Appliance Standards Awareness Project
American Council for an Energy-Efficient Economy
Natural Resources Defense Council

December 10, 2021

Mr. Jeremy Dommu
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Building Technologies Office, EE-5B
1000 Independence Avenue SW
Washington, DC 20585

RE: Docket Number EERE-2019-BT-STD-0018: Energy Conservation Standards for Distribution Transformers

Dear Mr. Dommu:

This letter constitutes the comments of the Appliance Standards Awareness Project (ASAP), American Council for an Energy-Efficient Economy (ACEEE), and the Natural Resources Defense Council (NRDC) on the preliminary technical support document (PTSD) for distribution transformer standards. 86 Fed. Reg. 48058 (August 27, 2021). We appreciate the opportunity to provide input to the Department.

DOE's preliminary analysis shows that amended efficiency standards for transformers could net upwards of 7 quads of energy savings and would be generally cost-effective for buyers. Further, consideration of the social benefits of higher efficiencies will further increase cost-effectiveness. Higher standard levels would drive a shift in liquid-immersed transformer (LT) core manufacturing: grain-oriented electrical steel (GOES) core transformers would be supplanted by amorphous metal (AM) core transformers. Moreover, US transformer efficiency standards have fallen behind India, China, and the European Union (EU), where the latter adopted higher transformer efficiency standards with a compliance date of July 1, 2021.[1] In some cases, the standards adopted by these major economies even surpass the intermediate standards levels evaluated by DOE in the PTSD. Overall, DOE's preliminary analysis shows that even higher standards may be warranted for the US: we would support standards that achieve the large cost-effective energy savings shown for the highest efficiency levels (ELs) evaluated.

However, we believe that the current rating point in the DOE test procedure forces designs that add cost to transformers without delivering commensurate savings. The disparity between the assumed transformer load in the test procedure and actual loads in the field yields inaccurate relative rankings of transformers and overestimates the cost increase to achieve a specified real-world efficiency increase. We thus believe that rating efficiency at per-unit loads (PULs) that more closely align with real-world PUL estimates would improve the cost-effectiveness of potential amended standards. DOE's estimated annual average PULs are approximately 30% for LTs,[2] while the test procedure PUL is 50%. Because

[1]Commission Regulation (EU) 2019/1783, Table I.7, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2019.272.01.0107.01.ENG&toc=OJ%3AL%3A2019%3A272%3ATOC
[2]EERE-2019-BT-STD-0018-0022, p. 2-60. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022

compliance with the standards is based on the test procedure PUL, designs at each EL are overinvesting in reducing winding losses at the expense of core loss reductions that would provide greater real-world savings. The EU prevents overinvestment in winding losses relative to core losses by setting maximum non-load and load loss requirements, wherein non-load losses must be about 10% or less of full load (100%) losses.[3] Moving the test procedure PUL to lower more realistic real-world PULs would similarly prevent overinvestment in winding losses.

Using DOE's preliminary analysis, we show that intermediate levels of efficiency improvement (e.g., ≈20% energy savings) can be achieved with small increases in transformer price if transformer designs are optimized for more realistic PULs. With this correction, we expect that all ELs examined by DOE will become more cost-effective for purchasers, opening additional pathways for DOE to propose stronger standards. Thus, we urge DOE to change the test procedure PUL from 50% to 30% for LTs. Concurrently, DOE estimated PULs (16%) for low-voltage dry-type transformers (LVDTs) are lower than the test PUL (35%), so DOE should consider lowering PULs for LVDTs as well. Herein we focus on LTs since they have more robust PUL estimates and the largest potential savings, but we expect that much of our analysis and comments are also applicable to LVDTs.

Moreover, we believe DOE may be overestimating both initial PUL and PUL growth in the preliminary analysis; this may negatively affect higher EL designs that prioritize core loss reductions. In addition, DOE has not done a fresh engineering analysis to reflect advances in core technology and instead is relying on analysis conducted for the previous rulemaking more than ten years ago. Manufacturers would not rely on decade old design sets that were not re-optimized for new core materials, and neither should DOE for the purposes of evaluating potential new standards. Therefore, we urge DOE to update both the engineering analysis as well as the initial PUL and PUL growth assumptions.

