Consequences for residential customers when changing from energy based to capacity based tariff structure in the distribution grid

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***Abstract* — This paper presents the trends towards capacity based grid tariffs and results from a work analysing the consequences different grid tariffs will have for residential customers, based on their consumption profile. The analyses are based on hourly meter data from 10.055 residential customers in Norway. The work is a result from the Norwegian research project "SmartTariff" (2014-2017), which aims to develop the future tariffs to be introduced when full-scale roll-out of smart meters have been performed. The results show that changing to capacity based tariffs will result in a reallocation of costs between different types of customers, and the customers will pay according to how they affect the distribution grid.**

***Index Terms*-- Meter reading, Power demand, Power system economics, Smart grids.**

I. Introduction

The EU target for 20 % reduction in green house gasses, 20 % share of electricity produced by renewable energy sources and 20 % energy efficiency (compared to normal development) – within 2020, has contributed to a marked increase in the amount of distributed generation from renewable energy sources in Europe. This environmental focus has also contributed to development in technology within generation, distribution and storage of electricity and new solutions on the customer side.

The trends with new appliances that are more energy efficient, but with a higher peak power demand (for example instantaneous electric water heaters, large heat pumps and induction cookers), new building codes (passive houses) and electrification of transport, give a more volatile consumption of electricity, and results in reduced utilization time of the distribution grid.

For a household customer the peak load occurs in a limited number of hours during a year. This is illustrated with the annual duration curve in Fig. 1, developed for an average Norwegian customer based on hourly meter data of the electricity consumption of 10 residential customers (single family houses). For this average customer the load exceeds 70 % of peak load in only 5 % of the hours during a year. The trend with higher peak load and reduced energy consumption is illustrated with the arrows and the dotted line. 70 % of peak load is represented with the horizontal (dashed) line.

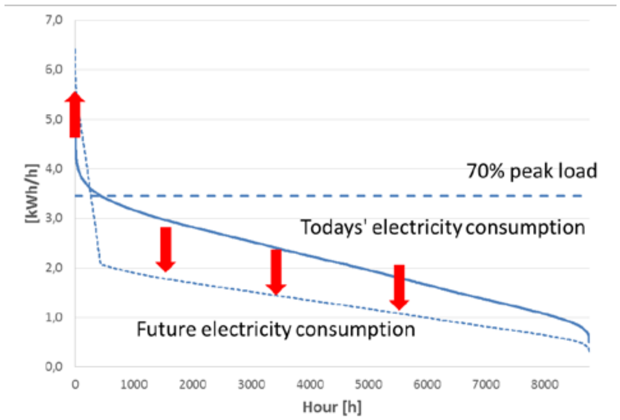

Figure 1. Annual duration curve for electricity consumption for an average residential customer in Norway, [1]. Unbroken line representing today's electricity consumption, dotted line representing future electricity consumption and dashed line representing 70% peak load.

Traditionally, the Distribution System Operators (DSOs) invest in grid upgrading to handle the increasing peak load, but this might not always be the socioeconomic best solution. A smarter alternative could be to give customers new incentives to change their consumption pattern, [2].

This paper presents analyses showing how changing to capacity based grid tariffs will result in a reallocation of costs between different types of residential customers, and how these customers will pay according to how they affect the distribution grid.

II. Background

This section presents background information relevant for the development of new grid tariffs, starting with a description of the stakeholders in the Norwegian power system, changes in how electricity consumption are metered, economic theory for developing grid tariffs and concluding with a description of the shift from today's grid tariffs towards capacity based grid tariff when smart meters are deployed.

A. Stakeholders in the Norwegian power system

In the Norwegian power system, the DSO and the power retailer are two separate entities, which imply that the customers have two different contracts for their electricity: one for the use of the grid and one for the use of the energy[1].

The DSOs are monopoly stakeholders, strictly regulated by the Regulator via revenue cap regulation. The national regulations define the criteria for developing the grid tariff [3], stating that the grid tariff should give signals for efficient utilization of the distribution grid. The power retailers are operating in the market, and have to fulfil the competition laws. They are free to develop their own energy contracts offered to their customers.

