Impact of Widespread Heat Pump Adoption on Grid Reinforcement Costs and Network Tariffs

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***Abstract*—The widespread adoption of residential heat pumps (HPs) increases overload risks for distribution grids. This paper evaluates the impact of widespread HP adoption using power-flow simulations with representative German data, finding that reinforcement costs rise exponentially up to 35–40% adoption and then grow linearly. Medium voltage (MV) and high voltage (HV) lines are the main cost drivers, given their extensive lengths and higher per-kilometer expenses. Urban grids incur greater reinforcement costs per household (HH) due to denser populations and a higher share of underground cables. Under current regulations, tariff increases disproportionately burden non-HP HHs, who bear up to 85% of costs at lower adoption levels. Tariff surcharges can reach 25% in urban areas and 21% in rural ones, creating significant financial burdens. We recommend prioritizing strategic MV and HV line upgrades and revisiting regulations to align cost recovery with cost causation, ensuring grid stability and an equitable energy transition.**

***Index Terms*—Distribution grid, grid reinforcement, heat pumps, network tariff, tariff structure**

I. INTRODUCTION

The electrification of residential heating is vital for reducing carbon emissions and achieving climate neutrality worldwide. Residential heating comprises 21.1% of the EU's energy consumption [1,2], making its decarbonization essential to meeting climate goals. In line with this, the European Union (EU) has set ambitious targets, aiming to install approximately 55 million residential heat pumps (HPs) by 2030 [3]. Yet large-scale HP adoption challenges electricity systems and grids.

HP adoption increases peak electricity demand, especially in winter, as households (HHs) operate their heating systems simultaneously [4–6]. This trend amplifies grid stress and increases the likelihood of transformer and line overload. Many studies emphasize the need for grid reinforcement, potentially costing billions of euros [7].

Given these projected investments, understanding cost dynamics is crucial. While prior research has primarily examined overall HP costs at certain grid levels, notable gaps persist. In particular, reinforcement cost distribution beyond the LV grid level remains underexplored – despite over 63% of the anticipated grid infrastructure investment until 2032 being expected to be allocated to MV and HV grid levels [8].

Under current regulations, reinforcement investments are recovered gradually through network tariffs [9,10]. With HP-induced grid reinforcement costs rising, assessing their impact on tariffs is essential for energy affordability and equity. However, limited research has explored how network tariff increases distribute reinforcement costs across rural and urban consumers, as well as HHs with and without HPs. Given that existing network tariffs in Germany already vary significantly [11], understanding these cost differences and their potential escalation is essential for ensuring fairness in cost distribution.

Our research addresses these gaps by examining the impact of residential HP adoption on grid reinforcement requirements and network tariffs across all levels of the German distribution grid. By focusing on geographic differences between urban and rural areas and analyzing cost allocation under existing regulations, this study provides valuable insights into the financial and infrastructural challenges posed by widespread HP adoption. The findings aim to inform policymakers, regulators, and grid operators in developing more sustainable and equitable energy infrastructure planning strategies.

Studies such as [4–6,12–19] have demonstrated grid overload and voltage stability issues tied to HP adoption across various countries and scenarios. Several studies have used grid simulation and modeling to estimate the reinforcement costs of integrating distributed energy resources (DERs) into power grids. Typically, this is done by modeling and inputting consumer load profiles into a grid model [20]. For instance, [21] conducted a cost comparison of DERs – including HPs – at low and medium voltage (MV) levels, analyzing the impact of their concurrent deployment. Their results indicate that, compared to other DERs, HPs account for the highest marginal and absolute reinforcement costs. Similarly, [22–25] simulated reinforcement costs with increasing HP adoption and found significant cost escalations associated with higher adoption rates. Additionally, [26] focused on the impact of building insulation at different HP adoption levels. While these studies provide important insights into the reinforcement costs associated with HP adoption, their focus on the low voltage (LV) grid level limits their applicability to the entire distribution grid. This is a critical limitation,

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considering that the LV grid level accounts for only 36% of all expected investments in the German distribution grid until 2032 [8].