We urge DOE to revise transformer efficiency ratings so that they provide a more accurate relative ranking of transformers. We recognize that DOE recently published a test procedure final rule in which the Department decided to leave the rating point (50% PUL) for LT transformers unchanged.[4] We urge DOE to reconsider that decision based on the data DOE itself has provided in the PTSD. DOE's analysis confirms that real-world LT average annual PULs are significantly lower than that prescribed in the test procedure. Table 2.8.1 of the PTSD shows estimated average annual PULs ranging from 27 to 32% for LT representative units (RUs); these PULs are lower than the Department's 2013 estimates of 34-44%. Thus, DOE estimates that current loads are lower than those assumed in the 2013 rulemaking analysis,[5] even as electricity use has grown by 1.1% per year over that same period according to the EIA's Annual Energy Outlook (AEO). DOE cites future electrification driven PUL growth as one justification for leaving the test procedure PUL at 50%. However, it would take 57 years to reach 50% PUL using an initial average PUL of 30% and a PUL growth rate of 0.9% per year as assumed in the PTSD.

DOE's analysis shows that higher ELs can lead to increased energy usage due to the disparity between the test PUL, where losses for each EL are evaluated, and the real-world PULs used in the overall energy savings and economic analysis. For example, the average first-year energy savings at EL1 in Table 7.2.2

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[3]Commission Regulation (EU) 548/2014, Table I.1, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2014.152.01.0001.01.ENG

[4]86 Fed. Reg. 51230.

[5]The test procedure final rule mentions a 0.4%/yr. growth from 2011-2018, but the source of this rate is unclear.

for RU2 are negative;[6] this is because designs that minimize load losses are selected even though they do not deliver first-year energy savings relative to EL0. This example highlights how the test procedure is not providing an accurate relative ranking of transformers. To illustrate this more clearly, Figure 1 plots efficiency and total loss curves for two transformers with equal efficiencies and losses at 50%; i.e., these two transformers could represent minimally DOE compliant transformers. The blue curve, prioritizing load losses (LL), reaches maximum efficiency at 50% while the red curve, prioritizing no-load losses (NL), reaches maximum efficiency at 30%. If these transformers were operating at a PUL consistent with DOE's own analysis (30%) the red curve transformer prioritizing core losses would have 22% less total losses.[7] For comparison, DOE's projected first-year average energy savings for EL4 in the preliminary analysis are 19-42% for LTs, as shown in Table 7.2.2.[8] Thus, these two transformers, while both representing minimally compliant designs at the 50% test PUL, would have much different relative efficiency rankings if evaluated at 30% PUL. The blue curve design has over-emphasized the winding loss minimization at the expense of minimizing core losses in a way that negatively impacts its energy efficiency at lower, more realistic loads. For simplicity, our analysis herein assumes that load factor equals PUL (i.e., peak load equals transformer nameplate rating).[9] The only two assumptions used to plot Figure 1 are well known relationships to estimate transformer loss curves.[10] Step-by-step details for the savings estimate calculations can be found in the Appendix on p. 10 of these comments. These savings calculations mirror those published previously by EPA.[11]

