

ABSTRACT

The goal of this article is to encourage electrical utilities and technical consultants to consider the use of the peak efficiency index (PEI) as an alternate energy efficiency metric for distribution transformers. Traditionally, for distribution transformers, either fixed loss values or efficiency at 50 % load has been used. In this article, the carbon emission equivalent (tCO_{2e}) impact is investigated for a 1,000 kVA

transformer with PEI Level 1 and PEI Level 2 specifications and compared with traditional values seen across multiple end-user specifications in the Asia Pacific, Middle East & Africa region. A section on return on investments is also included for economic comparisons.

KEYWORDS:

case studies, efficiency, greenhouse gasses emissions, peak efficiency index

Transformer technical specification is the first step in establishing the long-term effectiveness of transformers in reducing greenhouse gas emissions by considering efficiency metrics

Investigating the use of peak efficiency index as an alternative efficiency metric for distribution transformers

1. Introduction

Transformer technical specification is the first step in establishing the long-term effectiveness of transformers in reducing greenhouse gas (GHG) emissions by considering efficiency metrics. It has been reported by the UN that almost 730 million tons/year are contributed by distribution transformers [1]. There are international policies that support the energy efficiency of distribution transformers, such as the Minimum Energy Performance Standards (MEPS) in many countries such as the United States of America [2], Australia [3], Vietnam [4] and Star Ratings [5] in India. Transformers complying with these standards have reduced losses, so they reduce energy consumption and consequently reduce the need for the generation of electrical energy and consequently GHG emissions. These broadly fall into two main categories:

1. Specifying maximum no-load and load loss.

2. Specifying minimum efficiency values at 50 % load.

When no load loss and load loss are specified, this means that a minimum level of performance is assured, whatever the level of loading applied to the transformer. Similarly, when efficiency is specified, it allows transformer design engineers to trade off no-load and load losses while trying to produce an optimized transformer for a specific load. Apart from these two categories, IEC 60076-20 [6] also introduces another method of evaluating the energy performance of a transformer: the peak efficiency index (PEI), both for 50 Hz and 60 Hz transformers. IEC 60076-20 provides two levels of recommended PEI:

1. Level 1 is for basic energy performance.
2. Level 2 is for a high-energy performance.

PEI represents the highest efficiency value of any transformer design, irrespective of

In this article, PEI Level 1 = 99.431 % and PEI Level 2 = 99.541 % for a 1,000 kVA transformer is considered, and two different designs meeting PEI Level 1, and PEI Level 2 are evaluated against designs based on fixed losses

a specified loading point. PEI specification doesn't require the specification of a loading point as in most distribution transformers, and the expected loading point is "estimated" with quite high uncertainty. If the designed optimal loading point does not coincide with the average loading at all installation sites, this may result in lost energy savings [7].

The aim of this article is to encourage electric utilities and technical consultants to consider the use of PEI as an alternate energy efficiency metric for distribution transformers when the expected load varies between 10 %–100 %. The carbon emission equivalent (tCO_{2e}) impact of such specification is investigated for a 1,000 kVA transformer with IEC 60076-20 PEI Level 1 and PEI Level 2 specification and compared with a 1,000 kVA oil-filled distribution transformer with fixed no load and load loss specification.

2. Peak efficiency index

The peak efficiency of the transformer load is obtained when no-load loss equals load loss. The corresponding loading point is calculated as:

$$k_{PEI} = \sqrt{\frac{P_{NLL}}{P_{LL}}}$$

The formula for calculating the PEI is:

$$PEI = 1 - \frac{2 * P_{NLL}}{S_r * k_{PEI}}$$

Where P_{NLL}: No load loss (W), P_{LL}: Load loss (W), S_r: Rated Power of the transformer (VA).

Table 1 lists the PEI values specified in IEC 60076-20 [6] for transformers with voltage ≤ 24 kV and rating ≤ 3,150 kVA.

In this article, the PEI Level 1 = 99.431 % and PEI Level 2 = 99.541 % for a 1,000 kVA transformer is considered, and two different designs meeting PEI Level 1, and PEI Level 2 are evaluated against designs based on fixed losses.

Table 1. PEI values for oil-filled distribution transformers [6]

kVA	PEI Level 1	PEI Level 2
250	99.210 %	99.363 %
315	99.248 %	99.395 %
500	99.330 %	99.465 %
1,000	99.431 %	99.541 %
1,250	99.483 %	99.544 %
1,600	99.488 %	99.550 %
2,000	99.495 %	99.558 %
2,500	99.504 %	99.568 %

3. Typical fixed loss values for 1,000 kVA transformer

Based on transformer specification reviews across the Asia Pacific, Middle East & Africa region, typical loss values specified by end users for 1,000 kVA transformers are listed in Table 2. It can be calculated that approximately 42 % of the transformer specifications in this region have an average no-load loss = 1.2 kW and average load loss = 9.45 kW. Fig. 1 shows the efficiency vs load curves for the different values.

