics. In some cases, harmonics are cancelled out by aggregating thousands of separate loads with slightly different phase angles. Some of the harmonics cancel out, mitigating the impact upstream in the system.

For installations where harmonics are known to be (or will be) problematic, there are two approaches for dealing with them: either use a (de-rated) larger transformer that has the capacity to allow for higher losses, or use a transformer that is specially designed to minimise those losses. The latter option is preferable from an energy-efficiency point of view.

B.3 Test standards

Policymakers should be aware that there are two major standards bodies that have set out the testing specifications for distribution transformers: the IEC and the IEEE. The IEC has developed, published and maintains 19 standards in the 60076 family of standards as well as a number of standards on tap-changers, terminals and convertor transformers. IEEE has over 80 standards and guides within its family of standards covering transformers.

For the measurement of losses, most countries and economies working on policy measures for distribution transformers rely on a test standard based on IEC 60076, sometimes incorporating slight (local) modifications to the standard. In North America, policymakers tend to rely on test standards based on the IEEE.

B.4 Operating frequency: 50/60 Hz

Transformer regulations for a particular market should be drafted to apply to the appropriate operating frequency of the network: 50 Hz for Europe, China, India and elsewhere, and 60 Hz for the USA, Canada, the Republic of Korea and others. It is also important to bear in mind that the operating frequency is not a critical issue for energy efficiency. Transformers designed to operate at 60 Hz will tend to have higher no-load losses and lower load losses (keeping all other parameters constant). The resulting differences in performance between the 50 Hz and 60 Hz models are very small (0.1−0.2%) when compared to the variation in core and winding losses.

Appendix C: Links to key resources

- IEA-4E Mapping and Benchmarking reports: distribution transformers
  Link: http://mappingandbenchmarking.iea-4e.org/matrix?type=product&id=15
- Super-efficient Equipment and Appliance Deployment (SEAD) Transformer Reports
  Link: http://www.superefficient.org/distributiontransformersreport
- CLASP's Global Standards and Labelling Policy Database
  Link: http://www.clasponline.org/en/Tools/Tools/SL_Search
- Leonardo Energy website for energy-efficient transformers
  Link: http://www.leonardo-energy.org/projects/transformers
- International Copper Association – global manufacturer association for the copper industry
  Link: http://copperalliance.org/
- US Department of Energy website for distribution transformer regulation
  Link: http://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/66
- European Commission website for transformer regulation
  Link:http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/product-groups/transformers/index_en.htm

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