Given the substantial reinforcement costs, various demand peak mitigation strategies have been explored to alleviate the burden on the grid [16,18,27–30]. For example, [18] analyzed different HP blocking strategies to reduce the required grid reinforcement efforts. Their study concluded that a complete blocking strategy lacks efficiency; selectively blocking HHs with certain peak consumption levels is more effective. Additional insights from [29] suggest that active demand-side management of a larger pool of HPs can lead to a peak demand decrease of up to 21%. Yet real-world applicability is constrained by regulations and limited consumer participation [31,32].

Network tariffs, therefore, remain a central mechanism for managing the financial impacts of DER integration. They have been widely discussed as the primary tool for recovering reinforcement costs. Several studies have analyzed how tariff structures impact HH budgets and consumer behavior [29,30,33–36]. [30] demonstrated that time-varying tariffs could effectively shift HP consumption to off-peak periods. Regarding fairness, [35], argued that the inefficiency of volumetric charges increases with greater DER adoption, calling for alternative schemes to better distribute costs.

Despite these contributions, significant literature gaps remain. Many studies offer valuable theoretical insights into tariff design and consumer behavior but use hypothetical scenarios without incorporating detailed empirical or simulation data on reinforcement costs. Specifically, few assessments show how rising HP-driven costs translate into actual tariff increases under current regulations, nor how they affect HHs without HPs. Additionally, comprehensive analyses covering the entire distribution grid – including all voltage levels – and assessing reinforcement cost dynamics across urban and rural areas using real-world datasets are scarce.

This paper addresses these gaps by quantifying the impact of increasing HP adoption on grid reinforcement requirements and network tariff adjustments across all levels of the German distribution grid. We employ a Python-based power-flow simulation model to evaluate overloads under varying HP penetration rates in both rural and urban representative grids, translating resulting reinforcement needs into potential tariff changes and their implications for different types of HHs.

The paper is organized as follows: Section II details the methodology, Section III presents and discusses the results, and Section IV concludes with key findings and policy implications.

II. METHODOLOGY

We employ a Python-based pandapower [37] simulation to assess the German distribution grid (LV, MV, and HV). Using Newton–Raphson power-flow analyses under varying HP adoption scenarios, we identify overloaded grid components and quantify reinforcement needs and costs. We use stochastic sampling of HH and HP loads to account for consumption and HP penetration uncertainties. We focus on peak demand periods – the top ten load intervals throughout the year – to capture worst-case overloads. Our model includes representative rural and urban grids to reflect varied consumer densities.

For each grid type and HP adoption level, the simulation estimates overloads and reinforcement costs for the affected cables and transformers. The simulation is structured as follows:

- Sampling of HH and HP loads based on scenario-specific adoption levels.
- Aggregation of individual HH loads into building-level nodes in LV grids.
- Selection of peak demand periods by identifying the highest total grid load intervals.
- Power-flow analyses on LV grids to detect overloads and plan reinforcements (lines/transformers).
- Calculation of LV reinforcement costs based on standard component prices.
- Repeat steps 4–5 at MV grids using aggregated LV loads, then at HV grids using aggregated MV loads.
- Sum total reinforcement costs and compute additional network tariffs for each scenario.

A. Data inputs

1) Household and Heat Pump load profiles

We use 15-minute load profiles from [38], cleaned for 2019. Random sampling assigns these profiles to households and buildings according to census data on household sizes and number of apartments in urban and rural regions in Germany [39,40] – represented in Table 1 and Table 2.

HP loads are integrated into the HH loads based on the HP adoption scenarios. For each adoption level (from 0% to 100% in 5% increments), we randomly select the corresponding percentage of HHs to adopt HPs. From 1 January 2024, HPs ≥4.2 kW are controllable under §14a EnWG, so we cap HP load peaks above 4.2 kW [41].

Within each scenario, we identify peak demand periods by aggregating all node-specific loads for all time intervals and selecting the top ten time frames with the highest total demand. This focuses the analysis on periods most likely to cause grid overloads, typically during winter evenings when heating demand is highest.

B. Grid data modeling

We rely on the SimBench dataset [42] as the foundation for our grid modeling. The SimBench dataset provides detailed grid models representing typical German electrical distribution networks across various voltage levels (LV, MV, and HV). These grid models are interconnected to form representative German distribution networks encompassing urban and rural environments. We import the grid data into our simulation model using the pandapower toolbox [37].

