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Climate and economic impacts from reinforcement of the distribution grid due to different EV charging strategies

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Executive Summary

This paper assesses the climate impact brought on the distribution grid by the replacement of transformers to accommodate the foreseen load increase due to the full electrification of the light vehicle fleet in Sweden. A synthetic model of the entire Swedish distribution grid is used to estimate the need for additional transformers when assuming different charging strategies for the vehicles. This need for additional capacity is combined with a life cycle assessment of transformers of different power ratings to estimate the climate impact that each strategy would have. The results show significant differences in how much grid replacement is needed between the different charging strategies, which results in significant differences in costs and climate impacts. The highest economic burden and climate impact are seen when vehicles charge directly upon arrival at the home location, while lower impacts are seen when they charge when electricity prices are lower.

Keywords: Smart Charging, Climate Change, Life Cycle Analysis, Modelling & Simulation, Smart grid integration and grid management

1 Introduction

The transportation and energy sectors are currently in the midst of a paradigm shift towards electrification of the light vehicle fleet. This shift can allow for the reduction of well-to-wheel greenhouse gas emissions and other environmental impacts [1, 2]. Nonetheless, it creates an additional pressure on the current infrastructure of the electricity system [3, 4], on the equipment utilized for transmission as well as distribution of electricity. This pressure could first impact the distribution grid, being the point of connection between electric vehicles (EVs) and the rest of the electricity system [4].

The electrification of transport, specifically of light vehicles, could result in a large new load which the distribution network in its current form might not be ready to accommodate [5, 6]. The distribution grid, as it exists today, has developed according to historical needs, to fit a load that has evolved progressively. In order to accommodate new loads, investments in additional equipment for the reinforcement of the distribution system may be necessary, but since EVs do not act as a constant load on the electricity grid, but rather only interact with it when charging, modifying the charging strategy of EVs may alter their impact [7].

The overall impacts of charging of EVs on the electricity system has been previously studied in reviews by Nazari-Heris et al.[8], Kumar et al.[9], and Nour et al.[10]. Additionally, Hedegaard et al. [11] have shown that enabling flexible EV charging and discharging can support variable renewable electricity production, although they conclude that the effects of EVs on electricity systems will vary between different countries. Uncontrolled charging of EVs, i.e. typically corresponding to that EV owners start charging directly when arriving home, can further increase the load during hours of the day that already have high loads. EV charging will therefore add a new strain to the electricity grid [10, 12]. Even so, if a controlled charging strategy is applied, such as responding to a price signal, there is potential to lower the effect on the grid [10, 11, 13-17]. However, these studies do not quantify both costs and environmental burdens associated with the strain put on the electricity grid.

Assessing the environmental impact of a system or product can be done with different methodologies. Life cycle assessment (LCA) is a methodology that is commonly used to assess environmental impact of both the power and automotive sectors. With the electrification of transports, these sectors become intertwined and assessing them in combination is necessary. As an example, Xu et al. [18] combined LCA and energy systems modeling to estimate the impact that different EV charging strategies have on greenhouse gas emissions from electricity generation. Other studies set EVs in focus and combine future energy system models with LCA to determine the impact of EVs in different electricity grid contexts [19]. Also, many LCA studies have evaluated various grid infrastructure components [20-23], as well as complete distribution grids [13]. However, the climate impact that EV charging strategies have due to its demand for grid infrastructure reinforcements has typically not been addressed.

By combining a model of the low-voltage (LV) distribution grid at a country level with LCAs of the distribution transformers, this study aims to determine the cost and climate impacts of potential grid reinforcements required as a consequence of different EV charging strategies.

2 Methodology

This study consists of two separate modeling steps. The first, presented in Section 2.1, is an estimation of potential grid reinforcements in a system with a high EV penetration using a reference electricity grid analysis (REGAL) model. The second step, presented in Section 2.2 is to take the output from step 1 and use LCA to quantify the associated costs and climate impact.