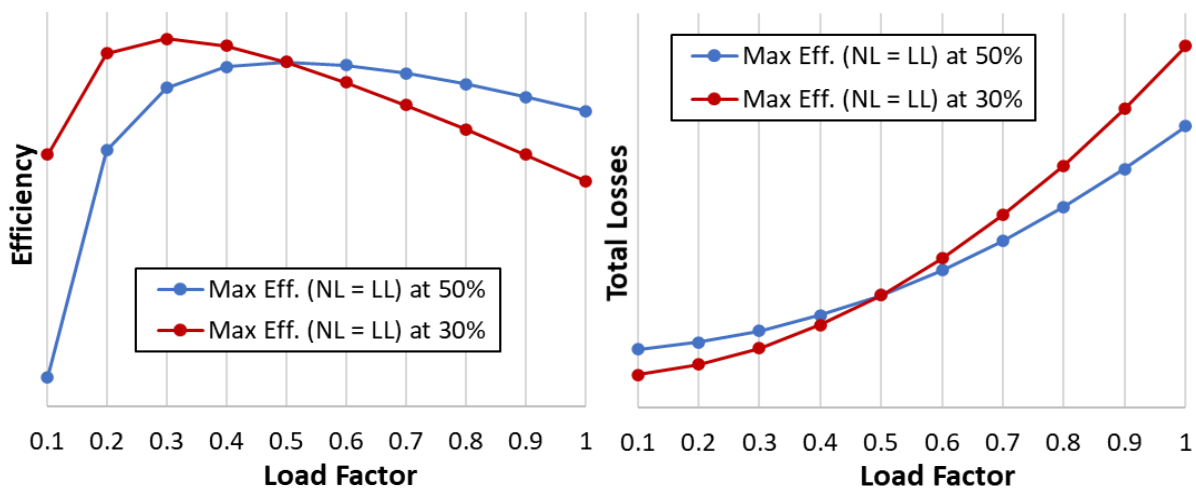

Figure 1: Transformer efficiency (left) and total loss (right) curves for designs optimized at 50% (blue) and 30% (red) load factor.

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[6]EERE-2019-BT-STD-0018-0022, p. 7-9. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022
[7]Maximum efficiency occurs where load losses equal no-load losses. If both curves have total losses of 100 W at 50%, the load and no-load losses of the blue curve will each be 50 W at 50% load, and those of the red curve will be 26.5 W each at 30% load. (The load and no-load losses of the red curve at 50% load will be 73.5 W and 26.5 W, respectively.) The load and no-load losses of the blue curve will be 18 W and 50 W, respectively, at 30%. Thus, total losses at 30% will be 68 W for the blue curve and 53 W for the red curve, for savings of (68 - 53) W / 68 W = 22%
[8]EERE-2019-BT-STD-0018-0022, p. 7-9. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022
[9]DOE estimates peak loading at 85% of nameplate. EERE-2019-BT-STD-0018-0022, p. 7-5. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022
[10]#1- maximum efficiency occurs when NL = LL, #2 - load losses increase with load factor squared.
[11]Energy Star Guide to Buying More Efficient Distribution Transformers, https://www.energystar.gov/sites/default/files/asset/document/Transformers%20Buyer%27s%20GuideFinal10-16-17.pdf

DOE discusses in the recent test procedure final rule that the risk of selecting too low a standard PUL is greater than that of selecting one too high.[12] While it is true that total losses and thus effects of efficiency will be higher at high PULs, significant savings are available for designs optimized at 30% PUL versus the 50% PUL test point even across a broad distribution of real-world PULs. For example, the left portion of Figure 2 plots average RMS loads (PUL) for RU2 from DOE's hourly loading model results; this data was obtained from the "Results-Consumer" sheet in the RU2 summary spreadsheets accompanying the PTSD.[13] Next, we calculated the total losses across these real transformer load points for both the 50% PUL optimized design (blue) and the 30% PUL optimized design (red), as shown on the right side of Figure 2; we set both transformer curve losses to 100 W at 50% PUL, then summed the total losses across all the transformer PULs shown on the left side of Figure 2. Overall, the transformer optimized for 30% PUL has 23% less total losses than the transformer optimized at 50% PUL. We note that only 5% of loads in Figure 2 are above 50% PUL. These results provide strong evidence that energy savings obtained at lower real-world PULs will more than offset any increased losses at PULs above 50%.

