IMPROVED RESIDENTIAL ELECTRICITY FEEDBACK THROUGH HOUSEHOLD-SPECIFIC BASELINES

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ABSTRACT

The benefits of the smart grids partially depend on household engagement. This engagement can be increased by providing proper feedback to households, but it is important that the feedback is reliable and makes sense to the end-users. This paper highlights some limitations of common feedback metrics and proposes a metric based on household-specific baselines that we argue could be more fair and therefore be better understood by the end users.

INTRODUCTION

The Paris agreement set the foundation for a transition in the global energy markets towards energy efficiency and phasing out fossil fuels in benefit of intermittent renewable energy sources. This transition is enabled by the emerging concept of smart grids that partially depend on engaged households [1, 2]. However, succeeding with long-term household engagement has been proven very difficult [3], and even harder where the cost of energy is low. To contribute towards feedback mechanisms that can overcome engagement barriers this paper proposes the concept of household-specific baselines.

To increase the likelihood of engagement, feedback on household energy performance should be carefully designed using best practices from the field of human-computer interaction and behavioural sciences [4, 5]. *Comparative* feedback is suggested to be an effective feedback mechanism as it has led to sustained engagement in some cases [6]. One problem with this type of feedback is that if it only considers the total household electricity consumption – usually the only data point that is available through smart meters – the feedback cannot be normalized in a fair way: a large family that actually make efforts to reduce their energy use will almost always perform worse than a single-member household in the same community.

One common normalized metric of energy use in buildings is *energy consumption per floor area* (kWh/m^2), which allows for meaningful comparisons of area-dependent energy use such as heating. For household *electricity* consumption (kWh_{elec}), however, this metric is not optimal since other factors such as the type of household, the number of residents, or the existence of certain electricity loads such as electric vehicles often affect the consumption more.

AIM

The aim of this paper is to i) highlight some of the limitations of electricity consumption metrics in general and the kWh/m^2 metric in particular, ii) propose household-specific baselines as metric that overcomes these limitations, and iii) present a model for calculating the baseline.

LIMITATIONS OF COMMON ELECTRICITY CONSUMPTION METRICS

In order for a household to better understand its electricity consumption performance, it is common to compare its consumption to its previous consumption or to the consumption of other households. These types of comparisons have limitations that are discussed below.

Comparisons with the household's previous consumption can show a decreasing or increasing trend in the consumption, but not whether the actual consumption is high or low taking into account the characteristics of the household. This makes it harder to set fair energy reduction goals. For example, a reduction goal of, say, 20% is easily achieved by a household with a wasteful energy behaviour, while an already energy-efficient household will find the same 20% reduction challenging. Therefore, knowing a baseline consumption based on the household's characteristics would be useful when setting reduction goals.

Comparisons with other households is often used to give comparative feedback. A *direct electricity use comparison* using kWh can be done between apartments, but it is only suitable when comparing apartments with similar characteristics; a small one-person apartment will most probably use much less than a large apartment having four residents. To make households comparable, the kWh/m^2 metric is often used, but household area is only one of many determinants of the energy consumption. Figure 1 shows the electricity consumption of 124 Swedish apartments divided into six groups of similarly-sized household. It shows a trend of increasing use per area, but the trend is broken for the largest household sizes. More importantly, the data reveals that the number of residents within each area group and their behaviour has an important effect on the total energy consumption. The importance of the number of residents is further confirmed by simulations (Figure 2): a large 110 m^2 single-person apartment consumes less than small 30 m^2 one with two residents.

Thus it can be unfair to use kWh/m^2 to compare apartments; for example, the energy use of a large two-person apartment with normal consumption could be similar to a smaller, energy-saving four-person apartment, but when divided by the area, the large apartment would seem more energy-efficient. The risk with this is that energy-saving residents feel that their saving or shifting efforts does not matter. This fairness aspect is yet to be addressed in demand side management programs and energy communities. A parallel can be drawn to the comparison of greenhouse gas emissions of cities that is always normalized per capita to avoid this very problem.