2.1 Distribution grid model

The distribution grid is modeled using the REGAL model, presented by Lundblad et al. [24]. It is an open data-based model designed to create a synthetic representation of a LV grid for a country-sized geographic area (Sweden in this case). The model uses “grid cells” with a spatial resolution of 1x1 km^2. It covers Sweden in 104,853 populated grid cells. In this study, the REGAL model is used to investigate power system violations linked to exceeding the operational limits (thermal capacity and voltage magnitude) of the Swedish LV grid when EV charging is added to households. Three EV charging strategies are evaluated: direct (charging directly when arriving at home); cost-minimized (charging based on an electricity spot price); and mixed charging (a mix of the first two charging strategies where 30 % of EVs charge according to the cost-minimized charging strategy and the rest according to the direct charging strategy). With EVs added to the household load, the model can simulate the frequency (i.e., how often limitations are exceeded) and amplitude (i.e., how much) of exceedances of the operational limits of the distribution grid. Simulations are run for a system in which 100 % of the current vehicle fleet is assumed to be electrified, to quantify the grid reinforcements needed (in terms of increasing transformer capacity) to meet the new demand with EV charging.

Modifications to a determined grid cell to meet the new load can be done in two ways:

1. One or more additional transformers can be added to the existing capacity to meet the new load, or
2. An existing transformer can be replaced by a new transformer of a higher capacity to meet the new load.

A visual representation of the reinforcement decision logic can be found in Figure 1. The determination must both ensure that the new load is covered as well as aim to minimize the economic impact that the transformer changes will have. In addition to these two criteria, conversations with distribution system operators (DSOs) provided other criteria for when a replacement is done and when a new transformer is added. This additional criterion is to always add a new transformer when the current capacity of the transformer is equal to or more than 800 kVA. Because of these requirements, a transformer is replaced with a larger one when: (a) there is only one transformer in the reviewed grid cell, (b) the capacity of the transformer to be replaced is lower than 800 kVA, and (c) a transformer of sufficient capacity exists. If the largest available capacity is not sufficient for replacement, an additional transformer is introduced instead. No transformer replacement or addition is performed when the needed demand for added capacity is lower than 10 % of the smallest transformer capacity (5 kVA). Following this logic, the required transformer reinforcement for a specific cell in the REGAL model can be determined.

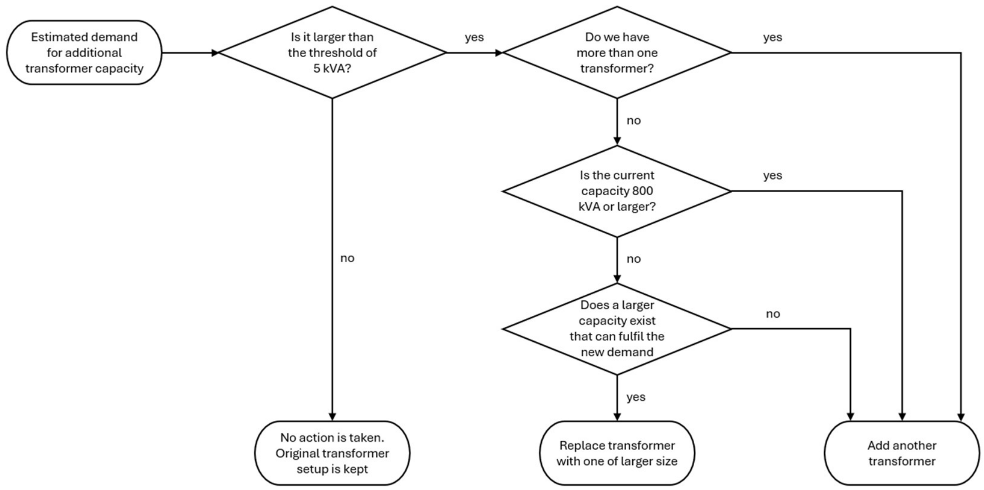

Figure 1: Decision logic for areas in which there is a need for additional transformer capacity and selection is to be made between replacing an existing transformer with one of a larger size or introducing an additional transformer to the area.

2.2 Environmental assessment of the distribution transformers

To obtain the climate impact derived from the grid equipment, cradle-to-gate LCA studies of distribution transformers with capacities matching those from the REGAL model (50, 70, 100, 150, 200, 315, 400, 500, 600, 700, 800, 900, 1000, 1125, 1250, and 1500 kVA) are performed. All transformers are assumed to be at an operational voltage of 11 kV. The functional unit is one manufactured transformer for each capacity level. The modeling covers the transformer's manufacturing and other upstream processes, but it does not include the use phase or the end-of-life stages, as the focus is set on the total investment costs, both in terms of economic expenses and greenhouse gas emissions. For the climate impact assessment, characterization factors for the global warming potential for 100 years (GWP100) were taken from IPCC 2021.