Table 2. Typical 1,000 kVA loss values specified by end users in Asia Pacific, Middle East & Africa (HV ≤ 24 kV)

Transformer rating 1,000 kVA	No-load loss (kW) average	Load loss (kW) average	% of specifications
Design 1	~1.4	~7	17 %
Design 2	~1.2	~9.45	42 %
Design 3	~0.98	~8.55	18 %
Design 4	~0.85	~10.5	20 %
Design 5	~0.7	~7.6	3 %

3.1 Does the typical values specified meet IEC PEI L1 and L2 values?

From Fig. 1 and Table 3, only Design 5 meets IEC L1 PEI requirement, while all other designs do not meet either PEI L1 or L2.

3.2 Does the typical values specified meet MEPS requirements?

Many countries in the world have introduced metrics for assessing the energy performance of distribution transformers, the most used metric being the Minimum Energy Performance Standard (MEPS) requirements [7]. In Australia and New Zealand (AU/NZ), AS 2374.1.2 standard [8] is mandated by the government to be used as a benchmark while purchasing distribution transformers. In this section, the typical 1000kVA loss specifications are evaluated against the AS 2374.1.2 standard for efficiency at 50% load. Table 4 shows the comparisons of the five designs against the standard MEPS level & high-efficiency HEPS level. From Table 4, all the five loss specifications meet the standard MEPS efficiency requirements and accordingly can be considered “efficient designs”.

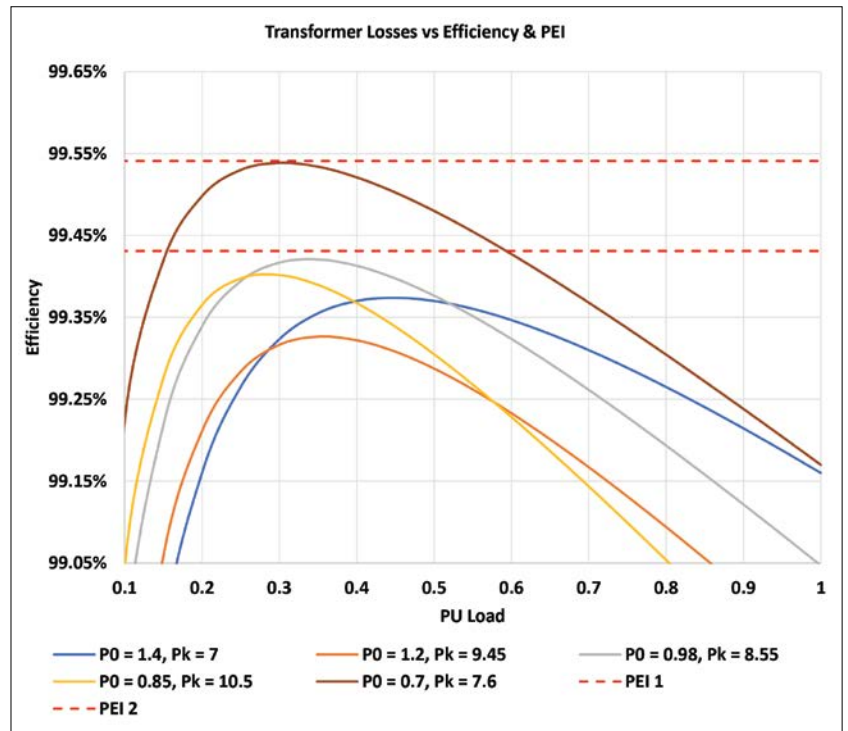


Figure 1. Efficiency vs load curves for typical 1,000 kVA fixed loss values (PEI benchmarking)

Many countries in the world have introduced metrics for assessing the energy performance of distribution transformers, the most used metric being the Minimum Energy Performance Standard

Table 3. Design PEI outcomes vs IEC PEI Level 1 and Level 2

Parameters	Design 1	Design 2	Design 3	Design 4	Design 5
No-load loss	1.4 kW	1.2 kW	0.98 kW	0.85 kW	0.7 kW
Load loss	7 kW	9.45 kW	8.55 kW	10.5 kW	7.6 kW
Total loss	8.4 kW	10.65 kW	9.53 kW	11.35 kW	8.3 kW
IEC PEI Level 1 required	99.431 %	99.431 %	99.431 %	99.431 %	99.431 %
IEC PEI Level 2 required	99.541 %	99.541 %	99.541 %	99.541 %	99.541 %
PEI design output	99.374 %	99.327 %	99.421 %	99.403 %	99.539 %
IEC PEI Level 1 achieved?	No	No	No	No	Yes
IEC PEI Level 2 required?	No	No	No	No	No
K_{PEI}	44.7 %	35.6 %	33.9 %	28.5 %	30.3 %
Efficiency at 50 % load	99.370 %	99.288 %	99.377 %	99.305 %	99.480 %

Table 4. Design outcomes vs MEPS (AU/NZ) and HEPS (AU/NZ)

