Exploring the impact of network tariffs on household electricity expenditures using load profiles and socio-economic characteristics

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Abstract

Growing self-generation and storage are expected to cause significant changes in residential electricity utilization patterns. Commonly applied volumetric network tariffs may induce imbalance between different groups of households and their respective contribution to recovering the operating costs of the grid. Understanding consumer behaviour and appliance usage together with socio-economic factors can help regulatory authorities to adapt network tariffs to new circumstances in a fair way. We assess the effects of eleven network tariff scenarios on household budgets using real load profiles from 765 households. Thus we explore the possibly disruptive impact of applying peak-load-based tariffs on the budgets of households when they have been mainly charged for consumed volumes before. Our analysis estimates the change in household network expenditure for different combinations of energy, peak, and fixed charges and can help to design tariffs that recover the costs needed for the sustainable operation of the grid.

Introduction

Residential electricity prices are made up of a number of components, including network tariffs, taxes and surcharges, such as a renewables surcharge, a usage surcharge, and an energy charge. In this article, we focus on network tariffs, which are the source for recovering the capital and operational expenditures of providing transmission and distribution of electricity, as well as the grid operators' rate of return on grid investments, and are thereby the main source for financing grid infrastructure.

Since power grids are considered natural monopolies, the distribution of these costs between consumers is not achieved autonomously through market forces [1]. In many modern economies, defining the cost shares for providing transmission and distribution of electricity between the consumers is assigned to an authorized entity, for which most EU nations have established a dedicated regulatory authority since the electricity market liberalisation in 2003. Commonly used and currently discussed network tariffs represent a combination of volumetric energy charges (charging customers for the amount of consumed electricity; €/kWh), fixed charges per customer (independent of their energy consumption but possibly varying over households based on their contracted capacity, but not relying on actual load measurements; €/per household per year), and peak demand charges (based on the actual measured capacity; €/kW peak load).

The costs of electricity networks are mainly determined by their capacity, the maximum amount of energy that the grid is dimensioned to stand at any given point in time. Despite this, volumetric tariffs, which do not directly reflect the nature of these costs, are still widely applied. In the past, when load profiles of residential users were approximately homothetic, the application of tariffs with a dominant volumetric charge was well justified. Nowadays, there is increasing diversity in daily load profiles, and part of this development is due to the increase of distributed generation, the advent of low-capacity storage (e.g. in-home batteries for storing PV-produced electricity), the arising prospect of an increasing number of electric vehicles, and the vision of house-to-house electricity trading to balance the overproduction from own-generation without the need (of higher levels) of the power grid [2, 3, 4, 5].

The deployment of renewable energy in the residential sector has increasingly severe repercussions on electricity grids; for a growing share of consumers, the connection to the public grid will largely serve as a backup option, rather than being the primary source for their electricity acquisition [6, 7]. For such consumers the volumes of electricity consumed from the grid will be subordinate and likewise will their contribution to the financing of the grid be low in the case of volumetric tariffs [8, 9, 10, 11]. These trends will inevitably lead to a reallocation of the burdens of grid cost recovery [12, 13, 14].

Considering that these innovations are more likely to happen first among a subgroup of the population owning single-family dwellings (since most of these innovations require property rights for installation), a significant social imbalance induced from shifting the burdens of financing the grid towards lower income classes may arise [15, 16]. This can hamper the public acceptance of these innovations. Moreover, some even envision a possible “death spiral scenario” [17, 18, 19, 20], where higher network tariffs will be charged to poorer customers, which eventually threatens to collapse the whole electricity supply system. Other recent studies (see e.g. [21, 22]) consider such worries overblown, but still call for a timely and careful revision of tariffs in order to avoid free-riding behaviour.

Several options have been proposed to deal with this issue, among them minimum network charges per household irrespective of actual grid utilization, increased fixed charges and peak demand charges [23, 24, 25, 26]. These latter charges have long been used in commercial and industrial network tariffs [27], but are a novel development in the residential electricity market.

Policy makers have to strike a proper balance between different objectives when designing network tariffs, e.g. they shall be easy to understand, fair, cost reflective, encourage energy efficiency and send the right signals to maximize the economic efficiency of power grids [28]. Therefore, difficult trade-offs have to be made that will directly influence the monthly bills of the consumers and network tariff decisions should be informed by empirical research that defines who these consumers are and how their bills will change.

With the advent of smart metering, recent literature has reconsidered volumetric network tariffs and discussed measured, capacity-oriented schemes to address the issues outlined above (for Australia see e.g. [29], for the UK see e.g. [30], and for the US see e.g. [31, 32, 33, 27, 34]). The goal of this article is to assess different network tariff schemes with respect to their effects on the budgets of individual households conditional on their socio-economic backgrounds. Our analysis aims at contributing to the ongoing tariff debate by presenting the effects of alternative tariff schemes. We use a unique real-world data set of 765 Austrian households, whose electricity consumption was metered for a one-year period, and for whom we have detailed socio-demographic data at the individual level. Our analysis shows that alternative tariff schemes, in particular changing from a volume-based scheme to a scheme which recovers a substantial portion of network costs through measured peak demand charges, may induce substantially increased electricity expenditures to a certain share of households. Further analyses provide evidence that these increasing expenditures cannot sufficiently be explained by the possession of electric appliances, but are due to noticeable and systematic differences in the electricity consumption patterns along the politically critical dimensions of, among others, the households' income situation and number of children.

Household survey data

Household-level data was gathered in two surveys among residential electricity customers, conducted between April 2010 and March 2011 in the region of Upper Austria, Austria. In the first survey, we contacted more than 10,000 households via mail and asked them to allow us to collect their 15-minute electricity load profiles. We recruited 973 households for participation, all of which gave their distribution grid operator written permission to send us the households' individual 15-minute electricity load profiles measured by smart meter, for the full period of our survey. In total, we collected 35,040 electricity load values for every household. Throughout the registration process households provided information about the number of people in the household, the type (apartment, single-family house, semi-detached house) and size (in m^2) of their dwelling, the technologies used for warm water and heat preparation (electricity, gas, district heating, heat pumps, biomass, oil), as well as their endowment with specific electric appliances that have a high power demand (swimming pool, fish tank, water bed, sauna, home cinema).

In the second survey, the same households were offered €10 if they provided us with additional information about their socio-economic characteristics (income and composition of the household) and further information about their electric appliances. The final dataset includes 765 observations (which we refer to as "full sample"), for 406 of which we have additional information about the household's income (henceforth called "subsample"). Details are provided in Supplementary Note 1 as well as Supplementary Tables 1 and 2.

