36th International Electric Vehicle Symposium and Exhibition (EVS36)
Sacramento, California, USA, June 11-14, 2023

Impact of Increasing Replacement Transformer Size on the Probability of Transformer Overloads with Increasing EV adoption

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Executive Summary

The growing number of electric vehicles (EVs) translates to more demand for charging, which can strain the electric grid and cause thermal issues for distribution system assets. Therefore, appropriately sizing replacement service transformers is increasingly important due to various factors, including the increased risk of thermal overloading from EV adoption and rising costs and lead times for replacements. The paper presents a case study that uses the Hotspotter tool to analyze transformer information from Sacramento Municipal Utility District (SMUD) and evaluate the impact of the increased adoption of electric vehicles on the electric grid and the potential for overloading service transformers. The EPRI's Hotspotter tool was used to evaluate the impact of EV charging demand on the grid, and three transformer replacement scenarios were compared to mitigate the risk of future overloads. The study recommends increasing transformer sizes by two levels for smaller transformers (15kVA, 25 kVA, and 37.5 kVA) to significantly reduce the number of overloads. However, for midsize transformers (50 kVA), increasing the replacement size by one level is optimal. Zones with larger transformer sizes (75 kVA and 100 kVA) experience a lower number of overloads, and replacing them with the original size increases the total cost without a substantial reduction in thermal overload. This study provides a guideline for selecting appropriate transformer sizes during residential service transformer replacement, considering cost calculations, the observed number of overloads, and other internal replacement criteria. The study's findings can serve as a guide for utilities to ensure they can accommodate the increased load associated with the higher adoption of ZEVs while ensuring grid reliability.

Keywords: electric vehicle (EV), charging, infrastructure, utility, cost

1 Introduction

Many states and nations have targeted to phase out the sale of internal combustion cars by 2050, and some states like California and New York aim to achieve 100% sales of zero emission vehicles (ZEVs) by 2035

[1,2]. The accelerated transition to ZEVs means higher electric vehicle (EV) adoption which creates a significant load on the electric grid and has potential adverse consequences to distribution systems assets. The surge in demand for electricity due to the higher adoption of electric vehicles may overload service transformers, which, in turn, can result in premature wear or failure of transformers and undesirable service voltage. Furthermore, service transformers have a limited capacity, and the addition of more EVs to the grid could surpass the transformer's capacity, which may necessitate upgrades or replacements earlier than planned. The concerns of service transformer overloading due to increased load are amplified by increasing transformer cost and increasing lead time to obtain new transformers [3]. Such concerns necessitate careful consideration of transformer sizes during service transformer replacement to mitigate the risk of future overloads.

EPRI's Hotspotter tool is utilized to evaluate the impact of electric vehicle (EV) charging demand on the grid. The tool uses statistical simulations of transformer load, based on service transformer information and EV charging profiles provided by SMUD, to assess potential overloads. The study compares three transformer replacement scenarios in which transformer sizes are increased or split to reduce the number of overloads. The total replacement cost of each transformer size is estimated, taking into account overloaded transformer replacement costs, lifecycle replacement, and energy supply losses from transforming efficiency. Ultimately, the study provides a recommendation for transformer replacement sizing based on cost calculations, the observed number of overloads, and other internal replacement criteria of SMUD. This study can serve as a guide for selecting the appropriate transformer size during the replacement of residential service transformers.

2 EPRI’s Hotspotter tool

EPRI’s Hotspotter tool is a probabilistic modeling tool that estimates the probability of a service transformer overloading with different levels of confidence based on the input of transformer asset data, expected peak loads, and EV details. The EV portfolio for this study was developed using EV charging rate (kW), EV adoption probability in the SMUD region, and EV charging behavior based on joint probability of miles driven and charging start time. Multiple utilities have used the Hotspotter tool [4,5] to evaluate the number of overloads along with a number of different applications in the past [6]. The tool aids asset managers and system planners in linking the electric vehicle portfolio, customer behavior projections, utility databases, and business cost specifications. The tool runs fast, allowing for quick reassessments as conditions change.

3 Modeling tool methodology

The EV HotSpotter (EVHS) tool uses a probabilistic model developed by EPRI to compute the probability that a given transformer will be overloaded in an hour, based on transformer loading, the EV adoption probability in the region, the type of EVs and their charging configuration. The vehicle charging start hour is determined using a joint-probability data derived based on miles driven and home arrival time. To determine the probability of transformer overloading, the total EV charging demand for a specific hour is calculated and compared to the remaining capacity of the transformer for that hour. By comparing these two values, the probability of the transformer overloading can be assigned. This process is repeated for each hour, and the probabilities are computed and analyzed for various EV adoption scenarios. Uncertainties associated with the parameter used in model means it is not possible to predit accurately the probability for each transformer. However, a probabilistic model can determine the expected number of transformers that may face overloading in the future when applied across the region.The Hotspotter tool is implementation of the modeling tool presented in [5] and working mechanism is shown in Figure 1.