C. Power-flow analysis and overload detection

a) LV level analysis

We run power-flow analyses in the LV grids for the identified peak intervals. Overloads are detected when line or transformer currents exceed the thermal threshold [43]. We plan reinforcement measures using German distribution grid protocols [43,44], such as upgrading cables or transformers. Reinforcement costs draw on authoritative sources (detailed in Section II.D).

2) MV and HV level analysis

Using a stochastic sample of LV loads, we repeat the power-flow analyses and reinforcement planning at the MV level, then propagate MV results to the HV level. This yields potential overloads, corresponding measures, and costs across all voltage levels.

D. Reinforcement cost calculations

1) Cost parameters

We calculate reinforcement costs by applying standard German component and installation cost parameters [43,45]. Table 3 and Table 4 summarize cable and transformer data, including material and installation costs.

2) Cost calculation methodology

The total reinforcement cost C_{total} is calculated by summing the costs of upgraded or additional transformers and the costs associated with reinforcing or adding lines, including both material and earthworks costs:

$$C_{total} = \left(N_{trafo} \times C_{trafo}\right) + \sum_{i=1}^{N_{lines}} [r_i \times \left(l_i \times \left(C_{cable,i} + C_{earthwork,i}\right)\right)] \tag{1}$$

where N_{trafo} is the number of new/ upgraded transformers, C_{trafo} is the cost per transformer, N_{lines} is the total number of line segments within the grid, r_i is a binary indicator variable for line segment *i* (1 reinforced, 0 if unchanged), l_i is the line segment length in km, $C_{cable,i}$ and $C_{earthwork,I}$ are per-km cost of line material and earthwork/overhead installation on line segment *i*.

E. Network tariff calculations

We calculate the additional network tariff (per kWh) to recover these reinforcement costs under Germany's revenue-cap system [9,10,41]. Simplified, the total allowed tariffs T_{Total} reflect the return on the regulatory asset base (*RAB x r*), depreciation, and OPEX:

$$T_{total} = (RAB \times r) + Depreciation + OPEX \tag{2}$$

We apply a 35-year investment horizon [10], computing the net present value (NPV) of costs:

$$NPV_T = NPV_{Total\ Cost} = NPV_{RAB\times r} + NPV_{Depreciation} + NPV_{OPEX} \tag{3}$$

In Germany's cost-cascading framework, grid costs are generally allocated at each voltage level based on actual usage, ensuring that HV and MV consumers only pay for the infrastructure they directly utilize [9]. Since industrial users at higher voltage levels are charged according to peak and volumetric demand, they usually do not cross-finance reinforcements driven by LV residential HP adoption. Instead, unrecovered costs cascade downward, with LV consumers absorbing the entire burden of grid reinforcements. The model in this paper aligns with this approach, allocating all additional reinforcement costs to HHs, consistent with Germany's tariff methodology.

1) Total network tariffs

Under current regulation, the total net tariff revenue T_{Total} is the product of the total consumption and the variable tariff t_{var}. Under Module 2 of §14a EnWG, HP adopters are granted a 60% tariff discount for all kWh consumed through the HP [10]. Let E_{HH} be the total annual non-HP household consumption and E_{HP} the total yearly HP consumption in kWh:

$$T_{total} = (E_{HH} \times t_{var}) + (E_{HP} \times t_{var} \times (1-d)) \tag{4}$$

where $d = 0.6$ to represent §14a EnWG. Assuming the annual electricity consumption remains constant over the investment horizon *n*, we compute the NPV of the total network tariffs collected using the Present Value Annuity Factor:

$$NPV_T = T_{total} \times \frac{1-(1+r)^{-n}}{r} \tag{5}$$

We then solve $NPV_T = NPV_{Total\ Costs}$ for t_{var}:

$$t_{var} = \frac{NPV_{Total\ Costs} \times r}{(E_{HH}+E_{HP}\times(1-d))\times(1-(1+r)^{-n})} \tag{6}$$

2) Return on Regulatory Asset Base

The annual return on RAB applies a capital cost premium r_{cap} to the asset's book value. Over an *n* years, its NPV is:

$$NPV_{RAB\times r} = \sum_{t=1}^{n} \frac{r_{cap}\times RAB_t}{(1+r)^t} \tag{7}$$

We adopt financing assumptions from the Federal Network Agency [46], with a 40% equity financing rate at 7.69% interest and a 1.71% debt rate [47].