Scenarios of Network Tariffs

Ever since Bonbright examined the principles of designing tariffs for recovering the costs of natural monopolies [35] in 1961, the topic has been intensely researched for public utilities in general, as well as for electricity networks specifically (see e.g. [29], [36], [37] and [38]). As these sources establish, among others, a comprehensive development of network tariffs has to consider the dimensions *system sustainability*, *economic efficiency* and *distributive justice*. In our study, tariff scenarios are exclusively designed to cover the range of potential network tariffs based on the candidate tariff components discussed above, to allow comparisons of the effects of these schemes on household expenditures. Technically, we follow the ultimate quantitative paradigm for designing network tariffs, which is to first determine the overall quantity of costs that shall be recovered and then to define a distribution key by putting weights on the candidate tariff components. According to this practice, and by treating our sample as if it was a tariff zone on its own, we first assess the sum of network charges to be paid by our full sample in the Austrian tariff scheme as it was in force in 2016, which we refer to as "reference scenario" henceforth, resulting in total charges of €136,209.10.

Tariff scenarios in our study recover this sum by putting different weights on the three components: energy charges per €/kWh, fixed charges in € per year, and peak charges in €/kW peak load. These different weights are given in Table 1. Details on the calculation of the respective tariffs are provided in Methods. Among the selected eleven alternative tariff schemes, eight scenarios include a peak demand charge. The three scenarios not relying on measured loads (f100, f50/e50 and e100), are similar to the network tariffs currently applied in Europe. As an example, scenario f100 is similar to the scheme applied in the Netherlands in 2016, where all customers faced the same network charges irrespective of their actual consumption patterns [39]. An overview of the volumetric share of tariffs as applied in some European countries in 2016 is given in [47].

For our analysis, we quantify the annual network expenditures of each household under the tariff scenarios. We define our quantity of interest as the percentage by which the network costs differ between the reference scenario and the respective alternative scenario. This allows interpretation of the results in direct relation to the households' expenditures in the status-quo, i.e. whether they would face increasing or decreasing costs under a certain alternative tariff scheme.

Table 1: Residential network tariff scenarios applied to the full sample of 765 households.

Scenario	**Description** (overall network costs are recovered through)	**Fixed charge** (per household per year)	**Energy charge** (per kWh)	**Peak/capacity charge** (per kW peak)
reference	tariff as applied in Austria in 2016	€24.60	€0.043	–
f100	100% flat tariff	€178.05	–	–
pa100	100% peak charge, based on the average of the 12 monthly measured peak loads	–	–	€39.07
pm100	100% peak charge, based on the one maximum load	–	–	€29.59
e100	100% energy charge, only based on consumed volume	–	€0.050	–
f50/e50	50% from fixed charges and 50% from consumed volume	€89.02	€0.025	–
f50/pa50	50% from fixed charges and 50% from peak charges (average of the 12 monthly peaks)	€89.02	–	€19.53
f50/pm50	50% from fixed charges and 50% from peak charges (one maximum load)	€89.02	–	€14.79
pa50/e50	50% from peak charges (average of the 12 monthly peaks) charge and 50% from consumed volume	–	€0.025	€19.53
pm50/e50	50% from peak charges (one maximum load) and 50% from consumed volume	–	€0.025	€14.79
f/pa/e*	14% from fixed charges, 43% from consumed volume and 43% from peak charges (average of the 12 monthly peaks)	€24.60	€0.022	€16.83
f/pm/e*	14% from fixed charge, 43% from consumed volume and 43% from peak charges (one maximum load)	€24.60	€0.022	€12.75

* the fixed charge is taken from the reference scenario, while the remaining portion is split into equal quantities, see Methods for details.

Tariff Impact on Household Network Expenses

We first assess the impact of the tariff scenarios from Table 1 on household annual network expenditures (see Methods for details). For the interpretation of our results we point to the ex-post nature of our investigation: each of the tariff scenarios sends a specific signal to households, e.g. pa100 and pm100 provide incentives for avoiding peak loads while they do not penalize high electricity consumption. Ideally, households would analyse their consumption patterns with respect to the applied tariff scheme and adapt their behaviour to minimize costs under certain boundary conditions [41, 40]. Since the data exploited in our study was already collected in 2010/2011, households were not provided with such signals.

Figure 1 shows box plots of the change (in %) of the annual network expenditures under the eleven tariff scenarios compared to the reference scenario for the 765 households (for analysis of the subsample see Supplementary Figure 1). Several outcomes are evident: first, the most significant change in households' network expenditures are calculated for scenarios with a dominant share of fixed or peak load charges and thereby deviate significantly from the reference scenario. The interpretation works vice versa, i.e. one would observe similar changes in household network costs if, say, f100 was currently applied and was substituted for the reference scenario.

Second, the box plots reveal that for some households the increased costs in certain tariff scenarios are very high compared to reference levels. For illustration we marked the two households which experience the highest increase in network expenditures under peak based scenarios by open and filled triangles. These are single person households that consume moderate volumes of electricity (i.e. 1,805 and 1,604 kWh in total during the observation period) and their current network costs in the reference scenario are low compared to the mean in our sample. At the same time, these households produce massive peak loads, see Supplementary Figures 2 and 3. Consequently, under tariff schemes charging exclusively for measured