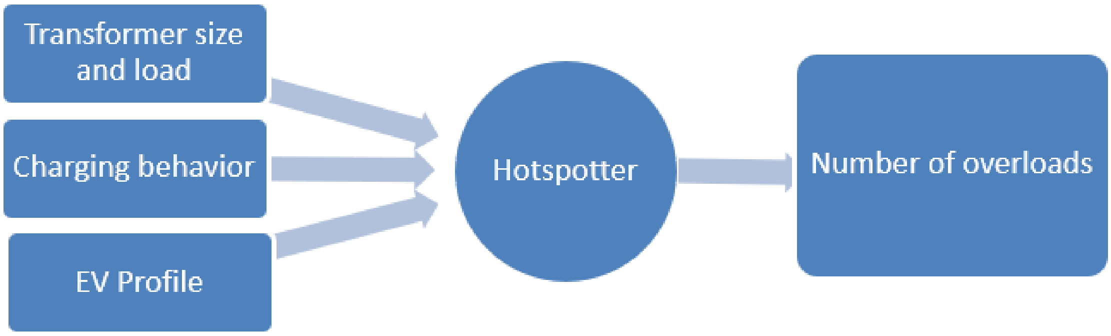

Figure 1: Working mechanism of Hotspotter tool

4 Case Study with SMUD

4.1 Study overview

The number of overloads in the present service transformer asset fleet provides information about impact load due to EV adoption and residential charging. Improved understanding of the appropriate sizing of replacement service transformers is studied by increasing the transformer size and evaluating the reduction in overloads/early replacement and energy losses in three scenarios – original, bump 1, and bump 2. In the first scenario - Original, transformers of six different sizes (as shown in Table 1) are grouped in a zone corresponding to their existing size to compute the number of overloads due to residential EV charging. For the second scenario – Bump 1, the size of each transformer is increased to one level higher, simulating upgraded transformer size during replacement. The largest two transformer sizes are split into multiple transformers. In the third scenario – Bump 2, each of the original transformer sizes is increased two levels higher compared to original, simulating a much larger replacement size to accommodate future EV loads. Three EV adoption levels (low, medium, and high) are analyzed for each scenario, while other EV characteristics are assumed based on EVs in SMUD's territory. Table 1 summarizes the three scenarios evaluated in this study and Table 2 presents the bumping and splitting criteria of the transformers based on sizing.

For this study, six zones were created corresponding to the original transformer sizes. After the bumping or splitting of the transformers, the updated transformers were kept on the same zone. For example, Zone 15 in original scenario has only the transformer sized 15kVA, and after bump 1, Zone 15 only has transformers sized 25kVA. For Zone 100, initially all transforermers are of size 100kVA but with bump 1, the zone has equal number of 100kVA and 75kVA transformers.

Table 1. Scenarios evaluated with EPRI's hotspotter tool for different transformer sizes and EV adoption levels

Scenarios	Transformer sizes	EV adoption levels
1 – Original	15, 25, 37.5, 50, 75, 100kVA	Low (15% in 2027), medium (25% in 2030) , high (50% in 2035)
2 – Bump 1	Increase transformer size of Scenario 1 by one step.	Low (15% in 2027), medium (25% in 2030) , high (50% in 2035)
3 – Bump 2	Increase transformer size of Scenario 1 by two steps.	Low (15% in 2027), medium (25% in 2030) , high (50% in 2035)

Table 2. Bumping or splitting criteria for transformer based on sizing.

Original (or previous scenario) transformer size (kVA)	Bump/Split Criteria for next scenario
15	Bump to 25 kVA
25	Bump to 37.5 kVA (for overhead) or Bump to 50 kVA for pad mount
37.5	Bump to 50 kVA
50	Bump to 75 kVA
75	Bump 50% of transformer to 100 kVA and split the remaining 50% of transformers into 75kVA and 50kVA
100	Split the transformers to 100kVA and 75kVA

4.2 Transformer data

A total of 47,025 residential service transformers from SMUD's territory are analyzed for overloading due to EV charging demand in scenario 1. For the remaining two scenarios, bump 1 and bump 2, due to increasing in size of transformer or splitting of larger two transformer sizes (75kVA and 100kVA), the total number of analysed transformers are higher compared to original scenario as shown in Table 3 and Figure 2. It can be observed that as the bump progresses, the number of larger transformers (75kVA and 100kVA) increase significantly (Figure 2). Table 4 presents the number of transformers associated with each zone for three scenarios.