The technical system boundaries start at the extraction of the raw materials and end at the gate of the manufacturing site, and include the production of subcomponents, manufacturing of the transformer, and transportation. The foreground system includes the manufacturing of the transformer itself, whereas the background system includes the production of supplied energy and material inputs. For background processes, LCA database Ecoinvent version 3.11 is used [25]. The production of the main material inputs are representing global market average values for the aluminium, different steel alloys, and paper; the production of the transformer and its subcomponents is assumed to take place within Europe, and so European-specific background data is used for these other steps where available. Temporal boundaries are set in the present day, with the equipment's lifetime being an estimated 35 years, after which either refurbishment or decommissioning is expected to take place.

The overall climate impact resulting from the reinforcement of the LV distribution grid is calculated by adding the required transformer reinforcement for every cell in the REGAL model and multiplying it by the climate impact of the modeled transformers. This allows for a consistent comparison of the different charging strategies from a climate impact perspective. Additionally, the total amount of reinforcement is multiplied by a determined cost for each transformer, providing an economic cost to each strategy. The costs are based on the standard value list for distribution grid equipment published by the Swedish Energy Market Inspectorate for the year 2015 [26].

3 Results

The results are split into four sections, where Section 3.1 presents the estimated loading of transformers as EVs are introduced to the LV grid, as well as the need for added transformers of different capacities. Section 3.2 presents results for the LCA modeling process for individual transformers for which the final quantified values are presented in Section 3.3. Finally, Section 3.4 provides the economic and climate impacts for the whole studied system for each of the charging strategies assessed.

3.1 REGAL model output

Table 1 shows an overview of some key figures for the loading of transformers in the distribution grid when EV charging is added in the REGAL model. As can be seen in the table, the load on the transformers in the LV grid caused by the EV introduction varies with different charging strategies. The cost-minimized charging strategy has the lowest number of transformers that exceed their capacity. However, this strategy has the highest loading of a transformer due to the high coincidence of EV charging when electricity prices are low. Most exceedances of the transformer capacity are seen with the direct charging strategy, as the loads for charging then correlate to other household loads.

Table 1 Key figures for the extent of exceedance of transformer capacity in grid cells when using different charging strategies

	Direct charging	**Cost-minimized charging**	**Mixed charging**
Number of grids where the transformer capacity is exceeded	36,927	7,195	18,613
Percentage of grids where the transformer capacity is exceeded	35.2 %	6.9 %	17.8 %
Mean exceedance of rated transformer capacity	10.5 %	24.7 %	11.1 %
Maximum exceedance of rated transformer capacity	338 %	374 %	317 %
Number of transformers added to reinforce the grid	21,344	7,394	12,744
Total capacity needed to reinforce the grid [MVA]	5,776	4,063	3,969

Figure 2 shows the additional transformers needed to reinforce the LV grid. Figure 2a shows the number of transformers of each capacity (represented by different shades), while Figure 2b shows the total capacity provided by each transformer size. From the figure, it can be concluded that the highest number of transformers and the highest total capacity are needed when EVs charge according to the direct charging strategy. When comparing Figure 2a and Figure 2b, it can be noted that although the mixed charging scenario has a substantially higher number of transformers needed than the cost-minimized scenario, the capacity needed is roughly the same. Further emphasizing that although more transformers have an exceedance of their capacity in the mixed charging scenarios, the maximum exceedances are higher with the cost-minimized charging scenario.