3) Depreciation

We apply linear depreciation over the investment duration [10]. The discounted NPV can be expressed as:

$$NPV_{Depreciation} = \sum_{t=1}^{n} \frac{D_{annual}}{(1+r)^t} \tag{8}$$

4) OPEX

Maintenance costs are modeled as a fixed percentage of the initial investment per year, consistent with the findings in [48]. The costs reflect the expenses incurred for routine inspections, minor repairs, and component replacements. At 1% of initial investment cost for lines and 2% for transformers per year, the NPV is:

$$NPV_{OPEX} = \sum_{t=1}^{n} \frac{m_L \times I_L + m_T \times I_T}{(1+r)^t} \quad (9)$$

where m_L and m_T are the maintenance cost rates for lines and transformers, and I_L and I_T are the total initial investment.

III. RESULTS AND DISCUSSION

A. *Peak load increase*

We first examine how rising HP adoption affects peak HH load in rural and urban grids, comparing our results with published models. Figure 1 illustrates the relationship between HP adoption levels and the percentage increase in peak HH load for rural and urban grids.

At 20% HP adoption, rural and urban peak loads increase by 19.8% and 19.6% relative to the baseline. These results align with [4], which reported a 14% increase at 20% HP adoption in the UK. At 75% HP adoption, peak load rises by 140% in both grids, comparable to the 126% increase reported by [24]. Slight differences observed in our study can be attributed to regional differences in climate conditions, heating requirements, or grid characteristics.

B. *Reinforcement costs*

We calculate the reinforcement costs required to upgrade transformers and lines for identified overloads at various HP adoption levels, expressed in € per HH for direct rural-urban comparisons. For cost parameters, refer to Table 3 and Table 4. Figure 2 illustrates the total reinforcement costs per HH at various HP adoption levels in rural and urban grid models.

1) *Cost growth*

Reinforcement costs rise exponentially at lower HP adoption, then linearly at higher levels. In early (0-15%) adoption, costs increase minimally but accelerate sharply between 15-40%, where the grid reaches its capacity limit. The exponential cost growth during this phase reflects the widening impact of network overloads, necessitating extensive reinforcements. Beyond ~35-40% adoption, costs climb steadily and linearly as upgrades extend across multiple grid levels.

The steep cost escalation between 15% and 40% HP adoption underscores the need for accurate forecasting and proactive grid planning. Delayed reinforcement measures risk rapid cost inflation and network instability, necessitating urgent and more costly emergency interventions.

2) *Cost driver analysis*

Specific grid components strongly influence total reinforcement costs, particularly network lines and transformers at different voltage levels. Figure 3 breaks down costs by grid components in rural and urban systems.

In both rural and urban grids, MV and HV network lines are the primary drivers of total reinforcement costs. The extensive distances of required upgrades and higher per-kilometer costs make their upgrades substantially more expensive than transformer replacements. In rural grids, lines account for ~79.5% of total expenses averaged over all HP adoption rates, with HV lines at 35.8% and MV lines at 33.6%. Urban grids show an even higher line share (88.9%), with HV lines alone at 60.5%.

Two key factors explain HV line cost dominance:

- Significant line volumes: e.g., at 100% HP adoption in rural grids, 373 km of new HV lines are required vs. 273 km MV and 263 km LV
- Higher per-km costs: overhead HV lines cost €520k/km vs. €400k/km for MV, and HV underground lines can reach €1,300k/km in urban areas, far exceeding MV (€180k–€400k) and LV (~€100k) lines.

Transformers, in contrast, are less expensive to upgrade but remain critical for load management and grid reliability. Despite their smaller share of total expenses, transformers offer significant value. Early upgrades to MV/HV transformers can effectively alleviate bottlenecks at lower HP adoption levels, enhance grid performance, and postpone the need for more extensive and expensive line reinforcements.