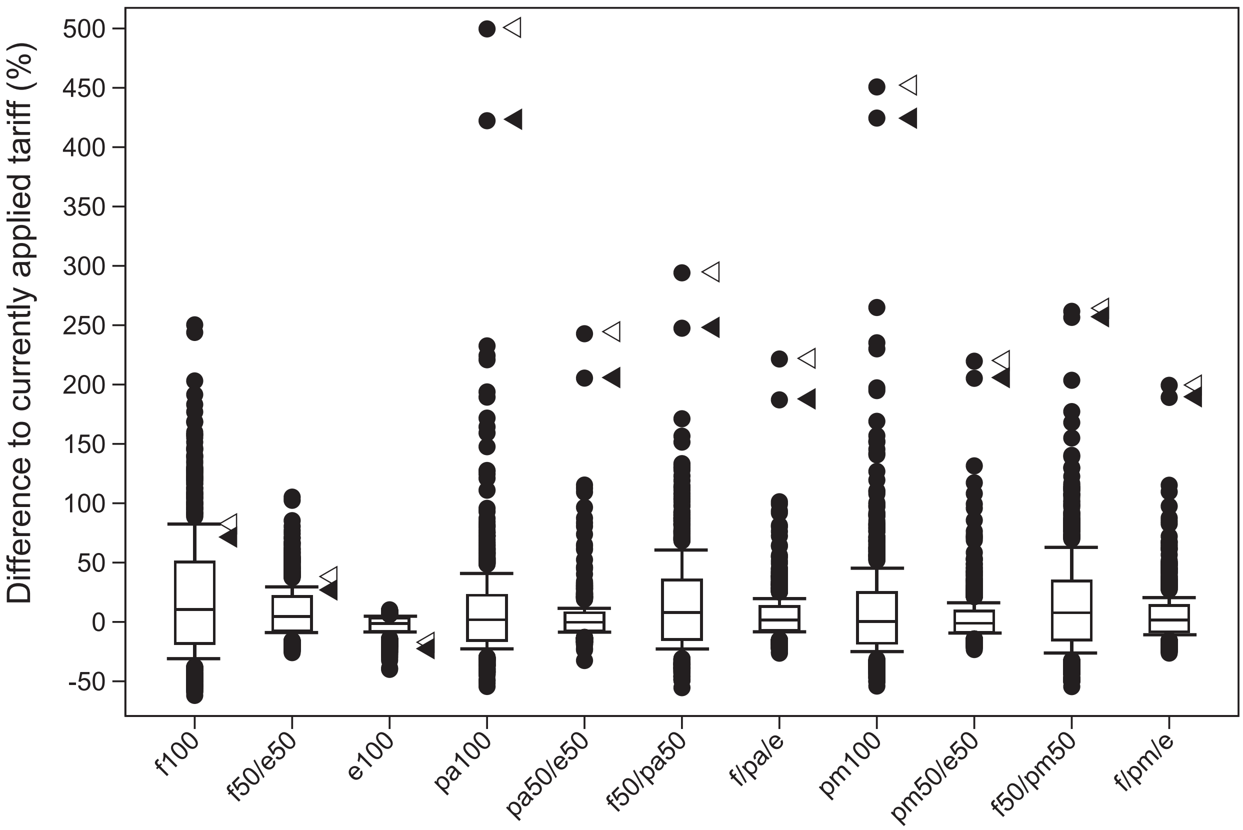

Figure 1: Change in annual network expenditure under different tariff scenarios. The full sample of 765 households is analyzed in each of the scenarios.The bottom of each box is the 25^{th} percentile, horizontal line in the middle of each box represents the median and the top of each box is the 75^{th} percentile, vertical lines outside of the box (whiskers) end at 10^{th} and 90^{th} percentiles, the dots are considered as outliers. For illustration the two households with the highest increase in network expenditures under scenarios including a peak component are marked by open and filled triangles.

peak demand, such as pa100, they have to pay up to €435.40 and €471.60 more, translating to +422% and +499%, respectively. In contrast to their sensitivity to tariffs, which emphasize measured peak demand, the same two households face only around 80% higher charges in scenario f100. When neglecting peak demand and applying scenario e100, which is determined by the volume of consumed energy only, the opposite effect occurs and these households would actually pay around 10% less than in the reference scenario.

Even when the households marked by open and filled triangles are considered as outliers in our sample, these cases are still observed in a relatively small sample of 765 households, suggesting that a relevant number of households may face significant additional burdens when/if household peak-load-based charges are introduced. We check how many households in the sample also tend to have increasing costs under some of the scenarios while experience cost savings in others. We find that 321 households face lower costs in scenario e100 and higher costs in scenario pa100, which means that nearly 40% of the households consume relatively moderate volumes of energy in total, but at the same time frequently produce significant peak loads. This example demonstrates that a different weighting of the volumetric, peak, and fixed components can have strongly diametrical effects on the network expenditures of individual households.

While we do not think that this result shall prevent the application of such innovative network tariffs, prior to their introduction a careful impact assessment appears necessary, which may be followed by mechanisms balancing hardship cases during the transition period.

Network Expenditures and Socio-Economic Characteristics

In this section, we assess which household characteristics aid in explaining the impact the tariff scenarios have on households' network expenditures. Regression results of the full sample with seven explanatory variables and a constant are shown in Table 2 (for main results excluding outliers see Supplementary Table 4), while results of the regression exploiting the subsample, including information about the households' income, household type and electricity consuming amenities, are presented in Table 3. The results of both regressions show similar impact on household expenditures for network tariffs, with only minor changes in the magnitude of the coefficients and their significance, which we interpret as evidence for the robustness of our results. The applied statistical model is presented in Methods.

The regression results shown in Table 2 suggest that the number of residents of a household

(Nr_persons), the living space (Square), whether the dwelling is in a rural or an urban environment (Rural), or whether the dwelling is a single family house (House), are associated with lower network costs under scenarios with a fixed charge compared to the reference scenario, and higher costs in the fully energy based scenario e100. This is explained by the fact that these households (ceteris paribus) consume higher volumes of electricity and thereby benefit from tariffs, which put only subordinate weight on the number of consumed units. Interestingly, almost the same household characteristics (with exception of a rural vs. urban environment and living space) are related to lower network costs in scenarios emphasizing measured peak demand (pa100, pm100, pm50/e50, and pa50/e50), providing evidence that households with more residents and households situated in a single-family house tend to produce fewer peak loads, ceteris paribus.

The inclusion of the household amenities in the regressions is essential even though it is not the focus of our analysis, as they would likely suffer from omitted variable bias otherwise, since these are correlated with the policy relevant variables. The signs of their effects are as expected conditional on which tariff component the respective scenario emphasises. Tumble dryer and PC increase households' costs in the fully energy based scenario e100, while flow heaters become increasingly costly in the scenarios charging for peak loads. Pool owners benefit from peak or fixed tariffs compared to the status-quo, and households with a sauna have a significant disadvantage in tariffs charging for measured peak demand. Further analysis of whether the amenities are related to high energy volumes or peak loads are given in Supplementary Note 3 and Supplementary Tables 5 and 6.