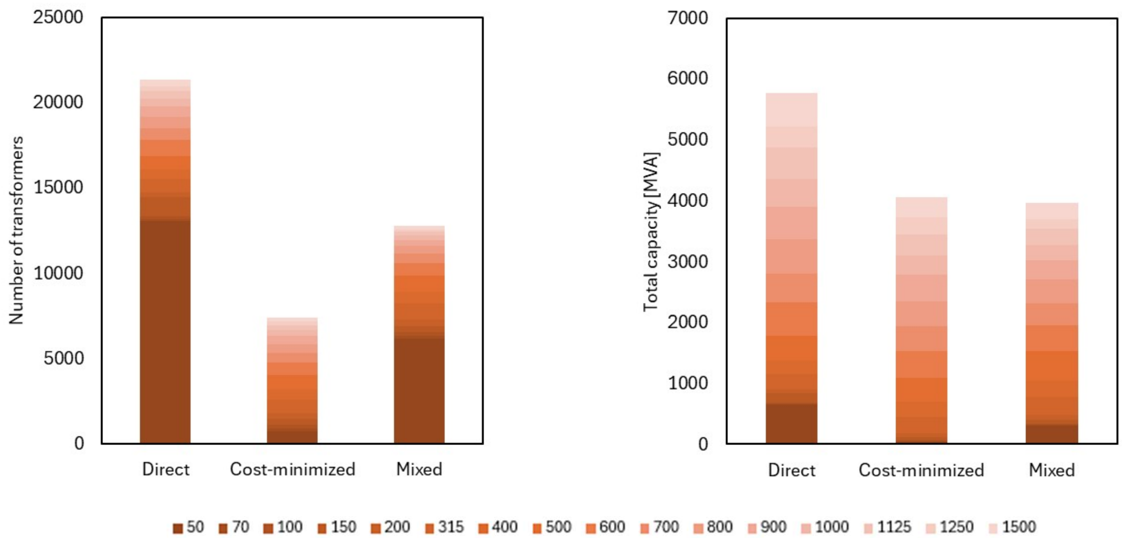

Figure 2: Needed reinforcements in transformer capacity in terms of (a) number of transformers of different capacities, and (b) total capacity in MVA added per transformer size (which is shown in kVA)

3.2 Transformer Modeling

To model the transformers, data was used from a combination of manufacturer catalogues, safety datasheets, environmental product declarations (EPDs), conversations with DSOs, and scientific literature. Oil-immersed transformers were pointed out as the default alternative for distribution transformers by the DSOs. The use of aluminium for the transformer windings was also confirmed as a valid alternative for Sweden by one DSO.

The overall mass of the transformers was taken from a manufacturer's catalog for oil-immersed distribution transformers [27], and where specific capacities were not found, their expected mass was decided through interpolation from the closest existing values within the catalog. The overall composition of the transformers was calculated as the average composition from various EPDs of distribution transformers of different capacities [28-32], within the previously mentioned parameters. The composition stated in some EPDs contained uncertain data in the form of generalized categories, leading to difficulties in ascertaining an average composition. Added to this, not all EPDs present the same material composition. To remedy this, an average transformer composition was identified using the clearly identified material share from multiple EPDs and averaging them, obtaining a consistent composition that covers 91.9% of the total mass. This allows for an assumed transformer model that is not solely representative of a specific design, but rather one that can be used more generally. Afterwards, this average composition was scaled to meet 100% of the mass, for all the capacities required.

Figure 3 shows the flow chart for the complete transformer manufacturing, from cradle-to-gate, along with input subcomponents and their production. Additional processes were used for modeling the production of the electrical steel sheet, aluminium enameled wire, aluminium foil, and subcomponents that arrive readymade to the manufacturing facility, such as stainless steel, copper, and plastic components. The inputs and outputs of the complete manufacturing stage were used, coming from both EPDs [30] and scientific literature [33].