Due to their substantial cost impact, planning and investment strategies should sensibly prioritize HV and MV line upgrades. Cost reduction efforts could include advanced materials like high-temperature superconducting cables or lightweight conductors, which enhance capacity with minimal physical upgrades. Innovative grid technologies can redistribute loads while adding new branches to mesh the grid more thoroughly, which could relieve congestion, especially in space-constrained urban settings. Early upgrades to MV/HV transformers are also critical, offering cost-effective ways to enhance capacity, improve reliability, and defer expensive line reinforcements.

3) *Cost regionality between rural and urban grids*

Building on the cost driver analysis, reinforcement costs differ significantly between urban and rural grids, shaping investment strategies and policy decisions. At 100% HP adoption, total reinforcement costs per HH reach €1,385 in rural and €1,679 in urban grids (a 21% difference, see Figure 2). Three factors drive this:

- More underground cables in urban grids (15.81% HV underground vs. 0.13% in rural, refer to Table 5).
- Urban HV lines serve more HHs per km (2.84 m/HH vs. 3.61 m/HH rural, refer to Table 5), and have lower thermal capacity (e.g., 0.652 kA vs. 0.68 kA for overhead lines), raising the overall average load on lines.
- Underground cable installation is significantly costlier (up to €1,300k/km for HV urban lines vs. €520k/km for rural overhead HV).

These factors underscore higher urban costs and complexity. Policymakers should consider cost-recovery mechanisms to avoid disproportionate urban burdens. Tariff structures (e.g., capacity-based pricing, targeted subsidies) may distribute costs more fairly. Additionally, utilities may need to prioritize urban reinforcements due to the higher load concentrations while ensuring that rural grids are addressed in long-term planning.

C. *Network tariffs*

1) *Tariff analysis*

Under current regulation, the additional network tariff applies to all HH consumption. HP adopters pay the surcharge on both base and HP consumption, albeit with a 60% HP discount (Module 2, §14a ENWG). Meanwhile, HHs without HPs also pay the additional tariff despite their electricity usage not contributing to reinforcement needs. Figure 4 shows steep tariff increases with HP adoption, especially in urban areas where underground cables dominate. Rural grids see smaller increases due to lower-cost overhead lines. However, HP consumption doesn't offset these costs sufficiently, partly because of the 60% discount.

2) *Cost recovery distribution*

Figure 5 illustrates how reinforcement costs are distributed between HP consumption, HH consumption of HP adopters, and HH consumption of non-HP HHs. At low HP adoption levels (≤30%), most reinforcement costs are disproportionately borne by non-HP HHs despite their unchanged electricity consumption patterns. This imbalance persists throughout the adoption trajectory, gradually shifting but remaining significant even at high penetration rates.

The high-cost burden placed on non-HP HHs at low HP adoption levels highlights the inequities inherent in the current cost recovery framework. Non-HP HHs effectively subsidize HP-driven reinforcement costs, even though their consumption doesn't add extra grid stress – while HP HHs benefit from discounted HP consumption tariffs. This system can create significant disparities, with non-HP HHs facing rising costs without contributing to underlying grid stress. In contrast, HP HHs contribute only partially to the reinforcement costs they drive.

3) *Household cost increase*

At 100% HP adoption, urban non-HP HHs face up to €77.37 in added yearly costs, rural non-HP HHs €63.89, urban HP HHs €128.86, and rural HP HHs €106.41. Compared to the 2024 baseline of 11.53 ct/kWh [49], this can be a 25.4% rise for urban HHs and 20.9% for rural ones.

The additional yearly costs due to HP adoption far exceed historical trends in electricity tariff growth. Between 2014 and 2024, Germany's gross electricity tariff grew from 6.63 ct/kWh to 11.53 ct/kWh, representing a compound annual growth rate (CAGR) of 5.7% [49]. In contrast, the maximum additional tariff increase faced by urban HHs at 25.4% equates to more than four years of historical tariff growth added to the already growing tariffs over the upcoming HP installation period. This underscores the potential financial strain reinforcement costs impose under the current regulatory framework.