SMUD obtained 24-hour historical AMI data, which includes decentralised photovoltaics (PV) system, for each transformer loading for 2021, which was used to compare the remaining capacity of each transformer at every hour. Transformer network model of 2021 was used to find customer to transformer association. When splitting transformers during bumping of the size, the number of residents and their associated load from the original transformer were proportionally split between the two new transformer sizes.

Table 3. Total number of transformers of various sizes

Scenarios	Transformer Size (kVA)						Total
	15	25	37.5	50	75	100	
Original	1,294	4,684	5,012	21,372	11,951	2,712	47,025
Bump 1	0	1,294	4,667	11,005	30,060	8,687	55,713
Bump 2	0	0	1,294	19,697	34,722	23,717	79,430

Table 4. Total number of transformers of in different zones

Scenarios	Number of transformers in differrent Zones						Total
	Zone 15	Zone 25	Zone 37.5	Zone 50	Zone 75	Zone 100	
Original	1,294	4,684	5,012	21,372	11,951	2,712	47,025
Bump 1	1,294	4,684	5,012	21,372	17,927	5,424	55,713
Bump 2	1,294	4,684	5,012	32,058	26,890	9,492	79,430

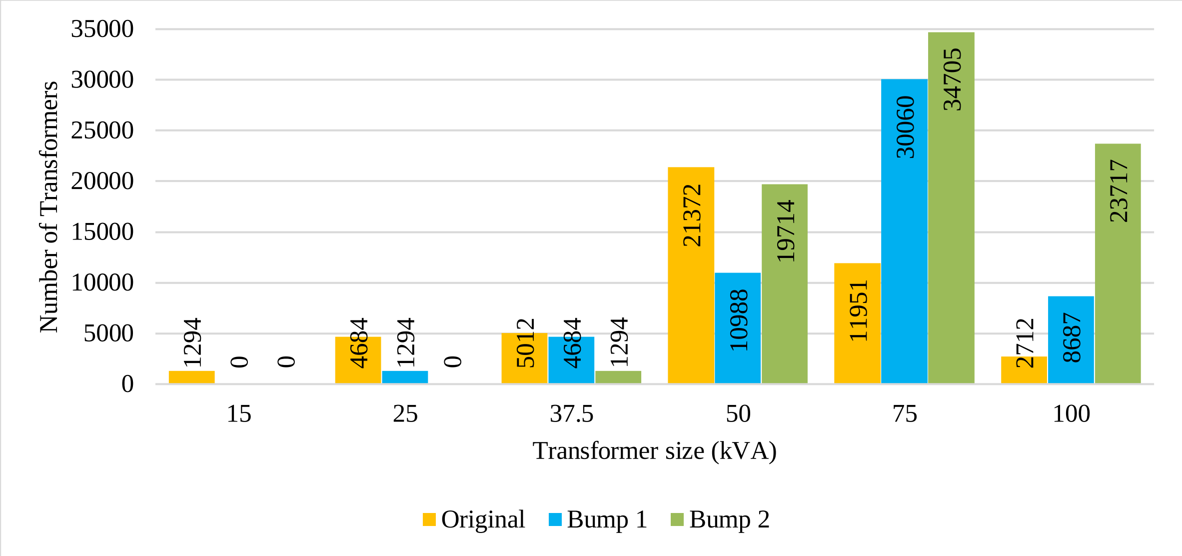

Figure 2: Number of transformers of different sizes in three scenarios.

In addition to the number of transformer to be replaced, the cost of each transformer plays important role for the upgrade decision. The cost of each transformer was modelled, depending on mounting type (pad or pole mount), size of transformer, and hardware and labor requirement for replacing the transformer.

4.3 Vehicle parameter assumptions

EV volume forecast was based on internal SMUD's analysis which came up with approximate years that the EVs would reach 15%, 25%, and 50% market penetration as 2027, 2030, and 2035 respectively. Table 5 shows the charging power level vehicle mixture in the territory of SMUD. Average vehicle efficiency of 350 Wh/mile is assumed for the study. Statistics for vehicle per household used in the study is shown in Table 6.

Table 5: Electric vehicle mixture and charging parameters

Charging Level	**Charging Rate (kW)**	**% Vehicles**
L1	1.4	20%
L2	3.3	5%
L2	7.2	25%
L2	11.5	25%
L2	19.2	25%

Table 6: Vehicles per household assumed for the study

Vehicles per household	**% of Household**
0	4.9
1	36.9
2+	58.2

4.4 Existing transformer replacement cost calculation

Replacement cost is computed for each size of transformer and for all three scenarios to make reprlacement transformer sizing recommendations. Total replacement cost is computed by aggregating three types of cost (i) overloaded transformer replacement cost, (ii) lifecycle replacement cost, and (iii) energy supply cost of transformer efficiency losses. Total replacement cost is compared for three scenarios to make the replacement transformer sizing decisions.