From a policy perspective, it is important to notice that most of the parameters that significantly contribute to lower network charges under the respective alternative scenario (i.e. households living in single family houses, having larger living spaces, and swimming pool ownership) are usually associated with higher income levels. Since the sum of collected revenues from all households together is required to remain unchanged under any new tariff scheme, a reduction of the financial contribution of higher income households would automatically mean an increase of burdens for lower income households compared to the situation under the reference scenario. As such distributional effects are problematic from a public choice perspective, it is important to identify whether certain tariff scenarios are actually associated with shifting burdens towards households with lower incomes.

Table 2: Effects of household characteristics and amenities on the relative difference of their network costs in our full sample.

	f100	f50/e50	e100	pa100	pa50/e50	f50/pa50	f/pa/e	pm100	pm50/e50	f50/pm50	f/pm/e
Nr_persons	-15.643***	-6.564***	2.515***	-6.275***	-1.880***	-10.959***	-3.782***	-7.351***	-2.418***	-11.497***	-4.245***
	(1.354)	(0.568)	(0.218)	(1.312)	(0.626)	(1.096)	(0.605)	(1.383)	(0.656)	(1.143)	(0.639)
Square	-0.173***	-0.073***	0.028***	-0.085**	-0.029	-0.129***	-0.049***	-0.050	-0.011	-0.112***	-0.034*
	(0.042)	(0.018)	(0.007)	(0.041)	(0.019)	(0.034)	(0.019)	(0.043)	(0.020)	(0.035)	(0.020)
Dummy_square	-8.391**	-3.521**	1.349**	-3.664	-1.158	-6.028**	-2.157	-3.384	-1.018	-5.888*	-2.036
	(3.641)	(1.528)	(0.585)	(3.528)	(1.683)	(2.948)	(1.626)	(3.720)	(1.765)	(3.074)	(1.718)
Pool	-23.022***	-9.661***	3.701***	-12.790**	-4.545*	-17.906***	-7.098***	-15.572***	-5.935**	-19.297***	-8.296***
	(5.860)	(2.459)	(0.942)	(5.678)	(2.709)	(4.745)	(2.617)	(5.987)	(2.841)	(4.947)	(2.765)
Sauna	-2.238	-0.939	0.360	9.864**	5.112**	3.813	4.096**	16.102***	8.231***	6.932*	6.784***
	(4.430)	(1.859)	(0.712)	(4.292)	(2.048)	(3.587)	(1.978)	(4.526)	(2.148)	(3.740)	(2.090)
Solarium	-12.620	-5.295	2.029	9.739	5.884	-1.440	3.327	9.265	5.647	-1.677	3.123
	(10.398)	(4.363)	(1.672)	(10.075)	(4.806)	(8.420)	(4.643)	(10.624)	(5.041)	(8.779)	(4.905)
Rural	-18.723***	-7.856***	3.010***	-7.644	-2.317	-13.183***	-4.584**	-6.262	-1.626	-12.493***	-3.988*
	(4.827)	(2.025)	(0.776)	(4.677)	(2.231)	(3.909)	(2.155)	(4.932)	(2.340)	(4.075)	(2.277)
House	-15.212***	-6.383***	2.445***	-18.694***	-8.125***	-16.953***	-9.104***	-19.303***	-8.429***	-17.258***	-9.366***
	(3.994)	(1.676)	(0.642)	(3.870)	(1.846)	(3.235)	(1.784)	(4.081)	(1.936)	(3.372)	(1.884)
Constant	108.497***	45.665***	-17.168***	52.072***	17.452***	80.285***	30.031***	49.352***	16.092***	78.925***	28.859***
	(5.875)	(2.465)	(0.944)	(5.692)	(2.715)	(4.757)	(2.623)	(6.002)	(2.848)	(4.960)	(2.771)
Observations	763										
R-squared	0.373	0.373	0.373	0.164	0.106	0.347	0.217	0.152	0.102	0.326	0.199

All values are given as percentage changes between the reference scenario and the stated alternative scenario.

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Most importantly, the regression output in Table 3 provides evidence for the distributional effects when the tariff scheme is changed from emphasizing the volumetric component as in the reference scenario, towards a stronger weighting of peak demand. A household's income level is expressed in two ways in our sample, i.e. directly through the income variable and indirectly through the household's amenities. The regression output provides evidence that the log of the monthly net income of a household is significant (at different levels) for all scenarios introducing a charge for measured peak demand, but it is not significant for the remaining three scenarios. A respective negative coefficient of income means that households with a higher income are associated with lower peak loads compared to households with the same characteristics but less income, ceteris paribus. Since our regression controls for a number of household characteristics and appliances, this effect cannot stem from the disproportionate equipment of wealthier households with these observed amenities per se, but either a) from households with lower incomes having load-intensive amenities not observed in our sample, which higher income households do not have, b) or, among those households having the same amenities, wealthier households have more modern and thereby less load-intensive ones, or c) that wealthier households utilize their amenities in a less load-intensive way, e.g. use their sauna differently. The question which of these options plays a role for the frequency and extent of peak loads is important from a policy perspective, considering that tariffs with a charge for measured peaks seem to favour higher income levels. In case that option a) and/or b) are relevant, policy could aid lower income households in identifying these load-intensive amenities and provide support for substituting them, where possible. To investigate such a potential relationship, in the Supplementary Table 3 we regress the frequency of peak loads and the annual energy consumption on household characteristics and amenities again, and extend the set of explanatory variables by an interaction term for households with an income below the median and the respective amenities. We find evidence that electricity consumption patterns of two amenities differ between the income groups: in below-median income households pools produce fewer peak loads, while flow heaters are responsible for about 1,000 additional kWh in this group. The higher energy consumption of flow heaters in lower income households may actually point to the need for respective policy measures (see Supplementary Note 2 for more details).