B. Deployment of smart meters

Periodical self-reading of the meter (4, 6 or 12 times per year) has been the most common solution for Norwegian residential customers with an electricity consumption larger than 8.000 kWh/year[2]. Up to now automatic meter reading has only been required for customers with a yearly consumption larger than 100.000 kWh, [4].

New regulations in Norway require that smart meters should be installed at all customers by 1st January 2019, [4]. In total, this represent approximately 2.9 mill. new meters. The regulations specify a minimum level of functionalities for the smart meters, requiring that the meter should be able to register both consumption and generation (active and reactive power) on an hourly basis, and it should be possible to change the sampling frequency down to metering every 15 minutes.

In EU the requirement is that where the rollout of smart meters is assessed positively, the Directive on internal markets demands that at least 80% of customers shall be equipped with intelligent metering systems by 2020, [5].

C. Economic theory for developing grid tariffs

All DSOs operate as a natural monopoly, due to the benefit of having one power grid, instead of several parallel infrastructures. A natural monopoly exists in a particular market if a single firm can serve that market at a lower cost than any combination of two or more firms, [6].

In economic theory, a natural monopoly is characterized by falling average costs with increased volume, [7]. This means that the marginal costs are lower than the average costs.

If the grid tariff is set equal to the marginal costs, the income will cover the costs, [8].

Fig. 2 illustrates the curves for marginal costs (MC) and average costs (AC), and the link between price and volume for a natural monopoly, with volume (q) at the x-axis and price (cost) (P) at the y-axis, [9].

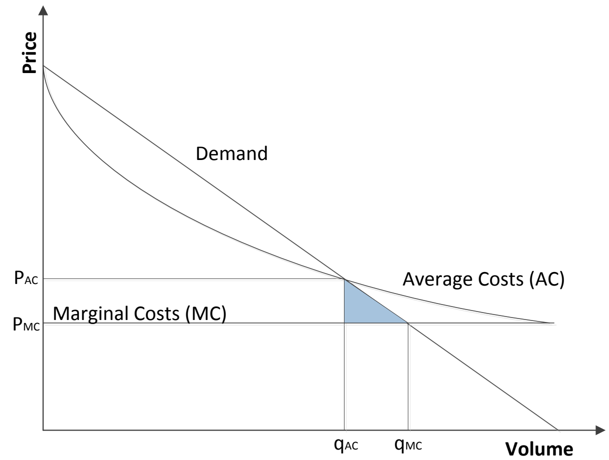

Figure 2. Cost structure for a natural monopoly

A price equal to the marginal costs (P_{MC}, q_{MC}) will give a loss equal to the shaded area (triangle), limited by the marginal costs and average costs, the volume between q_{MC} and q_{AC} and the demand curve.

To cover their costs, natural monopolies should use a two parts tariff containing a fixed part and a unit part, where the price per unit is equal to the marginal costs and the fixed part covers the rest of the costs.

This is the basis for discussing today's and the future grid tariffs for residential customers located in the distribution grid.

D. From energy to capacity based grid tariffs for residential customers

Today, the normal grid tariff to Norwegian residential customers with self-reading of their meter, is an energy based grid tariff consisting of two parts, [4]. The first part is a fixed charge [€/year] that at least shall cover the costs associated with customer management and support. The second part is an energy charge [€/kWh], which is usage dependent and shall at least cover the marginal network losses. Additionally, a seasonally differentiated energy charge should be offered to all customers with an electricity consumption larger than 8.000 kWh/year.

An example of how today's energy based grid tariff does not give residential customers information about how they affect the distribution grid, is presented in Fig. 3. (Keeping in mind that the peak load is the dimensioning criteria for development of the distribution grid.) The first customer lives in a new house with passive standard, have a yearly electricity consumption of 5.000 kWh and a peak load of 20 kW due to an electrical vehicle and an induction oven for cooking. The second customer lives in an old house, with a yearly electricity consumption of 25.000 kWh due to electric space heating, and a peak load of 10 kW. With the traditional energy tariff with a fixed part of 250 €/year and an energy part with

[1] A common invoice for both the use of the grid and the energy part is possible.