4) *Implications of tariff increases and cost allocation*

Our findings highlight the present framework's equity, sustainability, and acceptance issues. Non-HP HHs bear disproportionate costs at low HP adoption, while discounted HP tariffs shift burdens to others. Sharp tariff hikes may strain HH budgets, especially in urban areas, reducing acceptance of HP adoption and broader grid modernization. Policymakers might consider alternative tariff structures – capacity-based or time-of-use – to better align costs with usage and promote off-peak consumption [50]. Further research is needed to assess these approaches' effectiveness in stabilizing grids and mitigating equity concerns.

IV. CONCLUSION

This paper demonstrates that the widespread adoption of residential HPs significantly impacts the distribution grid, increasing peak electricity demand and substantial grid reinforcement costs. Using a Python-based power-flow simulation with real-world input data from Germany, we determined that overloads in distribution grid transformers and lines escalate with higher HP adoption levels. Reinforcement costs grow exponentially at lower HP adoption levels (up to 35–40%) and linearly beyond that, with lines at the MV and HV levels being the dominant cost drivers due to their extensive lengths and higher per-kilometer upgrade costs. Urban grids incur higher reinforcement costs per HH throughout all adoption levels, primarily due to higher HH densities, the denser infrastructure required, and the associated deployment of expensive underground cables.

Under the current German regulatory framework, the additional network tariffs required to recover these costs disproportionately burden non-HP HHs, especially at lower HP adoption levels. Here, HHs without HPs cover up to 85% of reinforcement costs despite not contributing to increased grid stress. Network tariffs rise sharply with increasing HP adoption, imposing significant financial burdens on all HHs, with network tariff increases exceeding 20% of current tariffs.

DSOs should focus on proactive, strategic grid expansion planning that prioritizes upgrading critical bottlenecks like MV/HV transformers and reinforcing MV and HV lines to efficiently accommodate increased loads. This is essential to mitigate exponential cost growth and prevent grid failures. Policymakers should further consider equity issues when designing regulatory frameworks and tariff structures that incentivize HP adoption, ensuring that cost recovery aligns more closely with cost causation.

Future research should refine tariff structures that better reflect HP-driven costs and explore innovations in line and transformer upgrades—such as new materials, dynamic load management, and improved grid architectures. Examining how different tariffs affect equitable reinforcement cost recovery will further promote long-term resilience and cost optimization.

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APPENDIX

A. TABLES

Persons per household	**Rural**	**Semiurban**	**Urban**
1	34%	40%	50%
2	35%	32%	27%
3	15%	13%	11%
4 or more	16%	15%	12%

Table 1 - Average distribution of household size per area type in Germany

Households per building	**Rural**	**Semiurban**	**Urban**
	50%	52%	57%
2	26%	19%	9%
3-6	11%	8%	3%
7-12	9%	13%	13%
13 or more	5%	8%	17%

Table 2- Average distribution of households per building and area type in Germany

Line type	**Grid level**	**Type**	**Material cost (€k per km)**	**Earth-work cost rural (€k per km)**	**Earth-work cost semiurb (€k per km)**	**Earth-work cost urban (€k per km)**	**OH instal-lation costs (€k per km)**
NAYY 4 × 150	LV	Cable	9	60	100	100	-
NAYY 4 × 240	LV	Cable	15	60	100	100	-
NA2XS2Y (70-400 mm2)	MV	Cable	20	140	180	180	-
AL/ST (40-70 mm2)	MV	OH line	20	-	-	-	400
NA2XS2Y (630 mm2)	HV	Cable	30	1,300	1,300	1,300	-
AL/ST (265 mm2)	HV	OH line	30	-	-	-	520

Table 3 - Standard cable and overhead (OH) lines deployed in SimBench grids

Transformer type	**Grid level**	**Installation costs (€k)**
160 – 630 kVA	LV	10
25-63 MVA	MV	470

Table 4 - Standard transformers deployed in SimBench grids

HV Grid model	**Line type**	**Total length deployed (in km)**	**Percentage of total line length**	**Lines deployed per household (in m)**
HV Rural	Overhead line	1,082.1	99.9	3.61
	Underground cable	1.4	0.1	
HV Urban	Overhead line	632.8	84.2	2.84
	Underground cable	118.8	15.8	