Table 3: Effects of household characteristics and amenities on the relative difference of their network costs in our subsample.

	f100	f50/e50	e100	pa100	pa50/e50	f50/pa50	f/pa/e	pm100	pm50/e50	f50/pm50	f/pm/e
Logincome	-7.526	-3.183	1.160	-12.400**	-5.620**	-9.963**	-5.875**	-12.187**	-5.514**	-9.857**	-5.782**
	(5.014)	(2.121)	(0.773)	(5.124)	(2.435)	(4.235)	(2.373)	(5.551)	(2.646)	(4.417)	(2.556)
Dummy_income	6.012	2.543	-0.927	-2.266	-1.596	1.873	-0.580	-2.719	-1.823	1.646	-0.777
	(4.418)	(1.868)	(0.681)	(4.514)	(2.145)	(3.731)	(2.090)	(4.890)	(2.331)	(3.891)	(2.252)
Square	-0.223***	-0.094***	0.034***	-0.087	-0.026	-0.155***	-0.052**	-0.050	-0.008	-0.136***	-0.036
	(0.055)	(0.023)	(0.008)	(0.056)	(0.027)	(0.046)	(0.026)	(0.061)	(0.029)	(0.048)	(0.028)
Dummy_square	-3.457	-1.462	0.533	-4.063	-1.765	-3.760	-1.991	-2.447	-0.957	-2.952	-1.291
	(4.229)	(1.788)	(0.652)	(4.321)	(2.053)	(3.572)	(2.001)	(4.681)	(2.232)	(3.724)	(2.156)
Rural	-17.282***	-7.309***	2.663***	-6.530	-1.933	-11.906**	-3.983	-5.243	-1.290	-11.263**	-3.425
	(5.934)	(2.510)	(0.915)	(6.064)	(2.882)	(5.012)	(2.808)	(6.569)	(3.132)	(5.227)	(3.025)
House	-18.469***	-7.811***	2.846***	-10.319*	-3.736	-14.394***	-5.704**	-11.259*	-4.206	-14.864***	-6.111**
	(5.257)	(2.223)	(0.810)	(5.372)	(2.553)	(4.440)	(2.487)	(5.819)	(2.774)	(4.630)	(2.680)
Nr_persons	-10.824***	-4.578***	1.668***	-4.959*	-1.645	-7.892***	-2.871**	-6.442**	-2.387	-8.633***	-3.514**
	(2.816)	(1.191)	(0.434)	(2.878)	(1.368)	(2.379)	(1.332)	(3.118)	(1.486)	(2.480)	(1.436)
Dryer	-10.605***	-4.485***	1.634***	-0.213	0.710	-5.409	-0.801	-2.266	-0.316	-6.435*	-1.690
	(3.933)	(1.663)	(0.606)	(4.019)	(1.910)	(3.322)	(1.861)	(4.354)	(2.076)	(3.464)	(2.005)
Dishwasher	-5.062	-2.141	0.780	2.821	1.801	-1.120	0.884	-0.302	0.239	-2.682	-0.469
	(5.754)	(2.433)	(0.887)	(5.879)	(2.794)	(4.860)	(2.722)	(6.369)	(3.036)	(5.068)	(2.933)
Pool	-6.495	-2.747	1.001	-15.068**	-7.034**	-10.781**	-6.962**	-15.695**	-7.347**	-11.095**	-7.233**
	(6.230)	(2.635)	(0.960)	(6.367)	(3.025)	(5.262)	(2.948)	(6.897)	(3.288)	(5.488)	(3.176)
Sauna	3.280	1.387	-0.506	14.893***	7.193***	9.086**	6.671***	24.390***	11.942***	13.835***	10.786***
	(5.184)	(2.193)	(0.799)	(5.297)	(2.517)	(4.379)	(2.453)	(5.739)	(2.736)	(4.566)	(2.643)
Flowheater	0.539	0.228	-0.083	9.293*	4.605*	4.916	4.062*	11.837**	5.877**	6.188	5.164**
	(4.842)	(2.048)	(0.746)	(4.948)	(2.351)	(4.090)	(2.291)	(5.361)	(2.555)	(4.265)	(2.468)
Boiler	-1.252	-0.529	0.193	0.238	0.215	-0.507	0.019	-1.092	-0.450	-1.172	-0.557
	(4.011)	(1.696)	(0.618)	(4.099)	(1.948)	(3.388)	(1.898)	(4.440)	(2.117)	(3.533)	(2.045)
Pc	-18.551***	-7.846***	2.859***	-6.555	-1.848	-12.553***	-4.078*	-7.860	-2.500	-13.205***	-4.644*
	(4.876)	(2.062)	(0.752)	(4.983)	(2.368)	(4.119)	(2.307)	(5.398)	(2.573)	(4.295)	(2.486)
Householdtype2	-7.891	-3.337	1.216	-4.129	-1.456	-6.010	-2.316	-4.803	-1.793	-6.347	-2.608
	(13.331)	(5.638)	(2.055)	(13.623)	(6.474)	(11.260)	(6.308)	(14.758)	(7.035)	(11.742)	(6.796)
Householdtype3	-27.576***	-11.663***	4.250***	-14.860**	-5.305	-21.218***	-8.279**	-13.619*	-4.684	-20.597***	-7.741**
	(7.120)	(3.012)	(1.097)	(7.276)	(3.458)	(6.014)	(3.369)	(7.882)	(3.758)	(6.272)	(3.630)
Householdtype4	-24.570***	-10.392***	3.787***	-0.861	1.463	-12.716**	-2.014	-1.216	1.285	-12.893**	-2.167
	(6.719)	(2.842)	(1.036)	(6.866)	(3.263)	(5.675)	(3.179)	(7.438)	(3.546)	(5.918)	(3.425)
Householdtype5	-11.895	-5.031	1.833	-0.521	0.656	-6.208	-1.020	1.329	1.581	-5.283	-0.218
	(10.098)	(4.271)	(1.556)	(10.319)	(4.904)	(8.529)	(4.778)	(11.179)	(5.329)	(8.894)	(5.148)
Householdtype6	-20.376**	-8.618**	3.140**	-5.744	-1.302	-13.061*	-3.849	-3.351	-0.106	-11.864	-2.812
	(9.071)	(3.837)	(1.398)	(9.270)	(4.405)	(7.662)	(4.292)	(10.042)	(4.787)	(7.990)	(4.624)
Householdtype7	-20.485	-8.664	3.157	-5.315	-1.079	-12.900	-3.670	-9.601	-3.222	-15.043	-5.527
	(20.805)	(8.799)	(3.206)	(21.260)	(10.103)	(17.572)	(9.843)	(23.031)	(10.979)	(18.325)	(10.606)
Householdtype8	16.867	7.134	-2.599	2.876	0.138	9.871	2.372	5.545	1.473	11.206	3.528
	(16.390)	(6.932)	(2.526)	(16.748)	(7.959)	(13.843)	(7.755)	(18.144)	(8.649)	(14.436)	(8.355)
Householdtype9	-29.454***	-12.457***	4.539***	-15.589	-5.525	-22.522***	-8.720*	-14.585	-5.023	-22.020**	-8.285
	(10.246)	(4.333)	(1.579)	(10.470)	(4.975)	(8.654)	(4.848)	(11.342)	(5.407)	(9.024)	(5.223)
Constant	198.240***	83.846***	-30.552***	143.948***	56.698***	171.096***	75.599***	143.489***	56.468***	170.866***	75.400***
	(36.683)	(15.515)	(5.653)	(37.485)	(17.813)	(30.983)	(17.356)	(40.609)	(19.359)	(32.310)	(18.700)
Observations	404										
R-squared	0.534	0.534	0.534	0.204	0.138	0.452	0.270	0.203	0.147	0.437	0.260

All values are given as percentage changes between the reference scenario and the stated alternative scenario.