Parameters	Design 1	Design 2	Design 3	Design 4	Design 5
No-load loss	1.4 kW	1.2 kW	0.98 kW	0.85 kW	0.7 kW
Load loss	7 kW	9.45 kW	8.55 kW	10.5 kW	7.6 kW
Efficiency at 50 % load	99.370 %	99.288 %	99.377 %	99.305 %	99.480 %
MEPS AU/NZ requirement	99.27 %	99.27 %	99.27 %	99.27 %	99.27 %
HEPS AU/NZ requirement	99.37 %	99.37 %	99.37 %	99.37 %	99.37 %
MEPS AU/NZ achieved?	Yes	Yes	Yes	Yes	Yes
HEPS AU/NZ achieved?	Yes	No	Yes	No	Yes

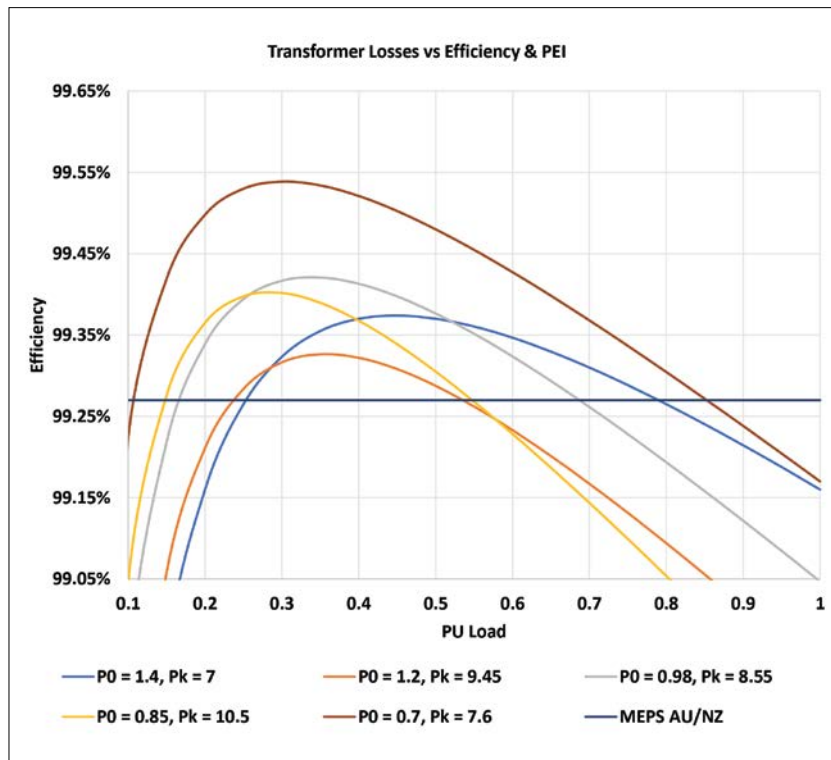


Figure 2. Efficiency vs load curves for typical 1,000 kVA fixed loss values (MEPS benchmarking)

Table 5. Three 1,000 kVA designs with different PEI levels

Design 2 (current specification)		Improved design 2 (PEI L1)		Improved design 2 (PEI L2)	
NLL (kW)	LL (kW)	NLL (kW)	LL (kW)	NLL (kW)	LL (kW)
1.20	9.45	0.99	8.10	0.69	7.60
PEI Achieved = 99.327 %		PEI Achieved = 99.434 %		PEI Achieved = 99.542 %	

4. Operational carbon footprint assessment comparison: MEPS vs PEI compliant design

In this section, operational carbon footprint assessment is carried out for the most common 1,000 kVA specification, i.e., average no-load loss = 1.2 kW and average load loss = 9.45 kW, with two other designs which meet IEC PEI Level 1 and IEC PEI Level 2 requirements as listed in Table 5.

Quantification of carbon emission during the operational phase is calculated as follows:

$$tco_{2e} \text{ (tonnes of carbon dioxide equivalent)} = (P_{NLL} + k^2 \cdot P_{LL}) \cdot t_{years} \cdot Lifetime \cdot GEF$$

Where:

- P_{NLL} : power dissipated due to transformer no-load loss

- P_{ll} : power dissipated due to transformer load loss at a reference temperature of 75° C
- k : the expected average load factor
- t_{year} : the total amount of hours during a year, typically 8,760 hours.
- Lifetime: the expected service life of the transformer.
- GEF: Grid emission factor ($kgCO_{2e}/kWh$), typically expected at the midlife of the transformer.

The operational carbon footprint assessment is carried out for operation of the transformer in a geographical area where the average grid emission factors are:

1. Country 1 - 0.668 $kgCO_{2e}/kWh$ (fossil fuel-based power generation, 70 %)
2. Country 2 - 0.112 $kgCO_{2e}/kWh$ (renewable-based power generation, 80 %)
3. Country 3 - 0.011 $kgCO_{2e}/kWh$ (100 % renewable power generation)

4.1. Carbon footprint assessment comparison: Country 1 (0.668 tCO_{2e}/MWh)

In this scenario, the carbon footprint assessment for the three designs in Table 5 is evaluated for a geographical area with $GEF = 0.668 kgCO_{2e}/kWh$, which is typical for a fossil-based generation mix. Fig. 4 shows the reduction in equivalent tons of carbon at different load factors.