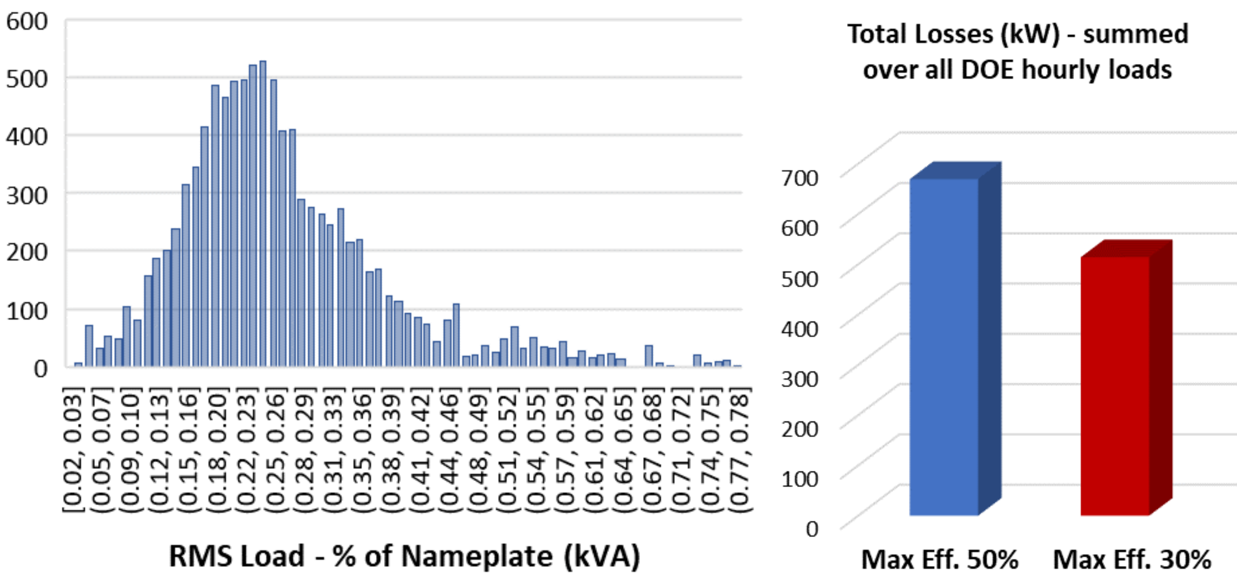

Figure 2: DOE RMS Load (PUL) data for RU2 (left) and total losses for the two transformers (right).

Importantly, DOE's own analysis suggests that most purchased transformers will have efficiency curves resembling the blue curve that overprioritizes load losses. DOE's model assumes that 90% of purchases of LTs are based on first cost.[14] Based on the published summary spreadsheets accompanying the PTSD, the lowest-cost designs at EL0 for LTs indeed have similar NL and LL at 50% (i.e., consistent with the blue curve transformer).[15] For example, the 12 lowest-cost designs for RU2, found in the "Engineering Inputs" sheet, have average NL and LL at 50% PUL of 70 and 62 W, respectively, and a manufacturer selling price of $1203 on average. In comparison, the red curve shown in Figure 1 would correspond to a transformer where *LL ≈ 3 x NL*. The 12 designs most closely resembling these criteria, with LL ≈ *2-5 x NL* for RU2, have average NL and LL of 34 W and 98 W, respectively, and cost $1248 on average. These 12 designs

[12] 86 Fed. Reg. 51240.
[13] EERE-2019-BT-STD-0018-0026, https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0026
[14] EERE-2019-BT-STD-0018-0022, p. 2-70. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022
[15] EERE-2019-BT-STD-0018-0026, https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0026

utilize both amorphous metal (AM) and grain-oriented electrical steel (GOES) cores. Thus, DOE's own engineering analysis suggests that real-world energy savings of 23%, from Figure 2, are possible with a cost increase of only 4% for RU2 with current EL0 designs. Based on design-specific reported load losses at both 50% and 100% found in the spreadsheet, the load loss characteristics of the designs examined herein are very similar to the red and blue curves shown in Figure 1; however, we encourage DOE to use available bid data to better understand the typical loss characteristics of purchased transformers.

To put these energy savings and cost increases in perspective, 23% savings would be equivalent to an efficiency between EL2 and EL3 for RU2 based on Table 7.2.2. However, the 12 lowest-cost designs at these ELs for RU2 have average manufacturer selling price estimates of $1283 and $1347; these initial costs represent increases of 7% and 12%, respectively, over the 12 lowest-cost EL0 designs. We obtained similar results using DOE's PUL data and engineering designs for RU4 and RU5, where energy savings of 24% and 18%, respectively, are possible with cost increases of 11% and 7%, respectively for EL0 designs. Energy savings of 18% for RU5 is equivalent to EL3, wherein the 12 lowest-cost designs cost 27% more than the 12 lowest-cost EL0 designs. Together, RU2, RU4, and RU5 combined represent about 90% of estimated shipped capacity.[16] These results suggest that significant savings would be available at a lower initial cost if the test procedure PUL was changed to 30%. In other words, ***these results indicate that the disconnect between the test procedure PUL and real-world PULs may be resulting in overestimates of the incremental cost to reach a certain level of energy savings.*** We therefore urge DOE to change the test procedure PUL from 50% to 30% for LTs.