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

With respect to the composition of the households, we observe that compared to single households, households made up of a couple with children (Householdtype5/6) or a couple without children (Householdtype3/4) have an advantage when tariffs with a substantial fixed charge are introduced, and experience disadvantages under a 100% energy based tariff. Further evidence on the systematically different consumption patterns of different household types are provided in Figures 2 and 3. Figure 2 compares the load profiles of these household groups on winter Saturdays and summer workdays: households with children (Householdtype2/5/6/7) have substantially higher loads than those without children, and higher income households consume more electricity. While the difference between households with and without children may, to some extent, be rooted in the higher average number of residents, the additional consumption during almost all times of the day supports the regression findings of energy based tariffs being in favour of childless households in absolute terms. Figure 3 compares the percentage of households exceeding certain load thresholds at different times of a day at least once during the observation period: again households with children are more likely to produce high peak loads than those without children, and higher income households are also more likely to produce significant peaks. However, despite higher income households being above the lower income households in both the average energy consumption (Figure 2) and the likelihood of exceeding a certain load threshold (Figure 3), the joint estimation suggests that peak-load-based tariffs are more favourable for high-income households than tariffs based mainly on energy charges (ceteris paribus).

Summarizing the results of our statistical analysis, we find that the living situation of a household and its electricity consuming amenities, as well as its income level and the number of children seem to play a role in whether a change from the reference scenario to a tariff scheme charging for peak demand is associated with benefits or additional burdens. Our results indicate that, ceteris paribus, households with higher income are better off when tariffs charging for measured peak demand are introduced. Among others, [42], showed that photo-

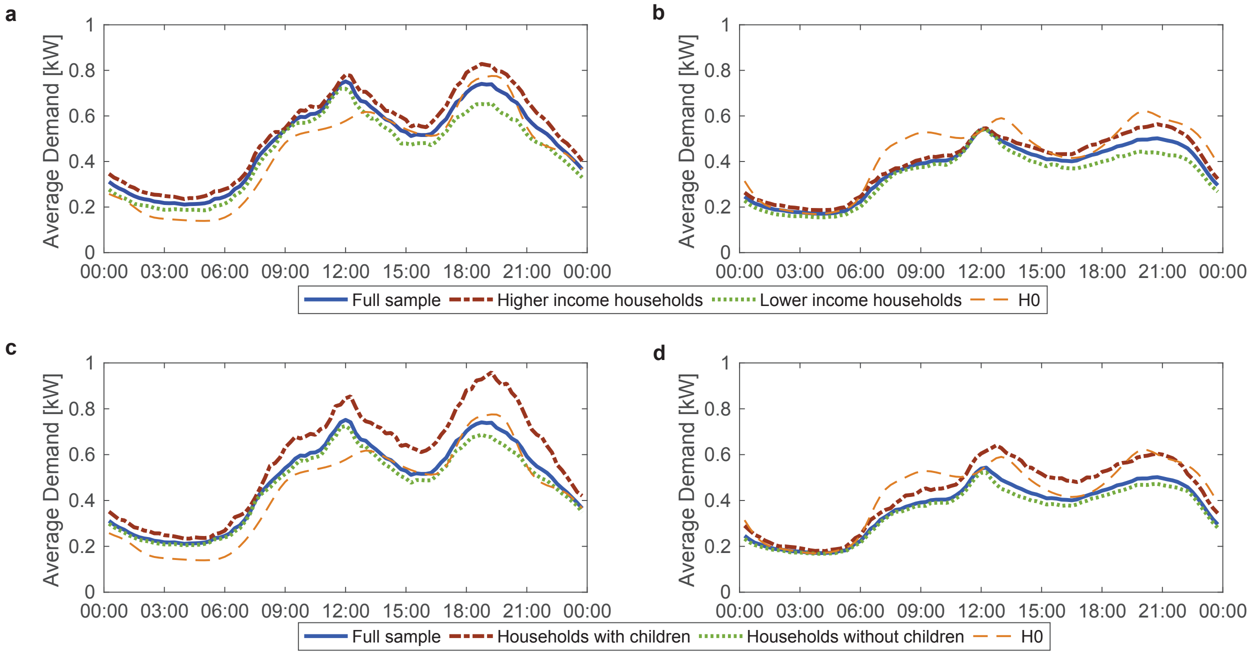

Figure 2: Comparison of the load profiles of different types of households in our subsample with respective standardized load profile H0. Load profile H0 is used by Austrian utilities for forecasting and accounting household electricity consumption when no data from load metering is available [48]). Panel (a) shows the average load on winter Saturdays for high income households (above median monthly net household income of €2,043; n = 209), low income households (below median income; n = 197), all households in the respective sample and the corresponding standard load profile H0; Panel (b) shows the average load of the income groups on summer workdays. Panel (c) shows yearly average load on Saturdays during winter of households with (n = 91) and without children (n = 315), compared to all households in the sample households and the corresponding standard load profile H0; Panel (d) displays the average load on summer workdays of these household groups.