Overloaded transformer replacement cost (OTRC)

Transformer replacement unit cost (TRC_{unit}) is computed as weighted average of pad mount and pole mount transformer of particular size. Number of overloaded transformer (N_{OL}) are obtained from Hotspotter tool for all three scenarios.

For the original case, the overloded transformer replacement cost ($OTRC_{original}$) is computed using equation (1), as a product of unit cost of replacement of transformer and number of overloaded transformers computed from Hotspotter. Practically, all the transformers are not bumped in size at once, but gradually changed over a period of time, so equation (2) is used to compute the overload transformer replacement cost ($OTRC_{Bump}$) for the bumped case of scenario 2 and 3.

$$OTRC_{Original} = TRC_{unit} \times N_{OL\_original} \quad (1)$$

$$OTRC_{Bump} = TRC_{unit} \times N_{OL} \times \frac{Years\ of\ analysis}{TUL} + \frac{TUL - Years\ of\ analysis}{TUL} \times OTRC_{Original} \quad (2)$$

Where, TUL means transformer useful life. The useful life of transformer is assumed to be 40 years. Year of analysis is the time between the base year of 2022 and what EV adoption case year is being evaluated. For instance, 50% EV adoption in expected for 2035 (Table 1), in this case the year of analysis difference between 2035 and 2022, which is 13 years. The equation (2) scales the cost based on time and also considers the fraction of transformers that are changed naturally because of being old.

Lifecycle replacement cost (LRC)

Lifecycle replacement cost represents the cost of replacing the transformers that reach the end of life and is independent of overloads and computed using equation (3). Transformer unit cost (TRC_{unit})is computed, as in previous section, by weighted average of transformer of two mounting types. Number of transformer requiring lifecycle replacement (N_{LC}) is computed based on fraction of year that has passed till the analysis year compared to total useful life of transformer.

$$LRC = TRC_{unit} \times N_{LC} \quad (3)$$

Energy supply losses cost ($Cost_{ESL}$)

Energy supply cost loss is computed based on total energy loss from transformer and the average marginal cost of supplying the energy (equation (4)).

$$Energy\ supply\ losses\ \ cost = Energy\ losses\ \times Average\ marginal\ cost_{energy\ supply} \quad (4)$$

$$Energy\ losses\ (kWh) = Years\ of\ Analysis\ X\ Avg\ load\ per\ customer\ X\ Avg\ tfmr\ loss\ X\ Number\ of\ customers \quad (5)$$

Average marginal cost of energy supply was estimated based on SMUD's internal marginal cost forecast and the annual marginal cost was averaged up to the year of analysis from base year of 2022. Total energy losses depends on average transformer loss and total load in the system, which is product of average load per customer and number of customers, as shown in equation (5).

Average transformer loss is interpolated based on load compared to nameplate rating of the transformer. No load loss is assumed to be 10% and loss with load at nameplate rating is assumed to be 6%, which are based on specifications of SMUD. This range of losses captures both transformer coil losses from internal resistance and core losses due to magnetizing/energizing the core. Actual loss may vary based on exact transformer type and have a non-linear relationship. However, linear approximation between no-load and nameplate load loss, is used to model transformer efficiency based on load experienced.

Average load per customer is estimated based on current (ie. 2022) average annual energy consumption without considering EV and adjusting it to incorporate EV load at higher adoption level assuming EVs consume 10kWh/day.

5 Observations and output

5.1 Number of overloads

Using the transformer details and EV vehicle parameters in SMUD's territory, number of overloads were estimated using the Hotspotter tool. For the three scenarios, simulation was ran to estimate the number of overloads for the years that corresponded to 15%, 25%, and 50% EV penetration. Overloads were computed for all six transformer sizes and are summarized in Table 7. These number of overloads are used for the overload transformer replacement cost to decide on transformer replacement sizing recommendations.

Table 7: Number of overloads for different transformers sizes computed by Hotspotter tool for three scenarios at different EV penetration level

Scenario	Year	EV %	Number of overloads in different transformer sizes					
			15 kVA	25 kVA	37.5 kVA	50 kVA	75 kVA	100 kVA
Original	2027	15%	1,294	3,638	2,282	2,161	151	12
Original	2030	25%	1,294	4,185	2,682	2,645	211	20
Original	2035	50%	1,294	4,684	4,091	4,733	548	67
Bump1	2027	15%	81	123	175	56	13	0
Bump1	2030	25%	133	200	242	76	20	0
Bump1	2035	50%	286	479	542	190	77	4
Bump2	2027	15%	4	5	6	46	0	0
Bump2	2030	25%	7	13	7	48	0	0
Bump2	2035	50%	30	61	23	69	7	0

Table 8: Percentage of overloaded transformers in each zone.