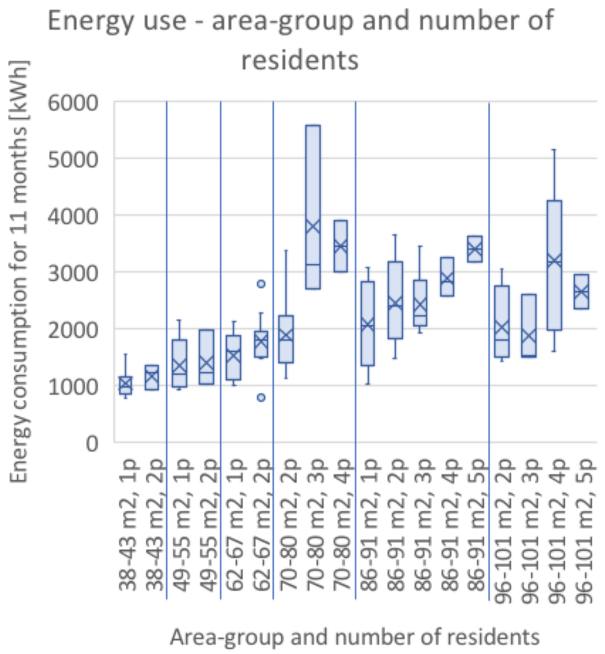

Figure 1. Energy consumption statistics (0-25-50-75-100 percentile) for 11 months in 124 apartments divided into six area groups. The apartments are recently built and participate in a pilot in the InteGrid EU project in Stockholm Royal Seaport, Stockholm, Sweden.

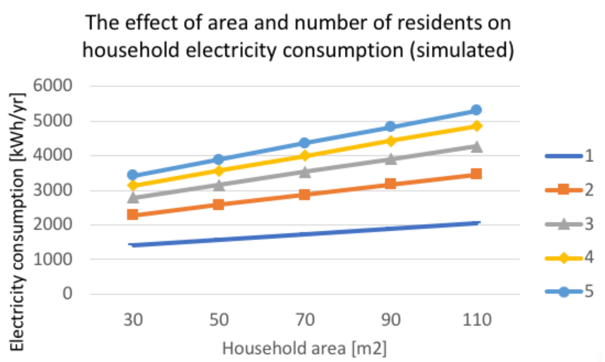

Figure 2. Simulated energy consumption for Swedish apartments for different combinations of area (30-110 m2) and number of residents (1-5). Simulated using Energikalkylen, an online household electricity calculator provided by the Swedish Energy Agency.

PROPOSED SOLUTION: HOUSEHOLD-SPECIFIC BASELINES

To overcome these limitations of conventional comparative feedback, our proposed solution is a *household-specific baseline*. The baseline is calculated using selected household characteristics and indicates how much an *average* household with the same characteristics would consume. Comparing the household's actual consumption with the baseline reveals how energy-efficient the household is compared to the average household. Household-specific baselines would allow for:

1. Personalized goals. Figure 3 compares two hypothetical households, A and B. By only looking at the current consumption (grey bars), household B seems to be more efficient than A. However, by introducing the household-specific baseline (black horizontal lines), it can be seen that A is actually more efficient since its consumption is below its baseline. When setting reduction goals, instead of giving both households a 20% goal (red bars) relative to their current consumption, the efficient household A could get a personalized goal of 10% while B gets 30% (green bars).

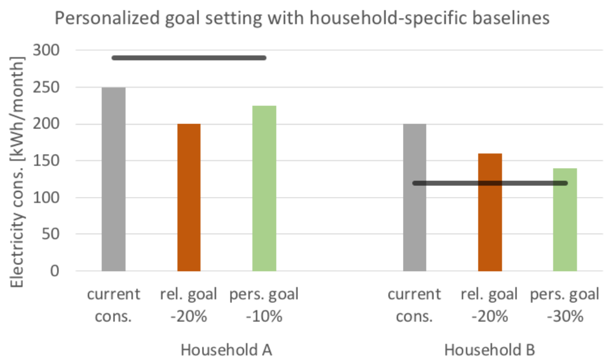

Figure 3. Example of personalized goal setting using household-specific baselines for two hypothetical households

2. A fairer comparison of energy efficiency between households. By using the *deviation in percent from the household-specific baseline* as a metric, households with differing characteristics can be compared with each other. For example, in Figure 3, household A is about 15% below its baseline while B is 65% above, so A is much more efficient than B. Another example: an apartment with a young couple consuming 300 kWh/month and a similarly sized household of four with both parents working from home consuming 800 kWh/month can be said to be equally energy efficient if they both consume 20% below their household-specific baseline.

Baseline construction: main determinants of household energy use

In order to calculate a fair baseline, the characteristics that are most relevant to the household energy consumption need to be considered. Common ways to calculate baselines include online energy calculators or energy simulations, but these often require many input parameters that are not readily available unless a detailed survey is given to the household. Our approach is to minimize the number of user-input parameters and do assumptions based on them to get a baseline that is more appropriate. For typical Swedish apartments, Vassileva [7] suggests that apart from behaviour and attitudes, the household income, number of residents and floor area affect the consumption. As the household income is likely to be correlated with the other parameters (i.e. larger income affords a household with a larger floor area), our hypothesis is that it is possible to create a meaningful baseline calculation using the following two *main determinants of household energy use*:

- the number of residents
- the floor area

We also suggest using *people hours* as a main determinant, but this is outside the scope of this paper and is explained in the Future research section.