[2] The electricity consumption for an average residential customer is approx. 16.000 kWh/year (www.ssb.no)

5 Eurocents/kWh, the yearly grid costs for the first customer is 500 €/year and the grid costs for the second customer is 1.500 €/year, even if the first customer affect the grid capacity twice as much as the second customer. The costs in this example are calculated based on the average energy tariff in Norway (2015).

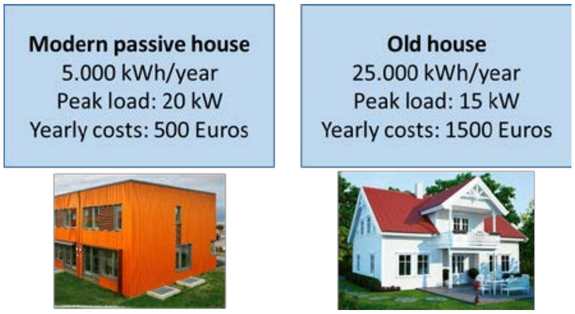

Figure 3. Disproportion between yearly costs and how the customers affect the distribution grid

The standard energy grid tariff for residential customers should be "rethought" [2], since the energy consumption today is reduced and the peak load is increasing. A capacity based tariff will give a long-term incentive for efficient utilization of the grid, and give income to the DSOs reflecting each customer's use of the grid.

III. RESEARCH FRAMEWORK

This paper presents the evaluation of the consequences different grid tariffs will have on the total yearly costs for different types of residential customers. These analyses are based on meter data and information about building types from 10.055 residential customers at Ringerikskraft (a Norwegian DSO) and alternative grid tariffs evaluated in the SmartTariff project. The total electricity consumption for these customers are 94,7 GWh, for a period of one year.

A. Data source/Customer groups

Hourly meter data [kWh/h] of the electricity consumption from the period 1st October 2014 until 30th September 2015 have been analysed through cross section analyses with use of USELOAD software[3].

The residential customers are divided into the following two groups, according to their building type:

- Single family house (B1)
- Apartment (B2)

These groups are further divided into the following five sub-groups according to their typical load profile:

- Highest load during night (C1)
- Highest load during day-time (C2)
- Highest load during afternoon (C3)
- Load with high utilization time of the grid (> 4000 h) (C4)
- Load with low utilization time of the grid (< 1500 h) (C5)

Subsequently, one representative customer are selected from each of these sub-groups, and in total we get 10 representative customers included in the analyses.

Each load profile is representing a different type of customer, all with a different yearly consumption. To be able to evaluate the differences in electricity consumption pattern for these customers, the load profiles have been scaled according to their peak load hour. This gives a value of 1.0 in the peak load hour, and all hours as a share of this.

The annual duration curves for different customer groups living in single-family houses are presented in Fig. 4. This figure confirms the trend illustrated in Fig. 1, showing the difference between a customer with high utilization time (T_u) of the grid (High T_u) and a customer with a low utilization time of the grid (Low T_u).

The customer with high utilization time (HighTu) has limited difference in load during the year, compared to the customer with low utilization time (LowTu) who has few hours with peak load, and very little consumption for most of the hours. The annual duration curves for customers with peak load during night, day and afternoon have not that clear characteristics.

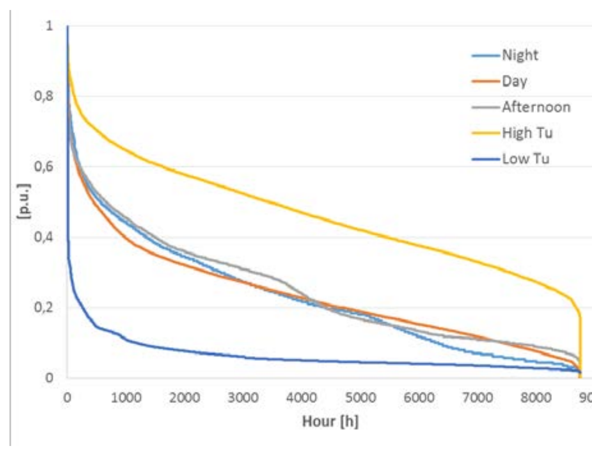

Figure 4. Annual duration curve for different customer groups living in single-family houses.