Table 5 - Breakdown of lines deployed by HV grid model

B. FIGURES

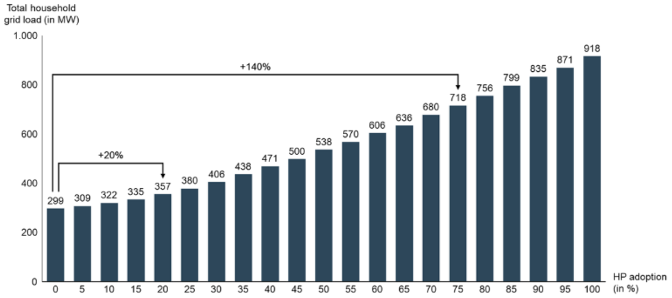

Figure 1– Total household-induced grid peak load by HP adoption in MW (total households: 282k)

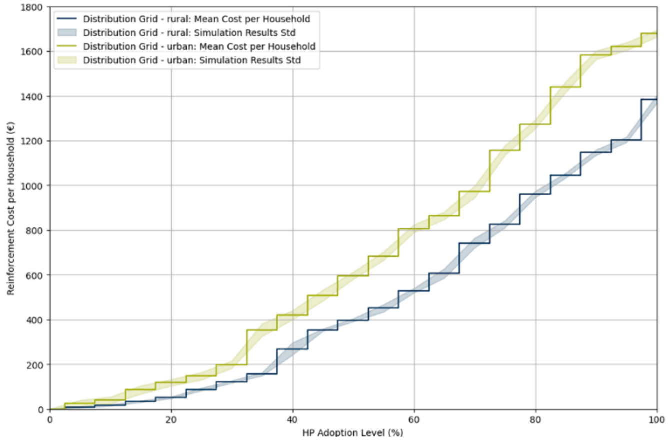

Figure 2 - Reinforcement cost per household by HP adoption level (in €)

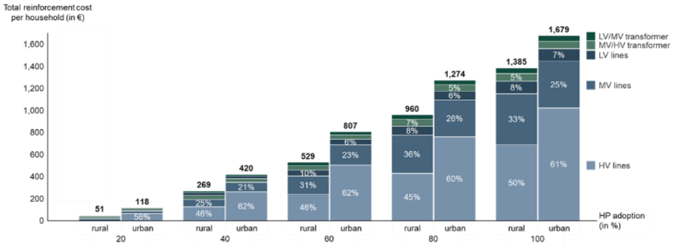

Figure 3 - Reinforcement cost breakdown by grid component and grid level for urban and rural grids

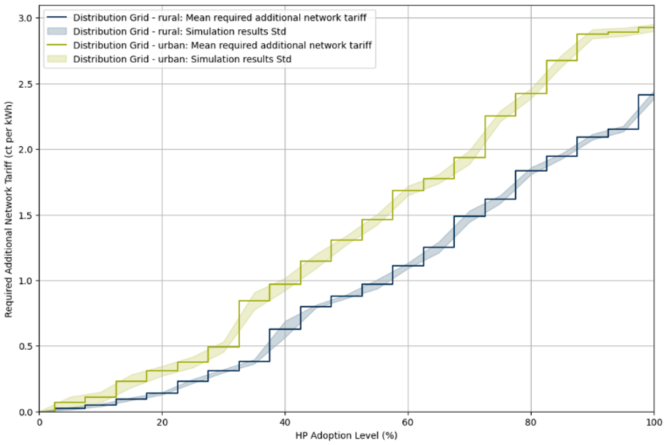

Figure 4 – Required additional network tariff by HP adoption level (in ct/kWh, rural and urban grid)

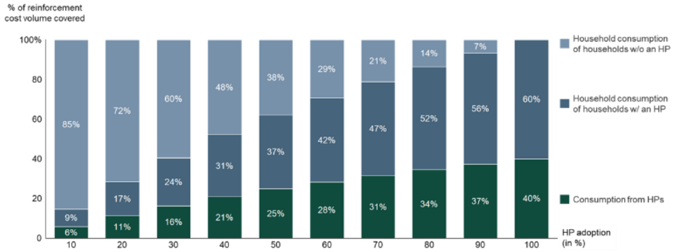

Figure 5 - Distribution of reinforcement cost coverage through network tariffs