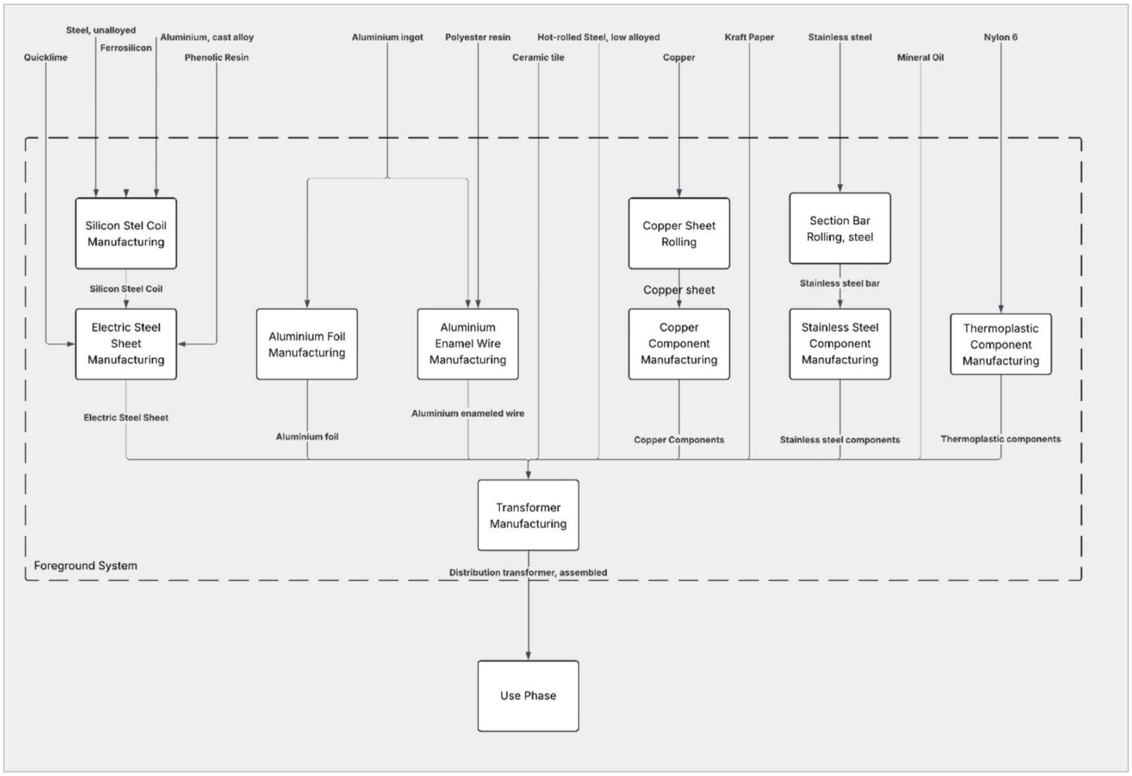

Figure 3: Flow chart for the manufacturing of an oil-filled distribution transformer, including manufacturing of other subcomponents

3.3 Life cycle impact assessment of individual transformers

The climate impact of each transformer assessed can be seen in Figure 4, along with the total mass corresponding to each transformer. Based on these results, the climate impact can be considered as directly tied to the mass value, which in turn increases evenly along the transformer capacity. This mass increase is consistent both with the information on the EPDs and catalog, as well as with transformer design principles and manuals (e.g., Nair et al. [34]), since additional power necessitates a bigger core cross-section and higher voltages and currents on the windings. Since the transformers are modeled from a baseline material composition and multiplied by mass, which does not scale linearly with the rated capacity, the increase in climate impact as mass increases is a consequence of the model design. Nonetheless, the results were compared to the climate impact of the manufacturing stage in the different EPDs and determined to be sufficiently accurate.

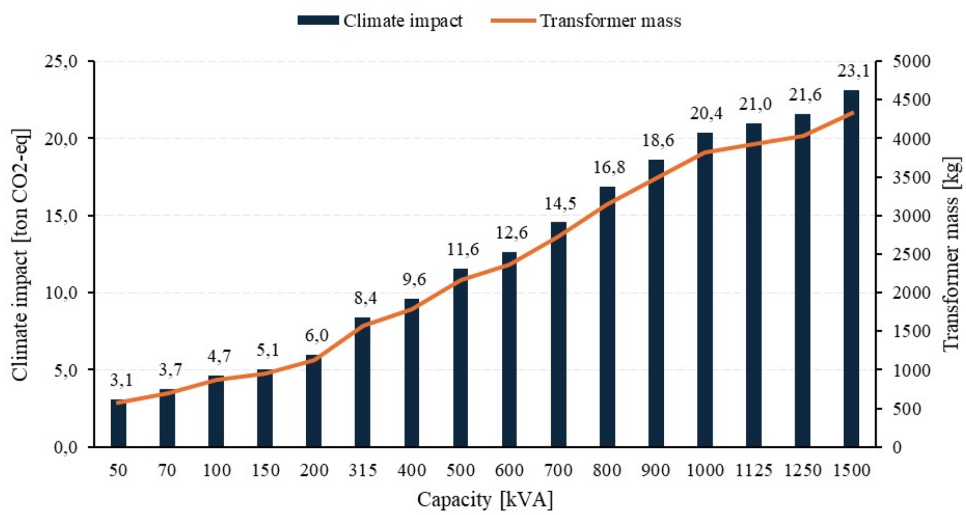

Figure 4: Individual transformer climate impact and mass, in tons of CO_2-equivalents and kilograms, respectively