Scenario	Year	EV %	Percentage of overloaded transformer in each zone					
			Zone 15	Zone 25	Zone 37.5	Zone 50	Zone 75	Zone 100
Original	2027	15%	100.0	77.7	45.5	10.1	1.3	0.4
Original	2030	25%	100.0	89.3	53.5	12.4	1.8	0.7
Original	2035	50%	100.0	100.0	81.6	22.1	4.6	2.5
Bump1	2027	15%	6.3	2.6	3.5	0.3	0.1	0.0
Bump1	2030	25%	10.3	4.3	4.8	0.4	0.2	0.0
Bump1	2035	50%	22.1	10.2	10.8	0.9	0.6	0.1
Bump2	2027	15%	0.3	0.1	0.1	0.2	0.0	0.0
Bump2	2030	25%	0.5	0.3	0.1	0.2	0.0	0.0
Bump2	2035	50%	2.3	1.3	0.5	0.3	0.1	0.0

From Table 8, the highest percentages of overloaded transformers occur in Zones 15, 25, and 37.5, and this problem worsens with higher EV penetration. Increasing the size of transformers in these zones greatly reduces the number of overloads. Conversely, Zones 75 and 100 have larger original transformer sizes and experience significantly fewer overloaded transformers, even without increasing transformer sizes at high EV penetration level.

5.2 Transformer replacement cost

Transformer replacement cost are calculated using the method described in Section 4.4 and the results are presented in Figure 3 to Figure 8.

For smaller transformer sizes of 15kVA (Figure 3), 25 kVA (Figure 4),and 37.5 kVA (Figure 5), bumping up the replacement size two levels up minimizes the total cost. At the two levels up sizing, the cost of transformer overloads reduces more than increases in lifecycle replacement costs or energy supply costs resulting in overall cost reduction. From Table 8, it can be seen that majority of overloads are in thes zones with smaller transformer size, which corresponds to higher proportion of overload replacement cost compared to lifecycle replacement cost and energy loss cost.

For midsize 50 kVA (Figure 6) transformers, which is the most common size, bumping up the replacement size one level up minimizes the total replacement cost for all EV adoption levels. The cost of transformer replacement due to overloads reduces with larger replacement size, however the increase in lifecycle replacement cost outweighs this benefit when sized at two levels up.

For larger transformer sizes 75 kVA (Figure 7) and 100 kVA (Figure 8), replacing with the original size increases the total cost. The high lifecycle costs and energy supply losses costs associated with the additional transformer seems to outweigh the benefits of replacing the overloaded transformers. Moreover, Zone 75 and Zone 100 (Table 8) have less than 5% of transformers overloaded even at 50% of EV adoption.

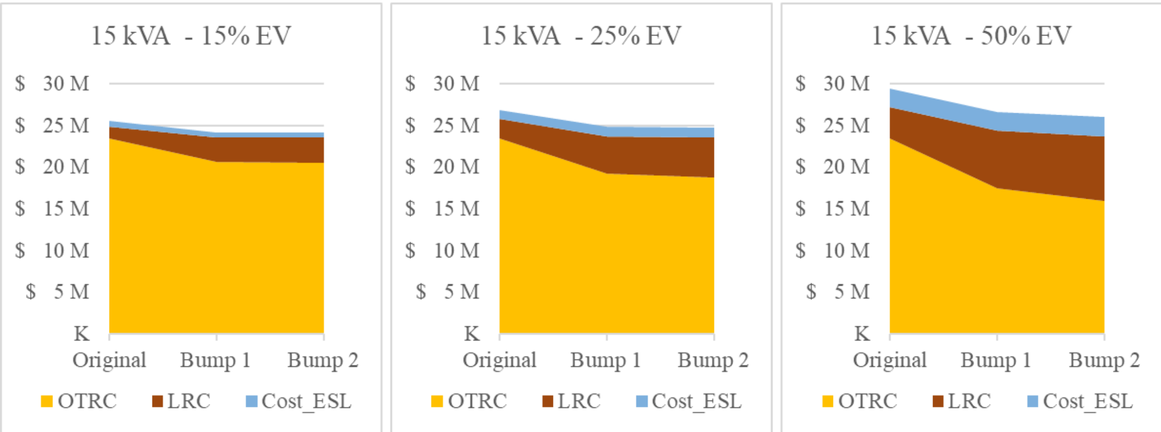

Figure 3: Replacement cost for existing 50kVA transformers for three EV penetration levels.