- At 30 % load, PEI 1 design has 48 tCO_{2e} lower emissions, and PEI 2 design has 99 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- At 50 % load, PEI 1 design has 80 tCO_{2e} lower emissions, and PEI 2 design has 142 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- At 80 % load, PEI 1 design has 157 tCO_{2e} lower emissions, and PEI 2 design has 248 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- At 100 % load, PEI 1 design has 228 tCO_{2e} lower emissions, and PEI 2 design has 345 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- On average, PEI 1 has 107 tCO_{2e} lower emissions, and PEI 2 has 178 tCO_{2e} lower emissions than the typical fixed loss design.

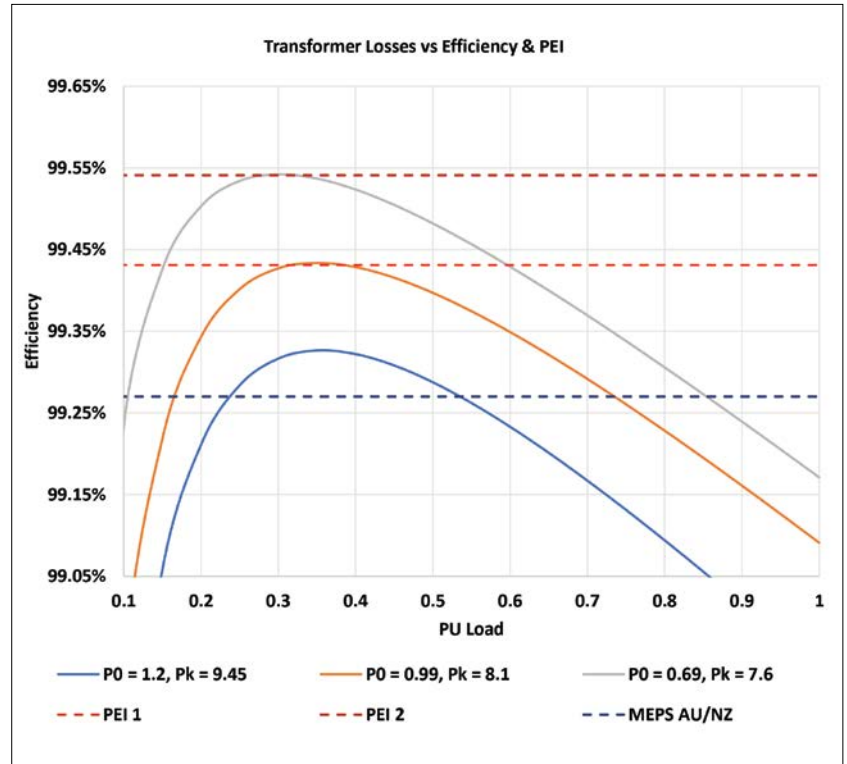


Figure 3. Efficiency vs load curves for typical 1,000 kVA: typical fixed loss vs PEI 1 and PEI 2 designs

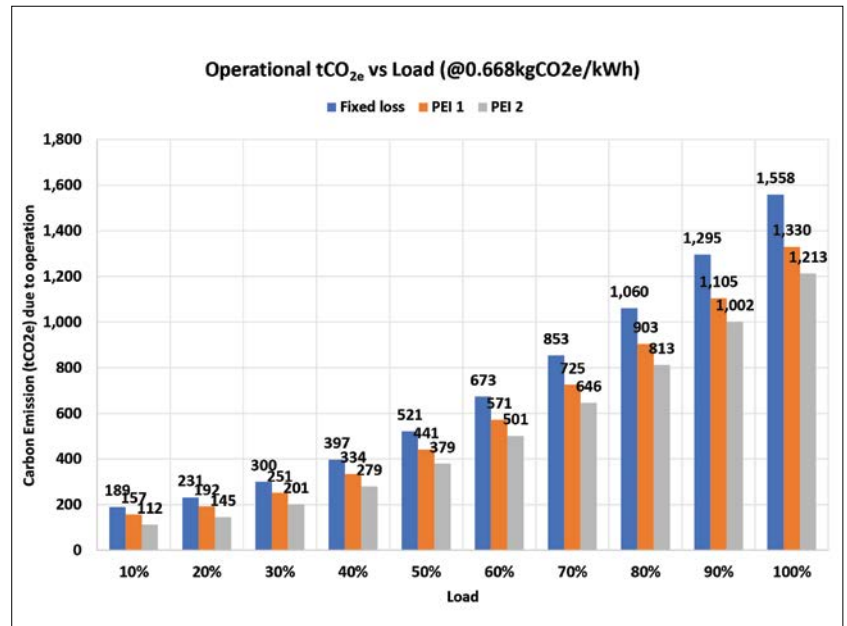


Figure 4. Operational carbon footprint comparison at 0.668 $kgCO_{2e}/kWh$: fixed Loss vs PEI L1 vs PEI L2