For additional insight into the most impactful components and processes within the transformers, a contribution analysis is performed. Since all transformers are based on the same assumed average composition, the contribution that each component and process have – in percentage – remains the same, regardless of which transformer capacity is analyzed. As such, an overall contribution can be found in Figure 5 for the assumed average composition.

This analysis shows that the transformer winding, both low and high voltage, is responsible for over half of the overall climate impact, mainly from the use of primary aluminium for both the foil and the wire manufacturing. The second highest impact comes from the grain-oriented electrical steel used for the core material. Core manufacturing processes (such as cutting, stacking, binding, etc.) are assumed to happen within the manufacturing process, core impact is directly derived from the material input. Interestingly, both the tank material and the mineral oil were relatively low on the impact share, despite both being a large share of the mass composition (16.2% and 17.6%, respectively).

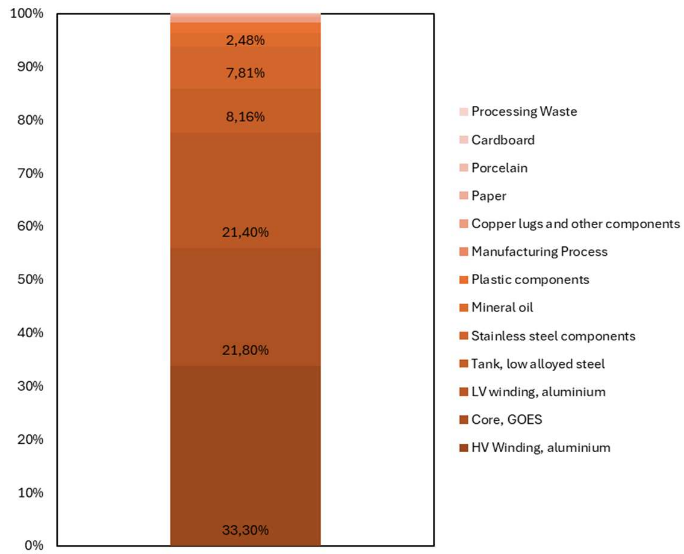

Figure 5: Contribution analysis of the climate impact of a manufactured distribution transformer

3.4 Climate and economic impacts of the grid reinforcements

Figure 6**Error! Reference source not found.** shows the overall climate impact of the different charging strategies as a combined result from the REGAL model and the LCA of the individual transformers. Similar to the case Figure 2, the shades represent results for the transformers of different sizes, in this case total climate impact. The cost-minimized charging strategy has the lowest total climate impact, with 89570 tons of CO_2 equivalents, followed by the mixed charging strategy with 99990 tons of CO_2 equivalents. The direct charging strategy has the highest impact, with 150400 tons of CO_2 equivalents. As seen in Figure 6, the direct charging strategy has a significantly higher impact than the other two strategies due to it requiring the largest reinforcement in both the number of transformers and in total capacity. The mixed strategy has a lower impact, but still considerably higher than that of the cost-minimized strategy. The cost-minimized charging strategy has the largest mean and maximum exceedances, but the lowest number of grids affected. This leads to the reinforcements needed for that strategy being lower overall in environmental impacts when compared to the other two strategies. This is notable since the cost-minimized and mixed charging strategies require similar reinforcements in terms of overall new transformer capacity installed.

One driver of the impact of both the direct and mixed strategies is the 50 kVA transformers added as reinforcement. If not counting the 50 kVA transformers, the reinforcement of the cost-minimized strategy requires more transformers and of a higher capacity than the mixed strategy. While this should lead to a higher climate impact, the significantly higher need for the smallest transformer results in this strategy having a higher overall impact. In comparison, the direct charging strategy has a considerably higher additional capacity requirement, and more transformers of both high and low capacities compared to the cost-minimized and mixed strategies.