Baseline construction: main household electricity loads

The *main household electricity loads* and their dependence on the main determinants are presented in Table 1. Out of the loads, only the lights is dependent on the household area, while the rest is mainly dependent on the number of residents and their behaviour. Our hypothesis of mainly person-dependent loads was verified by studying simulation results from Energikalkylen, an online household electricity calculator made by the Swedish Energy Agency.

Load	**Typical household elec. share**	**Floor area**	**# residents**	**People-hours (future research)**		
				Amount	Time of day	Awake
Lights	11% E_{lights}	L	L	x	x	x
Washing machine	15% E_{wash}		L			
Clothes dryer			L			
Cooking	24% $E_{kitchen}$		L	x		x
Dishwasher				x		
Fridge/Freezer	12% E_{fridge}		S			
Electric devices	38% $E_{devices}$		L	x		x
Standby			L	x		
Charging			L	x		

*Table 1. Electrical household loads, their typical share of household electricity use (Source: simulations using Energikalkylen), and their assumed dependency on floor area, number of residents and people hours. L = linear dependency (y=k*x+m), S = step function, x = affected by type of people-hour.*

A MODEL FOR CALCULATING A HOUSEHOLD-SPECIFIC BASELINE

Based on this understanding on how the main determinants of household energy use affect different household loads, we suggest the following simple model as a starting point for calculating a household-specific baseline:

Inputs:
A: household area [m^2]
r: number of residents
w: has/uses washing machine (1 or 0)
r_{home}: number of residents who usually work from home, can be a decimal value such as 0.5 or 1.5 if the residents work from home part-time.

Output:
$E_{baseline}$, the baseline household electricity consumption [kWh/year], which is a sum of the individual loads:

$$E_{baseline} = E_{lights} + E_{kitchen} + E_{devices} + w * E_{wash} + E_{fridge}$$

where the first four individual loads are calculated as linear dependencies (y = k*x + m) and the first three are increased if people are working from home:

$$E_{lights} = (k_{lights} * A + m_{lights}) * (1 + f_{home} * r_{homeupTo1})$$

$$E_{kitchen} = (k_{kitchen} * r + m_{kitchen}) + (k_{kitchen} * r_{home} + m_{kitchen}) * f_{home}$$

$$E_{devices} = (k_{devices} * r + m_{devices}) + (k_{devices} * r_{home} + m_{devices}) * f_{home}$$

$$E_{wash} = k_{wash} * r + m_{wash}$$

in which

f_{home} is a factor for increased energy use if working from home

$r_{homeUpTo1}$ decreases the use of lights if a single person is working part-time from home: $r_{homeUpTo1} = \{r_{home} \text{ if } 0 \leq r_{home} < 1,\ 1 \text{ if } r_{home} \geq 1\}$

The last individual load is a step function dependent on the number of residents, assuming that three residents or more need a separate fridge and freezer:

$$E_{fridge} = \{E_{combinedFridgeFreezer} \text{ if } r \leq 2,\ E_{separateFridgeFreezer} \text{ if } r \geq 3\}$$

The k and m linear equation parameters need to be customized for different countries and living conditions. For Swedish apartments, the following values are suggested based on the Energikalkylen simulations:

	k	*m*
lights	4.5	20
kitchen	120	400
devices	120	250
wash	180	0

The k_{home} parameter is assumed, and the energy use for the fridge/freezer are from Energikalkylen.

$\mathbf{f_{home}}$	0.2
$\mathbf{E_{combinedFridgeFreezer}}$	350 kWh/year
$\mathbf{E_{separateFridgeFreezer}}$	520 kWh/year

FUTURE WORK

The accuracy of the model could be improved by introducing the idea of *people hours* (number of people times hours at home). This concept can be divided into different subtypes, catering for different types of electricity use scenarios:

- Amount of hours: electricity use that is only dependent on people being at home
- Time of day-dependent hours - some usage such as lighting is not as heavy during daylight hours
- Number of awake hours - main part of the electricity use happens when people are awake. The more awake hours spent at home, the higher the baseline.

Some assumptions on how household electricity loads depend on people hours are made in Table 1.

Previous hourly consumption data could be used to determine and compare the standby energy, and also to detect when the residents are away for longer periods of time and thus exclude those days from statistics, energy savings comparisons and so on.

A suitable algorithm for setting personalized goals using the baseline needs to be developed.

DISCUSSION AND CONCLUSIONS

In this paper, some issues with unfair household electricity feedback metrics have been highlighted, including the kWh/m^2 metric. Our proposed solution is to use household-specific baselines. These make it possible to set better personalized electricity reduction goals and make fairer electricity consumption comparisons between households, thus improving the energy feedback given to households. This is expected to increase the household engagement and lead to a better utilization of smart grids. By aggregating the baselines, they can also be used in energy communities to evaluate the household electricity use efficiency of the community as a whole, and make comparisons between communities.

Our approach for improved residential electricity feedback through household-specific baselines will be implemented and evaluated in Stockholm and Lisbon within the InteGrid project.

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