The carbon footprint assessment for three transformer designs is evaluated for a geographical area with $GEF = 0.668 kgCO_{2e}/kWh$, which is typical for a fossil-based generation mix

The carbon footprint assessment for three transformer designs is also evaluated for a geographical area with GEF = 0.112 kgCO_{2e}/kWh, which is typical for a renewable-based generation mix

4.2. Carbon footprint assessment comparison: Country 2 (0.112 tCO_{2e}/MWh)

In this scenario, the carbon footprint assessment for the three designs in Table 5 is evaluated for a geographical area with GEF = 0.112 kgCO_{2e}/kWh, which is typi-

cal for a renewable-based generation mix. Fig. 5 shows the reduction in equivalent tons of carbon at different load factors.

- At 30 % load, PEI 1 design has 8 tCO_{2e} lower emissions, and PEI 2 design has 16 tCO_{2e} lower emissions when compared to the typical fixed loss design.

- At 50 % load, PEI 1 design has 13 tCO_{2e} lower emissions, and PEI 2 design has 23 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- At 80 % load, PEI 1 design has 26 tCO_{2e} lower emissions, and PEI 2 design has 41 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- At 100 % load, PEI 1 design has 38 tCO_{2e} lower emissions, and PEI 2 design has 57 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- On average, PEI 1 has 18 tCO_{2e} lower emissions, and PEI 2 has 30 tCO_{2e} lower emissions than the typical fixed loss design.

4.3. Carbon footprint assessment comparison: Country 3 (0.011 tCO_{2e}/MWh)

In this scenario, the carbon footprint assessment for the three designs in Table 5 is evaluated for a geographical area with grid emission factor = 0.011 kgCO_{2e}/kWh, which is for a 100 % renewable generation mix. Fig. 5 shows the reduction in equivalent tons of carbon at different load factors.

- At 30% load, PEI 1 design has 0.8 tCO_{2e} lower emissions, and PEI 2 design has 1.6 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- At 50% load, PEI 1 design has 1.3 tCO_{2e} lower emissions, and PEI 2 design has 2.3 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- At 80% load, PEI 1 design has 2.6 tCO_{2e} lower emissions, and PEI 2 design has 4.08 tCO_{2e} lower emissions when compared to the typical fixed loss design.

The carbon footprint assessment is finally evaluated for a geographical area with grid emission factor = 0.011 kgCO_{2e}/kWh, which is typical for a 100 % renewable generation mix

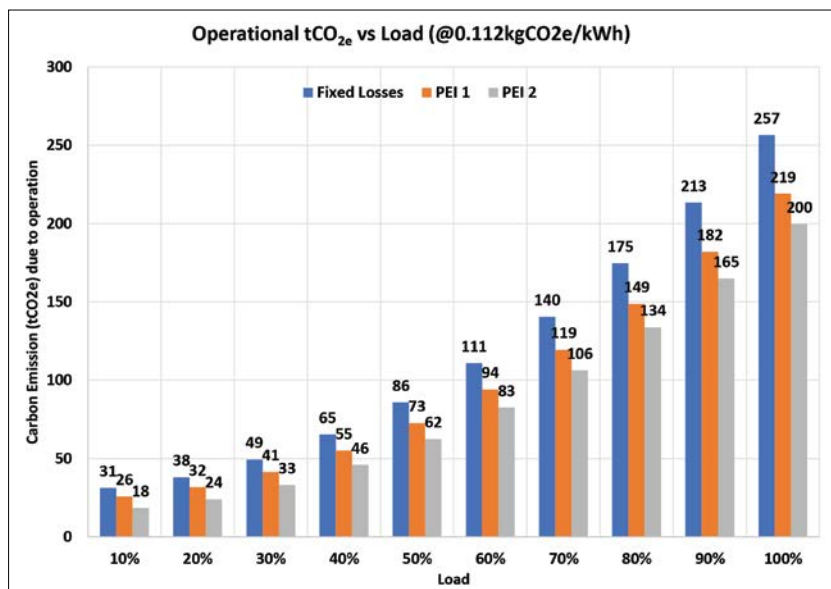


Figure 5. Operational carbon footprint comparison at 0.112 kgCO_{2e}/kWh: fixed loss vs PEI L1 vs PEI L2