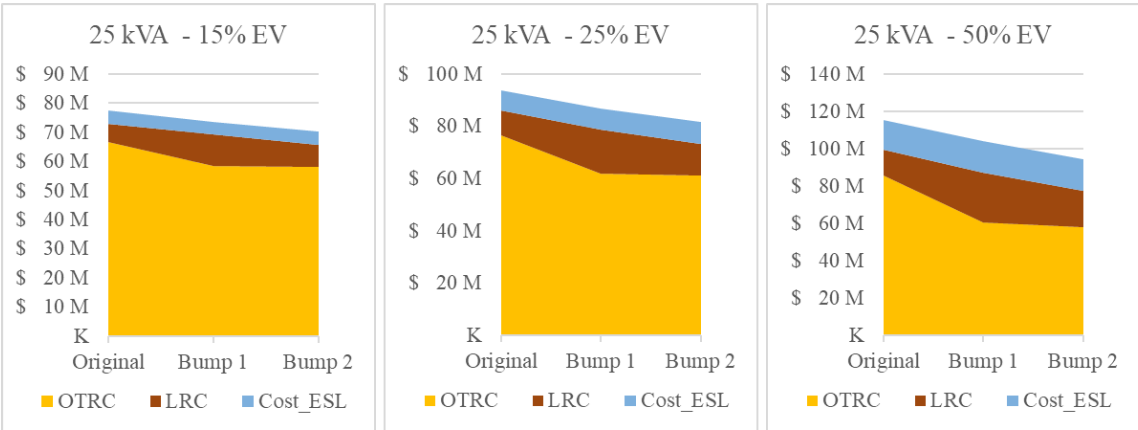

Figure 4: Replacement cost for existing 25kVA transformers for three EV penetration levels.

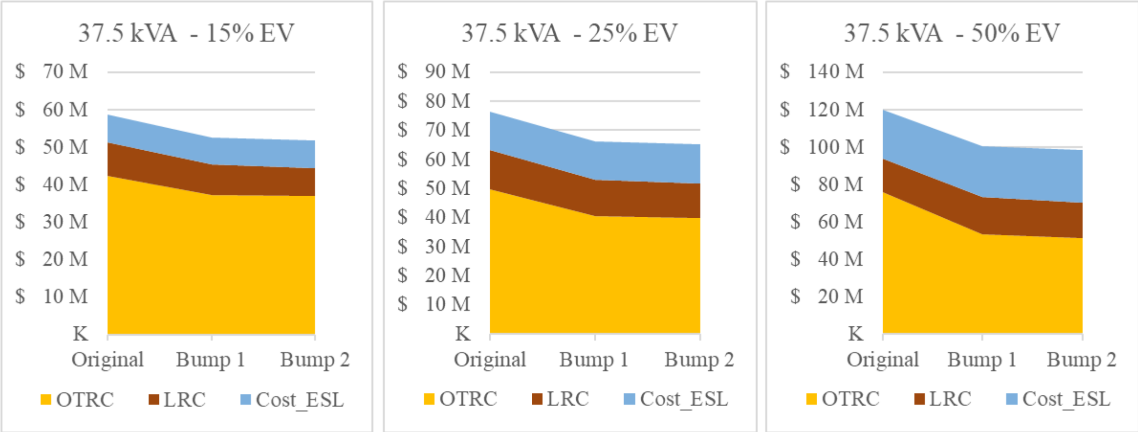

Figure 5: Replacement cost for existing 37.5kVA transformers for three EV penetration levels.