B. Alternative grid tariffs

The SmartTariff project is studying what could be a good/fair grid tariff for residential customers in the future, and alternative tariff structures have been discussed. To compare the different alternatives, and at the same time fulfil the

[3] https://www.sintef.no/en/software/useload-calculation-of-electrical-load/

requirement for revenue cap regulation, the grid costs for the total group should be unaltered for all the alternatives, compared to today's energy grid tariff. This will make it possible to study how changes in the tariff structure will reallocate grid costs between the customers groups.

The capacity based grid tariff is represented by different alternatives of power tariffs, where the hourly meter value [kWh/h] is used for settlement of the power consumption.

The alternative grid tariffs discussed in this paper are presented in Table I.

TABLE I. TARIFF ALTERNATIVES (T1-T8)

Tariff alternative	Description of parts[a]
Energy tariff (T1)	Energy charge [€/kWh]
Seasonal energy tariff (T2)	Energy charge summer/winter [€/kWh][b]
Energy tariff Day (T3)	Energy charge day/night [€/kWh][c]
ToD energy tariff (T4)	Energy charge in off peak hours [€/kWh] Energy charge in defined peak hours [€/kWh][d]
Peak power tariff (T5)	Energy charge [€/kWh][e] Power charge [€/kWh/h]
Seasonal power tariff (T6)	Energy charge [€/kWh][e] Power charge summer/winter [€/kWh/h][b]
Peak power tariff Day (T7)	Energy charge [€/kWh][e] Power charge day/night [€/kWh/h][c]
ToD power tariff (T8)	Energy charge[€/kWh][e] Power charge in defined peak hours [€/kWh/h][d]

a. All the tariff alternatives have a fixed part, at least covering the costs associated with customer management and support [€/year].

b. Winter: November-March, Summer: April-October.

c. Day: 0700-1600 workdays. Night: 1600-0700 workdays and weekend/ holidays.

d. ToD = Time of Day. A tariff with defined peak hours during the day, e.g. 0800-1000 in the morning and 1600-1800 in the evening.

e. Mainly covering marginal network losses.

The equation for the alternative energy grid tariffs are presented in (1).

$$C_{EN} = \beta_{EN} + \sum_{d=1}^{365}\sum_{t=1}^{24}\gamma_{d,t} p W_{d,t} + \sum_{d=1}^{365}\sum_{t=1}^{24}\alpha_{d,t} p W_{d,t} \qquad (1)$$

Where:

- C_{EN} The yearly costs with an energy grid tariff [€/year] (T1-T4)
- β_{EN} Fixed part [€/year]
- $\gamma_{d,t}$ / $\alpha_{d,t}$ Factors used to make the variable energy part active/inactive (0/1).
- p Energy charge in defined period [€/kWh]
- $W_{d,t}$ Energy consumption per hour [kWh/h]

The equations for the alternative power tariffs are presented in (2).

$$C_{Power} = \begin{array}{l} \beta_{Power} + \delta \sum_{d=1}^{365}\sum_{t=1}^{24} p W_{d,t} + \sum_{d=1}^{365}\sum_{t=1}^{24}\gamma_{d,t} p^{*} P_{d,t} \\ \quad + \sum_{d=1}^{365}\sum_{t=1}^{24}\alpha_{d,t} p^{*} P_{d,t} \end{array} \qquad (2)$$

Where:

- C_{Power} The yearly costs with a power grid tariff [€/year] [T5-T8]
- β_{Power} Fixed part [€/year]
- δ Marginal losses (part of $W_{d,t}$)
- p Energy charge [€/kWh]
- $W_{d,t}$ Energy consumption per hour [kWh/h]
- $\gamma_{d,t}$ / $\alpha_{d,t}$ Factors used to make the variable power part active/inactive (0/1).
- $p^{*}_{d,t}$ Power charge in defined period [€/kWh/h]
- $P_{d,t}$ Power consumption in defined period [kWh/h]

The value of $\gamma_{d,t}$ / $\alpha_{d,t}$ in the alternative tariffs are presented in Table II.