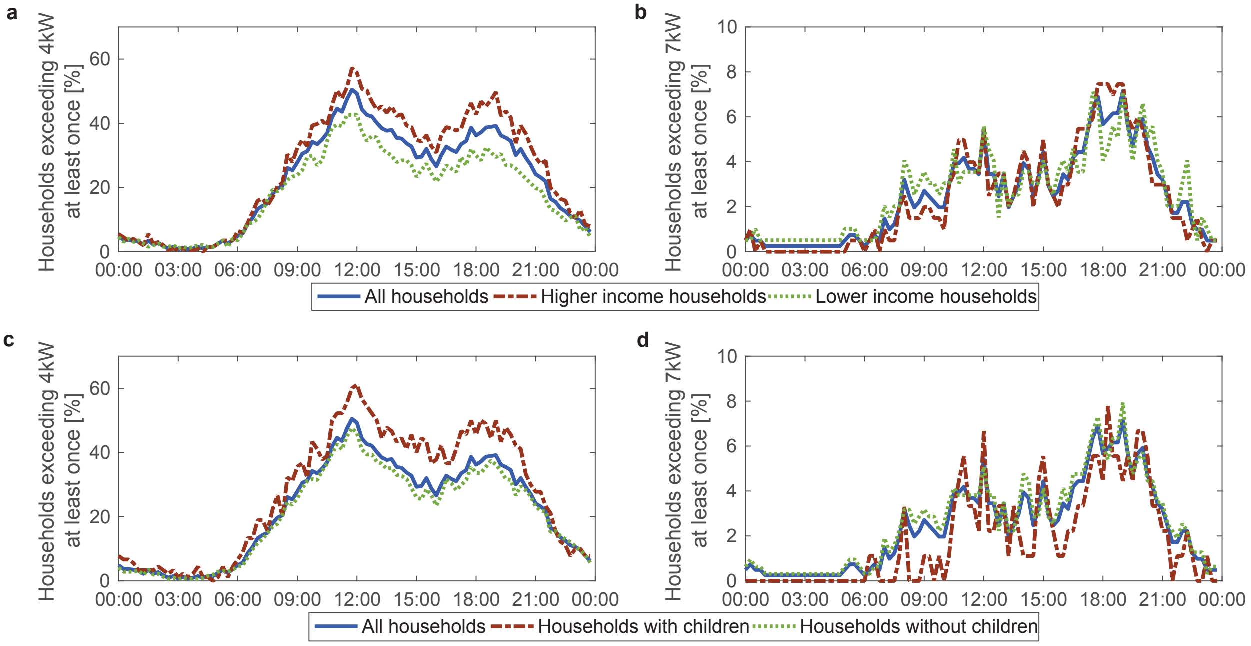

Figure 3: Percentage of households exceeding certain load thresholds at a certain time of the day at least once during the observation period. Panel (a) shows the percentage of exceeding 4 kW during the respective time of the day of high income households (above median monthly net household income of €2,043; n = 209), low income households (below median income; n = 197), all households in the respective sample; Panel (b) shows the percentage of exceeding 7 kW. Panel (c) shows the percentage of exceeding 4 kW during the respective time of the day of households with (n = 91) and without children (n = 315), compared to all households; Panel (d) shows the percentage of exceeding 7 kW of these household groups. Thresholds correspond to the available capacity contracts in the tariff zone of our sample; the minimum contract for households is for 4 kW, the next higher contract is for 7 kW. In practice, actual demand limitations of household connections are significantly higher than contracted.

voltaic panels in combination with home storage appliances reduce the peak loads of households significantly, while at the same time also reduce the volumes of electricity purchased via the grid. Higher income households are likely to install photovoltaic panels and related peak load-reducing equipment at higher rates than lower income households [43, 44]. Shifting the burdens of recovering network costs towards lower income households may therefore become an even more pressing issue in the future.

Discussion

The ongoing transformation of the electricity system calls for the reconsideration of the current network tariff schemes. Our analysis aims to provide evidence on the potential magnitude of such tariff changes, and identify whether potentially increasing costs are equally distributed among the population or are more pronounced for specific groups. Considering that the availability of residential load profiles is relatively new to policy makers and scientists, and that the lack of respective socio-economic background information associated with these load profiles is hampering comprehensive investigations, the knowledge gained in this study provides substantial input for the ongoing debate about developing and implementing new tariff schemes.

Investigating data on 765 households in Austria, we find that the change in network charges, depending on the scenarios applied, can (in extreme cases) reach a decrease of 50% or an increase of 500% in comparison to the status-quo. This demonstrates that some of the tested tariff scenarios may have a disruptive impact on some households' budgets if implemented from one accounting period to the next.

We find it important to highlight the potentially low predictability for households of their annual network costs under tariffs emphasizing peak charges (per measured kW). Considering e.g. tariff scenario pm100, where household network charges are defined by the highest load during one out of 35,040 quarters of an hour, significantly increased network costs from one year to the other can arise from one unusually coincidental use of appliances. The high level of sensitivity in household electricity costs to small lapses, on the part of the household when measured peak demand charges are used makes it necessary to apply such tariffs thoughtfully, following careful research. The need for a delicate handling of the roll-out of measured peak demand tariff schemes is particularly urgent when such schemes are not accompanied by support mechanisms, such as extended transition periods allowing households to adapt to the new price signals.

Due to the sensitivity of households' network expenditures to measured peak demand charges, the application of such tariff should be well thought out and supported by empirical studies. This is particularly true when new network tariffs are not accompanied with qualified support schemes, such as extended transition periods allowing households to adapt to the new price signals.

Under volumetric network tariffs every reduction of the units of consumed energy results in an under-recovery of network costs. This can either be compensated by increasing the price for the unit of consumed energy, or by decoupling the revenues from network tariffs from consumed volumes. Looking at the socio-demographic characteristics of the households in the sample, we see that tariffs combining measured peak demand and volumetric components could provide a new balance for the distribution of network costs – as these tariffs are cost-reflective and, due to the peak load charge, they signal the consumer to decrease overall consumption while not penalizing any specific group of consumers. An additional fixed component can account for costs invariant to consumption patterns, such as charges for metering itself. We find that such tariffs could provide a solid response to the increase of prosumers, while avoiding the shifting of burdens towards households not yet ready for taking this step.

This analysis is limited to data on Austrian consumers, so further research with data on more households, including data on PV ownership and home storage installations could improve our understanding of the tariffs' effects on both consumers and prosumers.

Methods

Statistical Methods

The quantity of interest in our analyses is defined as the percentage by which the network costs differ between the reference scenario and the alternative scenarios, and we refer to this quantity by

$$\Delta_{i,j} = \frac{C_{i,j} - C_{i,r}}{C_{i,r}} \times 100, \tag{1}$$

where $C_{i,r}$ are the annual network costs of household i in the reference scenario, while $C_{i,j}$ stands for $i's$ costs in the j^{th} alternative scenario, and $j \in$ (f100, e100, f50/pa50, f50/e50, f50/pm50, pa100, pm100, f/pa/e, pa50/e50, pm50/e50, f/pm/e). A negative sign of $\Delta_{i,j}$ therefore indicates a cost reduction under the alternative scenario j compared to today's regulatory practice, while a positive sign points to increased costs for household i.