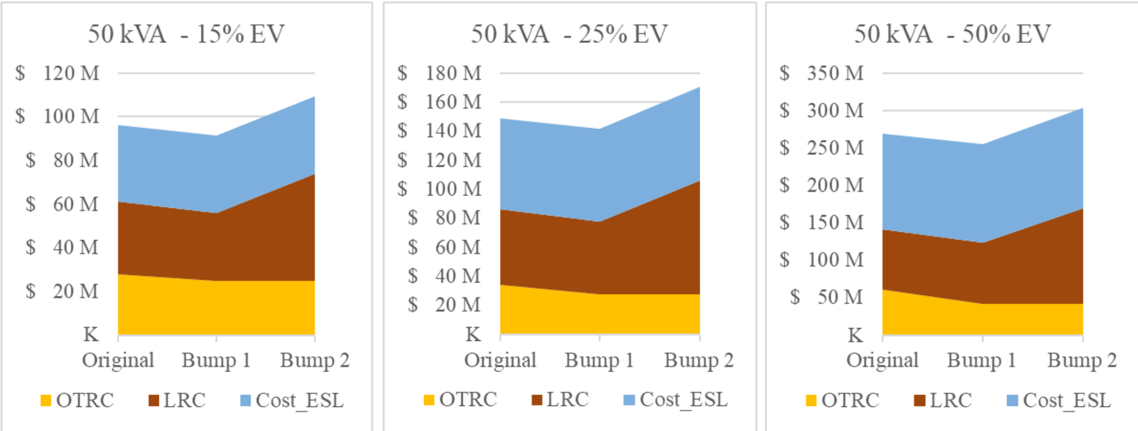

Figure 6: Replacement cost for existing 50kVA transformers for three EV penetration levels.

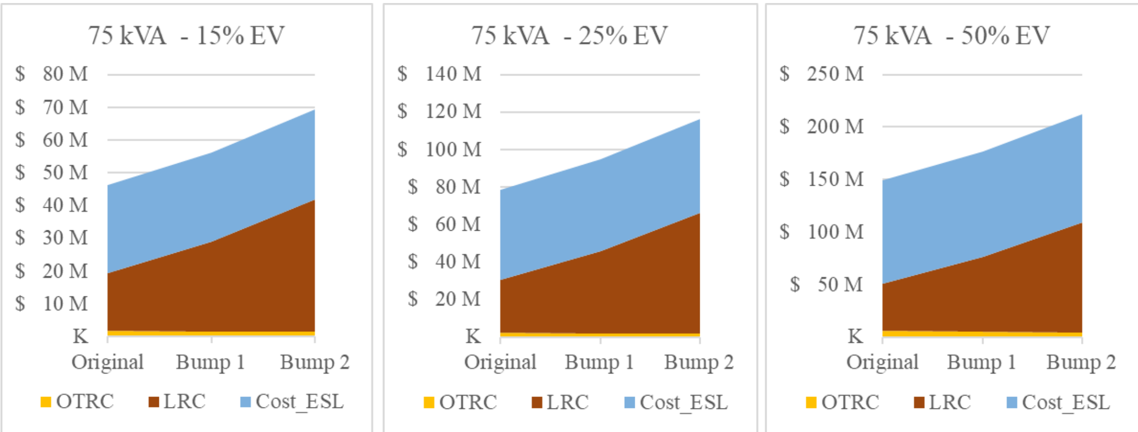

Figure 7: Replacement cost for existing 50kVA transformers for three EV penetration levels.

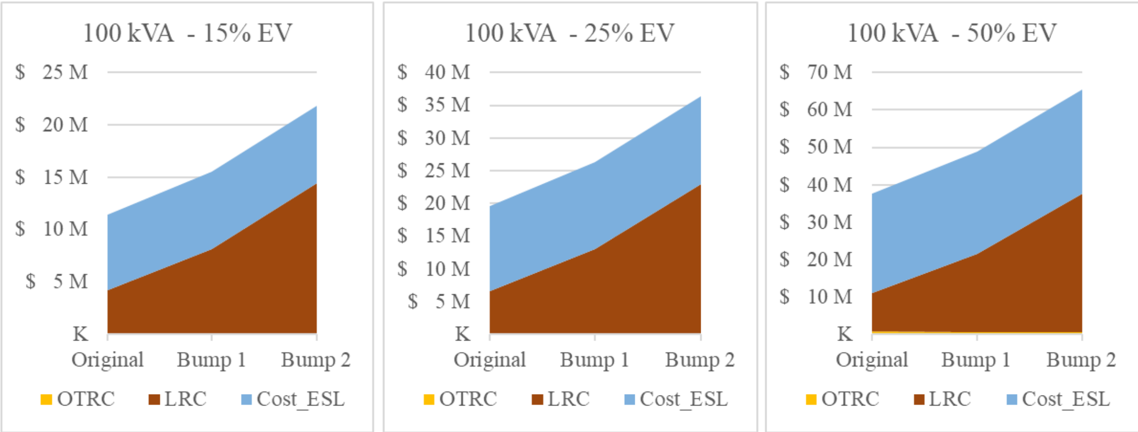

Figure 8: Replacement cost for existing 50kVA transformers for three EV penetration levels.

5.3 Transformer replacement sizing recommendation

Table 9 presents the proposed transformer replacement sizes based on the mount type. The recommendation incorporates the information from analyzed total cost calculations as well as practical recommendations from SMUD's Line Design/Grid Assets team about the transformer stock and availability.