DOE should consider using lower initial PUL and PUL growth assumptions in its analyses. An overestimation of initial PUL and PUL growth would only exacerbate the issues discussed above. DOE examined recent data made available through the IEEE Distribution Transformer Subcommittee Task Force which showed average LT load factors of about 30% and PULs of about 15% (i.e., peak loads were about 50% of transformer nameplate capacity).[17] Additional recent loading data from the Knoxville Utilities Board submitted to IEEE showed load factors of about 25% and PULs of about 12% for LTs.[18] We encourage DOE to consider other available data sources in addition to the PUL data used in the preliminary analysis. For example, NREL has powerful load modeling and forecasting analytics that could potentially be utilized for estimating current and future transformer PULs.[19]

For PUL growth, DOE assumed a load growth rate of 0.9%/year for LTs based on EIA's AEO projected electricity sales growth of 0.9%/year.[20] Thus, DOE appears to be suggesting that 100% of electricity growth will be handled by existing transformers. While we agree that electricity consumption going forward may grow due to electrification of the US economy, we understand that historically most additional load is handled by new installations rather than existing transformers. We recognize that electrification will alter this paradigm to some extent but believe that it is unreasonable to assume that all electricity growth will add on existing transformers. Since increases in average loads would correlate with increases in peak loads, transformers due for replacement will likely be replaced with larger units

[16] EERE-2019-BT-STD-0018-0022, p. 9-6. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022
[17] Discussion of New Dual Nameplate kVA for Distribution Transformers, 2020, https://grouper.ieee.org/groups/transformers/subcommittees/distr/EnergyEfficiency/F20-DistrTransfLoading-Mulkey.pdf
[18] Distribution Transformer Loading, Knoxville Utilities Board, 2020, https://grouper.ieee.org/groups/transformers/subcommittees/distr/EnergyEfficiency/F21-TransfEfficiency-Presentation.pdf
[19] Load Modeling and Forecasting, https://www.nrel.gov/grid/load-modeling.html
[20] 2021 EIA Annual Energy Outlook, https://www.eia.gov/outlooks/aeo/electricity/sub-topic-01.php

that would mitigate increases in PUL. Further, there is evidence that climate change will result in peak transformer loads increasing faster than average loads. One study, simulating the effects of global warming on electricity demand, projected peak load increases more than double that of average load increases under multiple scenarios; projected average and peak load increases by the end of this century were 2.8% and 7.0%, respectively, for a moderate warming scenario.[21] Thus, we believe utilities will plan conservatively by installing larger transformers capable of handling rare peak demand events. Evidence from the aforementioned IEEE load data suggests utilities are already doing this as reported average peak loads were only 50% of nameplate capacity. Utility decisions for how they size transformers are unlikely to change for new and replacement transformer installations given the uncertainties around future electricity demand.

An examination of model-selected transformer design loss curves at different ELs make it clear why load estimates, based on initial PUL and PUL growth, are important to the overall energy savings calculations and resulting relative efficiency rankings. For example, the lowest-cost designs at EL0 have core losses that roughly equal load losses at 50% PUL. Alternatively, at EL4, the lowest-cost designs have core losses that are 2-5x less than load losses at 50% PUL; i.e., these higher-efficiency designs begin to prioritize minimizing core losses rather than load losses. However, if estimated loads in the overall life-cycle cost (LCC) analysis are artificially large, then the potential energy savings from these higher EL designs that prioritize minimizing core losses over winding losses may be discounted in the overall energy savings estimates. These effects could impact both first cost and TOC-based purchases in DOE's modeling. Thus, DOE should attempt to ensure that the assumptions for initial PUL and PUL growth are accurate. If DOE decides to maintain these PUL inputs at their current values, the Department should provide a sensitivity analysis that enables commenters to evaluate the effect of PUL assumptions on the overall energy savings and economic analysis. The PTSD states that a PUL sensitivity analysis was performed, but to our knowledge no such data or information has been published.[22]

DOE should check the PUL calculations presented in the preliminary analysis. A transformer is typically supplying electricity to several customer meters. While load factor, or average meter load divided by peak meter load, is easily calculated using the meter data (e.g., average and peak loads) described in the preliminary analysis, transformer PUL estimates require additional calculation steps. To calculate transformer load, one must associate which meters were supplied by a single transformer with a given nameplate capacity. The PTSD does not mention these additional calculation steps in Appendix 7C.[23] DOE's estimate of average peak load is 85% of nameplate load,[24] so PUL is lower on average than load factor. We are concerned that load factor may have been misconstrued for PUL, and we urge DOE to clarify the steps taken to calculate reported initial PUL values.