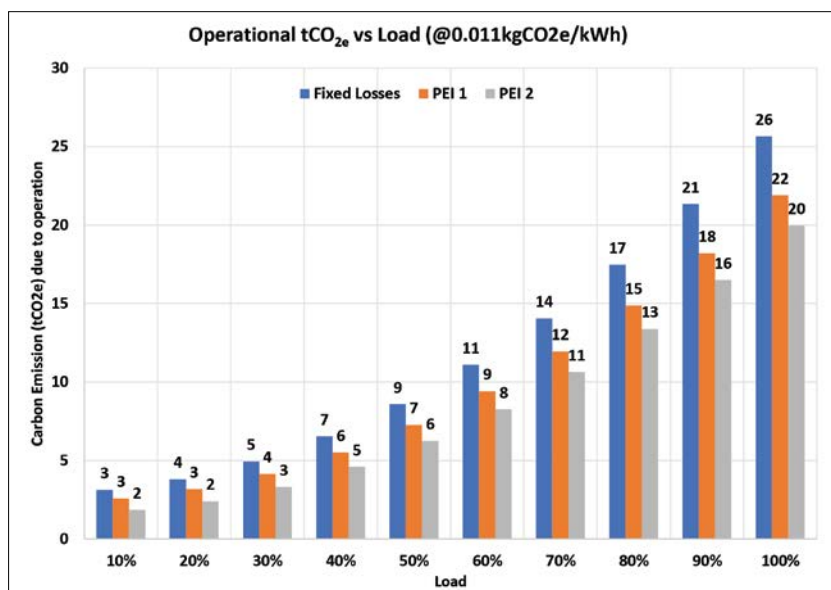


Figure 6. Operational carbon footprint comparison at 0.011 kgCO_{2e}/kWh: fixed loss vs PEI L1 vs PEI L2

Improving energy efficiency by using PEI will have a major implication in improving the operational carbon footprint for countries whose energy generation mix is dependent on fossil fuels

- At 100% load, PEI 1 design has 3.76 tCO_{2e} lower emissions, and PEI 2 design has 5.69 tCO_{2e} lower emissions when compared to the typical fixed loss design.
- On average, PEI 1 has 1.76 tCO_{2e} lower emissions, and PEI 2 has 2.94 tCO_{2e} lower emissions than the typical fixed loss design.

4.4 Inference

From sections 4.1–4.3, improving energy efficiency by using PEI will have a major implication in improving the operational carbon footprint for countries whose energy generation mix is dependent on fossil fuels, for example, Australia. As countries move towards integrating more and more renewables, the impact of loss specification on operational carbon footprint becomes much less significant, as seen in Fig. 7. Thus, it can be concluded that for many countries in the Asia Pacific, Middle East & Africa region, the use of fixed losses for distribution transformers is sub-optimal, and efficiency (overall operational carbon footprint) could be further improved using PEI.

4.4.1 Use case: Australia

According to the Australian Energy Update 2021 [9], electricity generation at a national level can be summarized as:

- Total electricity generation in Australia was steady in 2019–20 at 265 TWh;
- Black and brown coal-fired electricity generation was 54 % of the total generation in the calendar year 2020;
- Natural gas-fired generation was 20 % of total generation in the calendar year 2020;

- Renewable generation increased 15 % in 2019–20, contributing 23 % of total generation;
- Solar PV, especially large-scale solar PV, was the fastest-growing generation type.

The mix of energy sources used in each state varies widely, as shown in Fig. 8. Tasmania (98 %) and South Australia (59 %) are proportionally the heaviest users of renewable energy, especially due to hydropower in Tasmania and wind and solar power in South Australia. New South Wales (21 %), Victoria (27 %), Queensland (16 %), Western Australia (12 %), and

Northern territories (4.6 %) have relatively lower renewable energy generation compared to Tasmania and South Australia. Gas accounted for most of the generation in Western Australia and the Northern Territories, while coal dominated the generation for New South Wales, Victoria, and Queensland. The corresponding emission factors are provided in the Emissions and Energy Reporting System (EERS) [10] from the Government of Australia for 2020–21, as listed in Table 6.

Using the data provided by the Government of Australia as part of the Australian Energy Statistics [11], it can

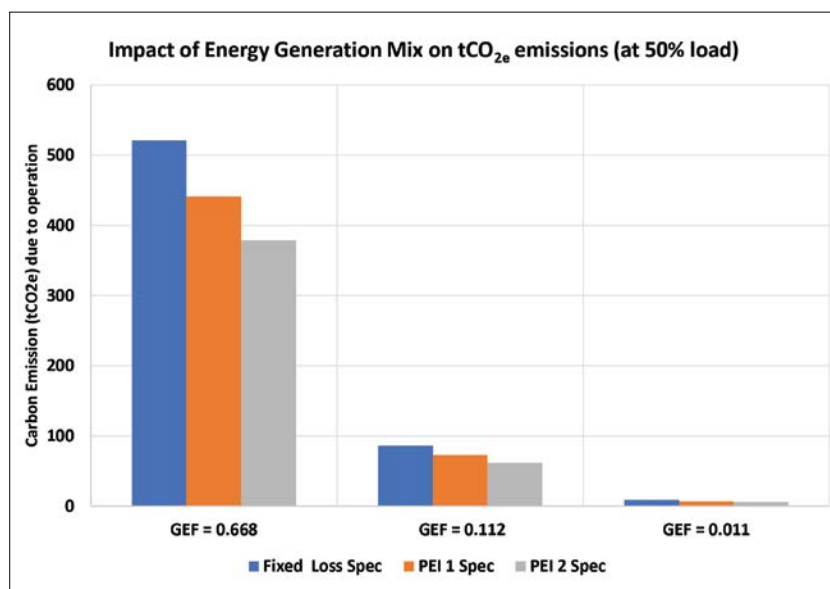


Figure 7. Impact of energy generation mix at 50 % load factor on operational carbon footprint