Pole mount 15 kVA transformer has 37.5 kVA as optimal replacement size based on cost calculation. However, the proposed size not being a standard stock for SMUD, the next step higher transformer of 50 kVA is proposed as optimal replacement size. Transformers of size 25 kVA and 37.5 kVA have two sized up transformers of sizes 50 kVA and 75 kVA respectively as the proposed optimal replacement size. For the 75 kVA and 100 kVA transformers, optimal replacement size are of same size.

For the 75 kVA pad mount transformer, the proposed replacement size of 75 kVA is due to economic decision being domnated by high cost of adding the second transformer and splitting the customer. For known overload conditions, if the customer panel AIC ratings can afford a larger 100 kVA transformer, that might be a better option than replacing with equal size. In case of known overload conditions of 75 kVA pole mount transfomers, splitting may be favorable per the recommendation of the Line Design/Grid Assets team.

The existing residential single family home transformer fleet averages about 5.3 kW capacity allocation per home in SMUD territory. With the proposed optimal sizes mix the transformer fleet averages about 8 kW per home capacity allocation.

Table 9: Recommended optimal transformer replacement sizes

Mount Type	Original size	Optimal replacement size
Pole	15 kVA	50 kVA
	25 kVA	50 kVA
	37.5 kVA	75 kVA
	50 kVA	75 kVA
	75 kVA	75 kVA
	100 kVA	100 kVA
Pad	25 kVA	50 kVA
	37.5 kVA	75 kVA
	50 kVA	75 kVA
	75 kVA	75 kVA
	100 kVA	100 kVA

6 Conclusion

Many states and nations are aiming to phase out the sale of internal combustion cars by 2050, with some states like California and New York targeting 100% sales of zero emission vehicles (ZEVs) by 2035. The increased adoption of ZEVs will put significant strain on the electric grid, potentially overloading distribution system assets. Concerns around transformer overloading due to increased load are amplified by increasing transformer cost and lead time to obtain new transformers. EPRI's Hotspotter tool is used to evaluate the grid impact of EV charging demand. Transformer asset data and 24 hour historical AMI data for each transformer loading for 2021 is used to determine the number of overloads at three EV penetration levels using EV charging profile in SMUD’s territory. This paper provides a guideline for selecting appropriate transformer sizes during residential service transformer replacement. Three replacement costs – overloaded transformer replacement cost, lifecycle replacement cost, and energy supply losses cost – are computed to find the total transformer upgrade cost.

The Hotspotter analysis revealed that the zones with smaller transformer sizes (15 kVA, 25 kVA, and 37.5 kVA) have the highest percentages of overloaded transformers, and this problem worsens with an increase in EV penetration. Increasing the replacement size by two levels in these zones can significantly reduce the number of overloads. On the other hand, zones with larger transformer sizes (75 kVA and 100 kVA) experience a lower number of overloaded transformers, even without increasing transformer sizes at high EV penetration levels. In terms of cost analysis, increasing the replacement size by two levels for smaller transformer sizes can reduce the overall transformer overload replacement cost. However, for midsize transformers (50 kVA), increasing the replacement size by one level minimizes total replacement cost for all levels of EV adoption, but increasing the size by two levels will increase lifecycle replacement cost, outweighing the benefit of reduced transformer overload replacement cost. Replacing larger transformer sizes (75 kVA and 100 kVA) with the original size increases the total cost due to high lifecycle costs and energy supply losses costs associated with the additional transformerAdditionally, 75 kVA and 100 kVA transformers have less than 5% of overloaded transformers even at 50% of EV adoption. Finally, considering these factors, transformer replacement sizing recommendation was made. It is important to note that this analysis focuses on statistical likelihood of overload for each transformer sizing population. In practice when details of overload condition of a specific transformer are known prior to replacement, adjustments may be need to be made.

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8 Authors Biography

Sachindra Dahal is an Engineer/Scientist at EPRI. He received his BS in Civil Engineering from Tribhuvan University in Nepal and his Masters and PhD in Civil and Environmental Engineering from the University of Illinois at Urbana Champaign. In his previous roles, he focused on pavement health monitoring and developing lane-keeping systems for autonomous vehicles in adverse weather conditions. Currently, his work centers around analyzing the impact of EV load on the grid, projecting future trends in EV technology, and demonstrating the potential of vehicle-to-building (V2B) projects.

Deepak Aswani serves as a Supervising Principal Engineer in Research & Development at the Sacramento Municipal Utility District (SMUD). He leads the team focused on application-focused research on clean generation, carbon capture, energy storage, and load flexibility. He has over 20 years of experience in Cleantech. Prior to joining SMUD, Deepak served as the head of operations at American Governor's hydropower business, and before that as a hybrid-electric vehicle controls engineer at the Ford Motor Company. Deepak received his BS and MS in Electrical Engineering from the University of Michigan-Ann Arbor and MBA from Cornell University.