We urge DOE to update the engineering analysis to better reflect advancements in core technology. In the preliminary analysis, DOE reports that significant advancements in core technology have been made since 2010, particularly involving high-permeability GOES. However, the preliminary analysis applied material prices to design sets analyzed back in 2010.[25] Crucially, even for high-permeability GOES

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[21] M. Auffhammer, P. Baylis, C.H. Hausman, PNAS, 2017, 114 (8), 1886-1891. https://www.pnas.org/content/114/8/1886.full

[22] EERE-2019-BT-STD-0018-0022, p. 8-23. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022.

[23] EERE-2019-BT-STD-0018-0022, p. 7C-1. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022

[24] EERE-2019-BT-STD-0018-0022, p. 2-61. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022

[25] EERE-2019-BT-STD-0018-0022, p. 2-45. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022

materials brought to market since the 2013 final rule, DOE simply adapted models of conventional GOES core designs by swapping in the new core material parameters and keeping all other model attributes unchanged. DOE's consultant acknowledged at the public webinar that manufacturers will often re-optimize core designs.[26] We understand that manufacturers maintain up-to-date tools for designing transformers for their customers which reflect materials and prices available in current markets. They do not simply swap in one core material for another since the materials do not have identical characteristics. In a highly competitive market, manufacturers that fail to optimize their designs will be at a competitive disadvantage. Since manufacturers would not rely on ten-year-old optimizations that swap one core material for another, neither should DOE for the purposes of evaluating potential new standards.

The engineering modeling presented in the PTSD include some anomalous results that further suggest issues with the engineering analysis. On slide 42 of the public webinar presentation, the purchaser decision model assumed 79% of cores sold for RU3, even at EL0, will utilize the newer high-permeability GOES cores.[27] Further, the other 21% of cores sold would be AM cores. If these model results were accurate, these shares would be reflected in the current market. However, we understand that most transformer cores currently sold are conventional GOES cores. This mismatch between the modeled results and the current market provides further evidence that this analysis needs to be re-done.

The bid data provided in the PTSD also suggests problems with DOE's analysis. We strongly support DOE's use of a model to develop predicted transformer prices and efficiency. However, observed prices can be used to assess whether a model is providing reasonable estimates. In the PTSD, DOE collected publicly available bid data for LTs using a combination of internet research and direct requests to the issuing agency.[28] DOE states that the data is informational, and no conclusions are presented. However, for three-phase LTs in particular (RU4 and RU5), significant differences between the real bid data and model estimated manufacturing selling price are present. These discrepancies reinforce the need for DOE to update the engineering analysis. Thus, to reflect up-to-date materials, costs, and designs, DOE must update the engineering analysis to properly assess the impact of core technology improvements on the overall economic and energy savings analysis.

DOE should aim to establish world-leading transformer energy efficiency levels. In the years since DOE last revised its standards, major economies around the world including India, China, and the EU have set new transformer efficiency thresholds. Many of these levels far exceed the current DOE standard levels and some are beyond even the intermediate ELs evaluated in the PTSD. For example, current efficiency thresholds for three-phase LTs, represented by RU4 and RU5, are shown in Figure 3;[29] the efficiency curves are adjusted to the common IEC definition of kVA and 50Hz performance. The five ELs defined in the PTSD are shown in black,[30] where the proposed EL1, EL2, and EL3 are exceeded by recent efficiency thresholds established in India, China, and Europe. Based on this initial comparison, we encourage DOE to evaluate international standards in greater detail to ensure that cost-effective technology solutions from international markets are fully considered in the revision of future US standards.