TABLE II. VALUE OF FACTORS MAKING TARIFF PARTS ACTIVE/INACTIVE

Tariff alt.	When the value of $\gamma_{d,t} = 1$	When the value of $\alpha_{d,t} = 1$
T1/T5	During the whole period	0
T2/T6	November – March	April-October
T3/T7	0700-1600 workdays	1600-0700 workdays and weekend/ holidays
T4/T8	0800-1000 in the morning and 1600-1800 in the evening	The rest of the time

When calculating the tariff costs with the energy grid tariffs, the energy consumption for defined periods are summed up. The tariff costs with the power grid tariff are calculated monthly, where the average value of the three maximum hours [kWh/h] within the defined peak periods are used. Using the average of three maximum values per month will reduce the cost consequence from high consumption in one hour, and give the customers the possibility to reduce the average value which is used in the settlement.

IV. THE CONSEQUENCEs OF ALTERNATIVE GRID TARIFFS

This chapter presents the results from the analyses calculating the consequences of alternative grid tariffs, when changing from energy based to capacity based grid tariffs.

Hourly meter data from residential customers and today's energy grid tariff are the basis for the analyses. Due to the revenue cap regulation, new grid tariffs should give the same income to the DSOs. This is a premise for the analyses, and the different cost elements in the tariffs are calculated to give unchanged costs in total for the customers, but there will be individual changes in the yearly costs due to the new tariff structure.

A. Structure of the calculations

The yearly costs for each tariff alternative (T1-T8), for each sub-group of residential customers (C1-C5), within each building type (B1-B2), have been calculated. In total 8 tariff alternatives are calculated for 20 different load profiles.

The reference for the calculations are today's energy tariff (T1), with a fixed part of 227,27 €/year and an energy part of 4,55 Eurocent/kWh [1]. With a total consumption for the whole group of 94,7 GWh, the total grid costs for the customers are 6,59 mill. €[4].

To find the total costs for the whole customer group, the costs for the different tariff alternatives are multiplied with the number of customers in each group (Table III).

TABLE III. NUMBER OF CUSTOMERS IN DIFFERENT GROUPS

Customer sub group	Building type		Sum
	Single family house B1	Apartment B2	
C1	393	76	**469**
C2	1779	425	**2204**
C3	5234	879	**6113**
C4	16	12	**28**
C5	599	642	**1241**
Sum	**8021**	**2034**	**10055**

Further, the different cost elements in the alternative tariffs (T1-T8), have been calculated, and the values are presented in Table IV. With these values the total costs for the whole customer group are unchanged.

TABLE IV. COST ELEMENTS IN THE TARIFF ALTERNATIVES (T1-T8)

Tariff alternative	Cost elements		
	Fixed part [EUR/year]	*Energy part [Eurocent/kWh]*	*Power part [EUR/kW]*
T1	227,27	4,55	-
T2		4,89/4,10	-
T3		4,09/5,72	-
T4		4,09/7,44	-
T5	79,55	2,84	8,06
T6			10,76/5,68
T7			9,17
T8			9,64

The results from the analyses give the main trends in reallocation of costs. 10 customers have been selected based on some initial criteria, and the results depend on the actual consumption of electricity – hour by hour for these specific customers. There might be a risk that the selected customers are not representative, since all customers have a unique consumption pattern of electricity.

[4] An exchange rate of 1 € = 8,80 NOK is used in the calculations.

B. Results

The results from reallocation of costs between customers with different load profiles (C1-C5), but with the same building type (B1-B2), are presented in Fig. 5-6.