To investigate which household characteristics are associated with cost savings or incremental costs under the different alternative scenarios we estimate $\Delta_{i,j}$ with a linear regression model. Thereby we consider that $\Delta_{i,j}$ is a function of household-level characteristics $x_{1,i}, \ldots, x_{k,i}, \ldots, \ldots, x_{K,i}$, such that

$$\Delta_{i,j} = x_{1,i}\beta_{1,j} + \cdots + x_{K,i}\beta_{K,j} + \varepsilon_{i,j}, \tag{2}$$

where $\beta_{k,j}$ holds the incremental average percentage points by which the network costs change when alternative scenario j is applied instead of the reference scenario, when household characteristic k increases by one unit. $\varepsilon_{i,j}$ references the error term. All regressions presented in this study estimate (2).

Considering that the alternative scenarios as used in our study are correlated, e.g., all f. scenarios rely on fixed charges, simultaneous estimation of all eleven alternative scenarios suggests itself. We pool the eleven resulting equations (one per alternative scenario) and estimate the resulting system by the seemingly unrelated regression model [45]. Since we rely on exactly the same set of household characteristics for explaining the deterministic portion in (2), results are identical to the ordinary least squares model. Whenever a variable is included in one of the regressions for which missing values have been imputed, a respective dummy variable is included to test whether the imputation has significantly affected the analyses. None of these dummies' coefficients has a significant opposing effect compared to the main variable's coefficient, so we conclude that our analyses do not suffer from bias caused by the imputations.

Scenarios

To cover the range of potential network tariff schemes, we design a total number of eleven scenarios.

First, we design one respective tariff scenario recovering the network costs through only one of the three components - volume, fixed charge, and measured peak load (average and maximum):

Scenario f100 is to 100% a fixed charge. Thereby, f100 represents a flat charge for all households, which is €136,209.10/765households = €178.05 per household per year for the full sample in our study.

Scenario pa100 represents a scheme charging for measured peak load only. In this scenario the definition of kW peak load follows the Austrian tariff structure in 2016 [46], where a so called "smart meter" tariff was included for testing only (in the residential sector). There, kW peak load as relevant for billing is not defined as the one maximum load out of the 35,040 metered load values during one year per Austrian meter. Peak load as relevant for setting a household's peak charge is defined as the average of the 12 monthly peak loads during the respective year. Scenario pa100 for the full sample analysis therefore sets ${}^{€136{,}209.10}/_{3{,}485.59\ kW\ total}$ = €39.07 per kW of billing relevant peak load, where *kW total* is the sum over all 765 corresponding peak load values.

Scenario pm100 also represents a scheme charging for peak demand only, but instead of averaging, the highest of the 12 monthly peaks is applied, such that it sets ${}^{€136{,}209.10}/_{4{,}603.3\ kW\ total}$ = €29.59 per kW of billing relevant peak load, where *kW total* is the sum over all 765 corresponding peak load values.

Scenario e100 is a fully volumetric tariff and includes only a payment per unit of consumed energy. Thereby it is ${}^{€136{,}209.10}/_{2{,}691{,}272\ kWh\ total}$ = €0.0506 per kWh consumed during the respective year, where *kWh total* is the aggregated electricity consumption of all 765 households.

Next, we define five scenarios each representing a hybrid of two of the candidate tariff components, fixed, peak load and volumetric charges:

Scenario f50/e50 puts 50% of the weight on the fixed charge and 50% on the consumed volume. Thereby, $€136{,}209.10 \times 0.5 = €68{,}104.55$ are recovered by the fixed component, and exactly the same amount comes from the volumetric component. The fixed component of f50/e50 is therefore given by ${}^{€68{,}104.55}/_{765 households}$ = €89.02 per household per year. The volumetric component of scenario f50/e50 results from distributing the respective quantity of $€68{,}104.55$ among the total number of consumed kWh, that is ${}^{€68{,}104.55}/_{2{,}691{,}272\ kWh\ total}$ = €0.025 per kWh consumed.

Scenario f50/pa50 represents a scheme with 50% of the costs recovered from a fixed charge and 50% from a measured peak charge. The fixed charge per household is the same as in the f50/e50, the peak charge is defined as ${}^{€68{,}104.55}/_{3{,}485.59\ kW\ total}$ = €19.53 per kW of billing relevant peak load, where *kW total* is the sum over all 765 corresponding peak load values (average definition).

Scenario f50/pm50 the peak charges are calculated as ${}^{€68{,}104.55}/_{4{,}603.3\ kW\ total}$ = €14.79 per kW of billing relevant peak load (based on the one maximum peak definition).

Scenarios pa50/e50 and pm50/e50 are each a combination where 50% of weight is put on the consumed volume of energy and 50% of the measured peak demand, average or maximum definition, respectively.

In addition, we also test two scenarios combining all three candidate tariff components:

Scenario f/pa/e imposes a fixed charged of €24.6 as found in the Austrian tariff as applied in 2016, and splits the remaining quantity in equal portions. Revenues collected from the fixed charge therefore result in a total of €24.6 × 765 = €18,819 for our full sample, which we subtract from the €136,209.10 to calculate the shares that have to be recovered by peak and energy components: (€136,209.10 - €18,819) × 0.5 = €58,695.05. The peak component is calculated as ${}^{€58,695.05}/_{3,485.59\ kW\ total}$ = €16.83 per kW peak and the energy component is equal to ${}^{€58,695.95}/_{2,691,272\ kWh\ total}$ = €0.022 for each kWh consumed.

Scenario f/pm/e fixed and energy charges are the same as in the previous scenario and the peak charge is calculated with the maximum peak definition instead of the averaged definition.

We compute the network charges for every household under each of the scenarios for the full sample as well as for the subsample of 406 households, for which the sum of network charges accumulates to €74,794.28 in the reference scenario.

Ethics statement.

The survey data were collected by Energy Institute at Johannes Kepler University Linz, following high EU standards of data protection and voluntary study participation.

Data availability.

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Please address all inquiries and correspondence to J.R. at reichl@energieinstitut-linz.at. A.K. and J.R. were primarily responsible for the creation and implementation of the survey instrument. D.E. and C.F. were primarily responsible for the creation and management of the dataset, including load profiles. V.A. and J.R. mainly contributed to data analysis. All authors contributed to the writing of the paper with V.A., A.K. and J.R. as the primary authors.

Competing interests

The authors declare no competing financial interests.