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[26] EERE-2019-BT-STD-0018-0040, p. 22. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0040
[27] EERE-2019-BT-STD-0018-0024, p. 42. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0024
[28] EERE-2019-BT-STD-0018-0022, p. 5-76. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022
[29] Data and figure provided by the Center for Law and Social Policy (CLASP).
[30] EERE-2019-BT-STD-0018-0022, p. 8-7. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022

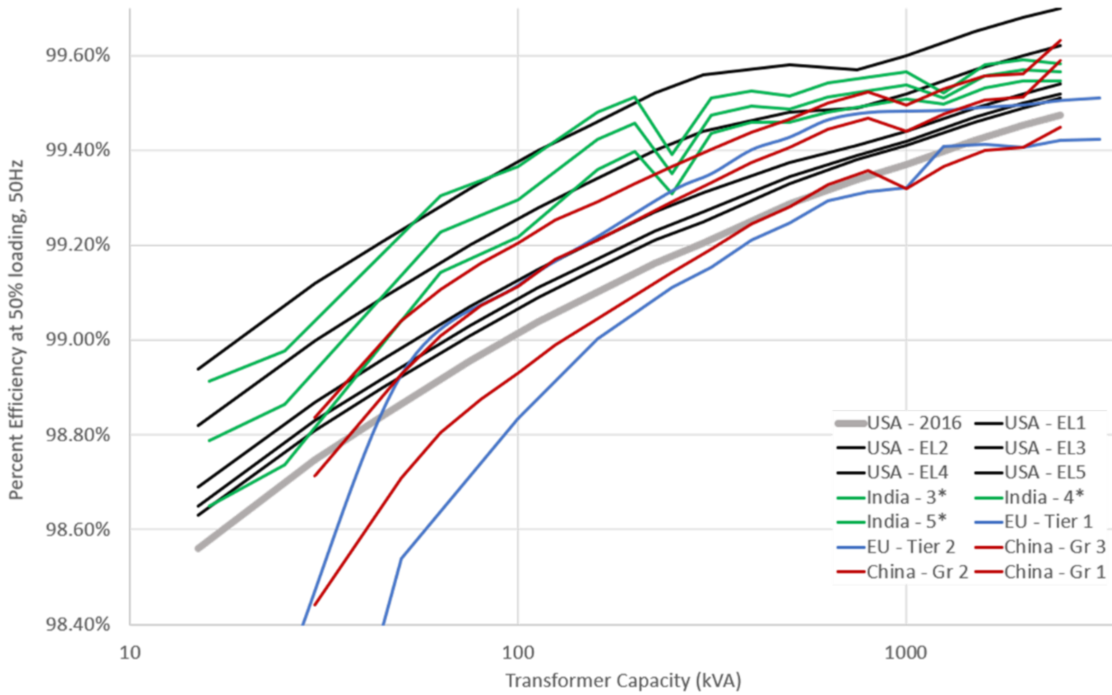

Figure 3: Comparison of LT transformer efficiency in the US, India, China, and the EU.

Further, consideration of current US standards levels by other countries demonstrates how US action can provide the basis for improved standards elsewhere, effectively multiplying the effects of US standards. For example, the United Nations United for Efficiency (U4E) procurement guidelines for LTs use the current DOE standards for their relevant Level II guideline.[31] U4E is working with 8 countries in Southern Africa[32] and 4 countries in Southeast Asia to adapt these guidelines into their national framework and develop transformer standards.

In considering amended efficiency standards, DOE could require EL4 or EL5 for a subset of LTs if AM core availability is a concern. EL4 and EL5 LTs utilize efficient AM cores that would offer substantial energy and LCC savings. DOE states in the NOPR that availability and quality of amorphous ribbon are not considered a significant barrier to adoption.[33] We agree that current AM manufacturing capacity may be sufficient to meet the needs of the US market and will increase in response to regulatory change. However, we understand that manufacturer impacts, as in the 2013 rulemaking, could influence DOE's final rule. In this scenario, DOE could require EL4 or EL5 for one or more transformer types. For example, the potential energy savings for single-phase pole-mounted transformers, represented by RU2, could be approximately 2 quads. This would provide meaningful energy savings and send a clear signal to stakeholders about the future of distribution transformer efficiency.

Thank you for considering these comments.

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[31] U4E Model Transformer Technical Specification, July 2019, p. 63, https://united4efficiency.org/wp-content/uploads/2021/06/U4E_DT_Model-Procurement-Specs_Final_20191002_2.pdf

[32] Botswana, Eswatini, Lesotho, Malawi, Namibia, Tanzania, Zambia and Zimbabwe.