Table 6. State-wise emission factors for Australia [10]

State or Territory	GEP (kgCO _{2e} /kWh)
New South Wales	0.81
Victoria	0.98
Queensland	0.81
Western Australia	0.68
South Australia	0.43
Tasmania	0.17
Northern Territory	0.62
Average emission factor for Australia	0.642

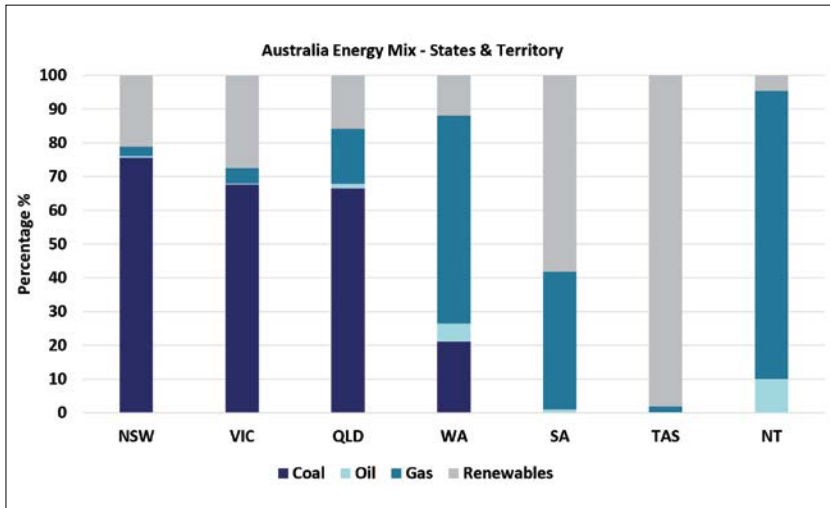


Figure 8. State-wise electricity generation: Australia [10]

Using the data provided by the Government of Australia as part of the Australian Energy Statistics, it can be estimated by 2040, the Australian energy generation mix will have 80 % of renewable sources and 20 % non-renewable sources

be estimated by 2040, and the Australian energy generation mix will have 80 % of renewable sources and 20 % non-renewable sources if the current transition rate is maintained.

It is clear from Fig. 9 for the next approximately 20–25 years that, the choice of PEI as a distribution transformer metric for Australia will help in improving the operational carbon footprint associated

with distribution transformers. By 2045, the average grid emission factors will reduce from 0.642 kgCO_{2e}/kWh to a lower value, depending on the percentage of the renewable electricity generation mix. By that point in time, the impact of the operational carbon footprint will be much less significant compared to today's value. Similar analysis should be carried out for other countries in the Asia Pacific, Middle East & Africa region.

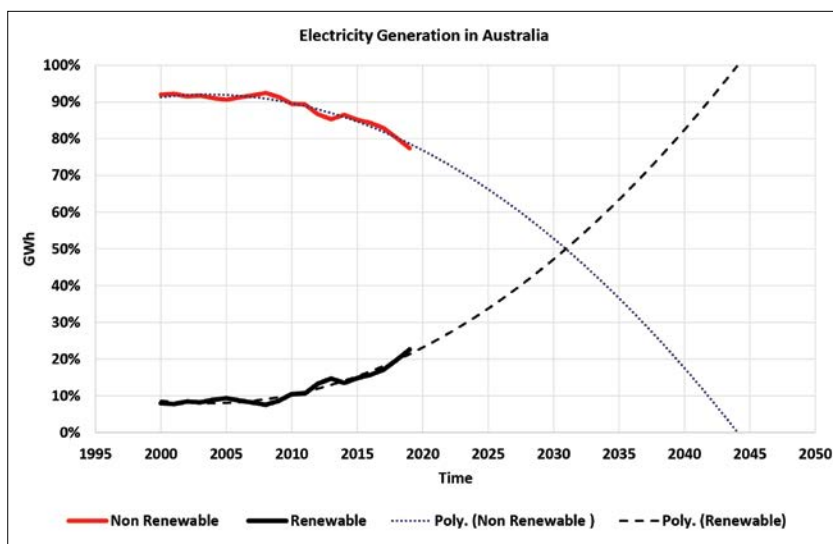


Figure 9. Electricity generation transition estimate for Australia.

5. Return on Investments under fossil-based power generation

There are some impediments towards to the adoption of energy-efficient transformers, such as:

1. Higher relative cost of energy-efficient transformers;
2. Poor promotion of efficient transformers;
3. Limited availability of energy-efficient transformers and high import costs or tariffs;
4. Split incentive—utilities lack the incentive to invest in efficiency because losses are simply passed along as a cost of business to end-use customers;
5. Lack of knowledge among policymakers, T&D system designers, suppliers, operations and maintenance facility managers;
6. Lack of sustainable financing schemes.