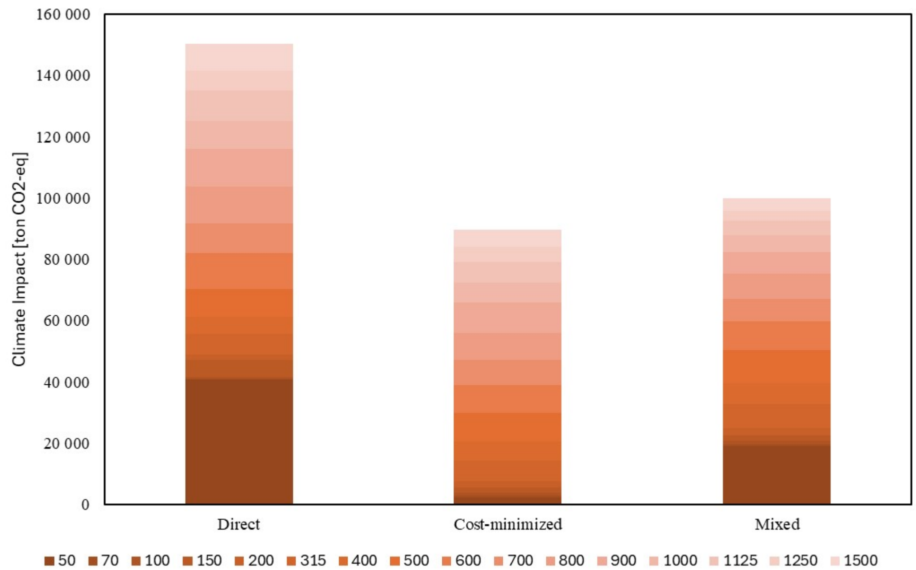

Figure 6: Overall climate impact for direct, cost-minimized, and mixed charging strategies, in tons of CO_2 equivalents

Table 2 shows the overall assessed consequences to the LV distribution grid that would come as a result of implementing the different charging strategies. In addition to the previously discussed added capacity and climate impact, the estimation of the overall cost of reinforcing the grid can be used as an additional parameter to understand the consequences of implementing one strategy. The information on transformer price comes from a 2015 report on the costs reported by Swedish DSOs [26], and it could thus be a low estimation, as prices have most likely gone up in the time since its publication.

Table 2: Total cost of the grid reinforcements, and climate impact of the grid reinforcement for the three assessed EV charging strategies

	Direct	Cost-minimized	Mixed
Total cost [MSEK]	1, 346.63	758.40	882.36
Climate impact [ton CO_2-eq]	150,374	89,567	99,958

Based on these results and the data presented in Table 1, it can be noted that both the economic and climate impacts are more dependent on the number of transformers added as reinforcement than on the total capacity of reinforcements installed. The direct charging strategy has both the highest number of transformers and of capacity installed. This leads to the highest climate impact and the highest reinforcement costs. Further, the mixed charging strategy has a slightly lower total capacity reinforcement than the cost-minimized charging strategy, but higher economic and climate impacts. These results provide useful information for DSOs and TSOs as inputs into the decision-making, when determining if and where to reinforce the grid.

4 Conclusions

This study shows that the combination of LCA of individual components and energy systems modeling allows for a thorough exploration of the implications of changes to the distribution grids. The need for reinforcements of the LV distribution grid to accommodate a full electrification of all passenger vehicles in Sweden is quantified and shown to be significant (4,063 MVA to 5,776 MVA of transformer capacity needed).

Furthermore, it is shown to lead to significant climate impact (90-150 thousand tons CO_2 eq) and economic cost (758-1346 million SEK). This study concludes that the implementation of a cost-minimized charging strategy can mitigate these impacts significantly compared to EVs charging directly upon arrival at their home location.

The study has limitations in the modeling of the transformers, which can be addressed in future studies by including copper-wound transformers, as well as higher operational values, e.g. 22 kV. Reinforcement of the distribution cables could also be included, as well as additional equipment (e.g., switchgear), to provide more details on the reinforcement impacts.

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Pedro Anchustegui has an MSc in Industrial Ecology and is a Ph.D. student in environmental systems analysis focusing on life cycle assessment of vehicle-to-grid. His research aims at assessing the environmental impacts of different potential implementations and technological requirements of bidirectional vehicle charging, including equipment and local and regional interactions with the electricity system.