[33] EERE-2019-BT-STD-0018-0022, p. 3-42. https://www.regulations.gov/document/EERE-2019-BT-STD-0018-0022

Sincerely,

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Appendix: Energy Savings Calculations

The derivation outlined below is intended to clarify how the energy savings discussed on pp. 2-3 are calculated. This approach mirrors that used in a 2017 EPA publication.[34] The same energy savings may be obtained from the efficiency curves plotted in Figure 1.

NL = non-load core losses
WL = full load winding losses
L = load factor
LL = actual load loss (based on WL and L)
TL = total losses

1. Max transformer efficiency occurs when LL = NL

Expressed mathematically

$$L^2 \; x \; WL = LL = NL \quad (1)$$

2. For the DOE minimum design at 50% load and peak efficiency (e.g. blue curve in Figure 1)

$$TL_{DOE} = LL_{DOE} + NL_{DOE} \; (2)$$

Since $LL_{DOE} = NL_{DOE}$

$$TL_{DOE,50\%} = 2NL_{DOE,50\%} \; (3)$$

3. Shown in Figure 1, losses of the DOE and TOC designs are equal at 50% load (same efficiency)

$$TL_{DOE,50\%} = \; 2NL_{DOE,50\%} = \; TL_{TOC,50\%} \; (4)$$

So, TOC (red curve) design losses at 50% load can be expressed as

$$TL_{TOC,50\%} = 2NL_{DOE,50\%} = NL_{TOC,50\%} + LL_{TOC,50\%} \; (5)$$

How do we know what $\mathrm{LL}_{\mathrm{TOC},50\%}$ and $\mathrm{NL}_{\mathrm{TOC},50\%}$ are?

4. Well, for a given design, we know that LL scales with L^2 and NL doesn't change with load, thus we can write

$$LL_{TOC,50\%} = \; LL_{TOC,30\%} \; x \left(\frac{L_{50\%}}{L_{30\%}}\right)^2 \; (6a)$$

and

[34] Energy Star Guide to Buying More Efficient Distribution Transformers, https://www.energystar.gov/sites/default/files/asset/document/Transformers%20Buyer%27s%20GuideFinal10-16-17.pdf

$$NL_{TOC,50\%} = NL_{TOC,30\%} \text{ (6b)}$$

Thus, we can re-write Eq. 5 as

$$TL_{TOC,50\%} = NL_{TOC,30\%} + LL_{TOC,30\%}\ x\ \left(\frac{0.5}{0.3}\right)^2 = NL_{TOC,30\%} + 2.778\ x\ LL_{TOC,30\%} \quad (7)$$

5. Next, we know that at 30% load (max efficiency point for TOC design) that

$$NL_{TOC,30\%} = LL_{TOC,30\%} \text{ (8)}$$

So we can write Eq. 7 as

$$TL_{TOC,50\%} = 3.778\ x\ NL_{TOC,30\%} = TL_{DOE,50\%} \text{ (9a)}$$

Or

$$NL_{TOC,30\%} = TL_{DOE,50\%}/3.778 \text{ (9b)}$$

6. Now, we calculate the losses for the 50% optimized DOE design at 30% load. First, NL doesn't change with load so

$$NL_{DOE,30\%} = NL_{DOE,50\%} \text{ (10)}$$

Since LL is assumed to scale with L^2, we can write LL for 30% for DOE design as

$$LL_{DOE,30\%} = LL_{DOE,50\%}\ x\ \left(\frac{L_{30\%}}{L_{50\%}}\right)^2 \text{ (11)}$$

7. Finally, let's give an example calculation and estimate the potential energy savings.

Let's say $TL_{DOE,50\%} = 100$ W (peak efficiency NL = LL = 50W)

Then from Eq. 9b

$$NL_{TOC,30\%} = \frac{100W}{3.778} = 26.5\ W$$

$$TL_{TOC,30\%} = 2\ x\ NL_{TOC,30\%} = 53\ W$$

Then from Eq. 11

$$TL_{DOE,30\%} = 50\ W + 50\ W\ (0.3/0.5)^2 = 68\ W$$

Finally, percent savings are:

$(TL_{DOE,30\%} - TL_{TOC,30\%}) / TL_{DOE,30\%}$ = *(68 W –53 W)/68 W =* ***22%***