In this section, the return on investment is investigated, with increased typical upfront costs for the three designs listed in Table 7. The costs will vary widely from country to country. For calculation purposes, a base value of \$35,000 is assumed for the current specification.

To evaluate the benefit achieved by energy-efficient transformers, the savings in energy generation and the social costs of carbon must be included in the analysis.

1. Savings in energy generation directly result from the reduction of losses. This saves decades of electricity waste, given non-stop transformer operation and long service life. An average value of 100 US\$/MWh is used in this calculation to calculate the cost-benefit [12].
2. The social cost of carbon translates the future harm inflicted by the release of one additional ton of carbon dioxide

The return on investment is investigated, with increased typical upfront costs for the three transformer designs, with an assumed base value of \$35,000

Table 7. Price variation estimates for different efficiency levels

Design 2 (current specification)		Improved Design 2 (PEI L1)		Improved Design 2 (PEI L2)	
NLL (kW)	LL (kW)	NLL (kW)	LL (kW)	NLL (kW)	LL (kW)
1.20	9.45	0.99	8.10	0.69	7.60
Price: 1 pu		Price: 1.06 pu		Price: 1.18 pu	
\$35,000		\$37,100		\$41,300	

into a present monetary value. It answers the question: How much will a ton of carbon dioxide emissions released today cause damage in the future? The variation in the social cost of carbon ranges from 1 US\$/tCO_{2e} in Shenzhen (China) up to 137 US\$/tCO_{2e} in Uruguay [13]. A value of 70 US\$/tCO_{2e} in this calculation to calculate the cost-benefit.

5.1 Annualized benefit from savings in losses

Table 8 presents the annualized benefit due to savings in losses.

5.2 Annualized benefit from social costs of carbon

Table 9 presents the annualized benefit due to carbon savings.

Despite the increase in the cost of energy-efficient transformers, the payback period is much lower than the typical transformer lifetime of 25 years

5.3 Payback calculation

It is clear from Table 10 that despite the increase in the cost of energy-efficient transformers, the payback period is much lower than the typical transformer, with an expected lifetime of 25 years. Financially it makes sense to invest in energy-efficient transformers.

A typical utility has a few thousand transformers and enormous potential to reduce carbon emissions. For example, if there are 1,000 x 1,000 kVA transformers,

shifting from fixed losses to PEI 2 would save 142,000 tons of CO_{2e} during their lifetime!

6. Conclusions

The results of this investigation show that end users must put effort into improving the efficiency of transformers and updating procurement methods that meet or exceed efficiency levels defined in current regulations. It has been shown that the use of fixed losses for distribution transformers is sub-optimal, and efficiency could be fur-

Table 8. Annualized benefit from loss savings of 1 x 1,000 kVA transformer

Parameter	Design 1	Design 2 (PEI 1)	Design 3 (PEI 2)
Lifetime losses (MWh) at 50 % load	780	660	567
Energy savings (MWh)	--	120	213
Cost-benefit at \$100/MWh	--	\$12,000	\$21,300
Annualized benefit (\$)	--	\$480	\$852

Table 9. Annualized benefit from carbon savings of 1 x 1,000 kVA transformer

Parameter	Design 1	Design 2 (PEI 1)	Design 3 (PEI 2)
tCO _{2e} (50 % load, 25 years)	521	441	379
Reduction in tCO _{2e} from D1	--	80	142
Cost-benefit at \$70/tCO _{2e}	--	\$4,000	\$7,100
Annualized benefit (\$)	--	\$224	\$398

Table 10. Return of investment calculations

Parameter	Design 1	Design 2 (PEI 1)	Design 3 (PEI 2)
Price	\$35,000	\$37,100	\$41,300
Increase in cost	--	\$2,100	\$6,300
Annualized benefit (\$) losses	--	\$480	\$852
Annualized benefit (\$) carbon	--	\$224	\$398
Internal rate of return	--	33.5 %	10.2 %
Net present value at 3 %	--	\$9,856	\$5,785
Payback period	--	4	11

ther increased by specifying PEI levels. The use of PEI provides scope for reduction in losses and subsequently reduces the operational carbon footprint associated with distribution transformers. For a 1,000 kVA transformer at 50 % load, in a country with GEF = 0.668 kgCO_{2e}/kWh, PEI 1 design has 80 tCO_{2e} lower emissions, and PEI 2 design has 142 tCO_{2e} lower emissions when compared to the typically fixed loss specified design, just from one transformer. Many countries in the Asia Pacific, Middle East & Africa depend heavily on fossil fuels for their energy generation. In such a scenario, the use of PEI provides scope for an increase in efficiency as it allows the transformer to be designed to match the load, either minimizing no-load loss or load loss as appropriate. End users in these countries should consider the use of the peak efficiency index as an alternate energy efficiency metric for distribution transformers until the energy generation mix becomes predominantly renewable-based.

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