Today's costs with an energy tariff is the starting point, represented by 100%. Values lower than 100% represent cost reduction, and values higher than 100% represent an increase in cost. Tariff alternatives are presented on the x-axis.

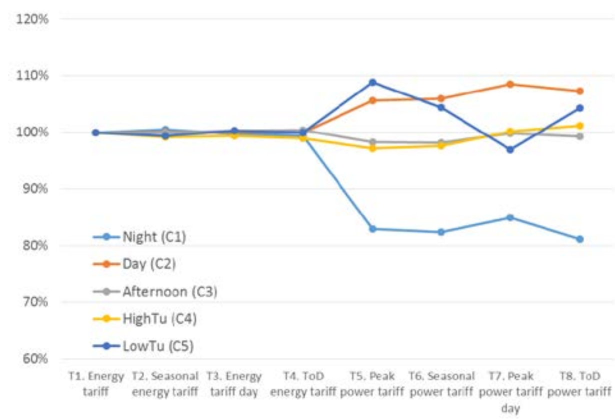

Figure 5. Reallocation of costs for single family house (B1) – related to load profile (C1-C5)

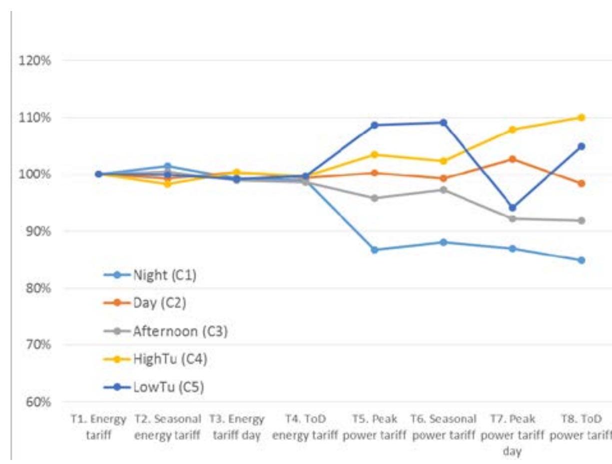

Figure 6. Reallocation of costs for apartment (B2) – related to load profile (C1-C5)

Fig. 5 and 6 show that there are only minor variations related to the energy grid tariffs (T1-T4), confirming that with an energy tariff the customers pay for volume of consumed electricity, and only to a limited degree related to when the electricity is used.

For the power tariffs (T5-T8), the cost variations for the different load profiles increase. The cost reduction is largest for customers with highest load during night (C1), both for single family house and apartment. With this load profile, the main consumption is not within the defined peak load period.

The customer with highest load during day-time (C2) has the highest cost increase for single family house. The apartment get an increase in the cost, but at a lower level. Customers with highest load during the afternoon (C3) get a limited reduction in costs, that varies between B1 and B2.

For the single family houses, the customer with a high utilization time of the grid (C4) get a limited reduction in the costs, but the costs are increased for the apartment customer with the same load profile. Studying the actual consumption volume, the selected customer living in an apartment has a higher consumption than the customer living in a single family house. The changes in the costs can be related to a larger share of the consumption in the peak load periods.

The customer with low utilization time of the grid (C5) has increased costs with the peak power tariff (T5). This confirms the principle that the customers should pay a grid cost reflecting how they affect the grid. However, there is a dip related to the peak power day tariff (T7) – both for B1 and B2. For the tariff T7 the peak load period is from 07:00-16:00, and the peak load periods of tariff T8 are from 08:00-10:00 and 16:00-18:00. The dip in the cost indicates that the customers have a peak load that mainly occurs before or after the peak load period of the day tariff.

The changes in costs for different building types and with different load profiles are presented in Table V.

TABLE V. COST ALLOCATION FOR DIFFERENT BUILDING TYPES (B1-B2) WITH DIFFERENT LOAD PROFILES (C1-C5)

	C1	C2	C3	C4	C5
B1	**Reduced** -	Increased +	Limited reduction 0-	Limited reduction 0-	**Increased** +
B2	**Reduced** -	Limited increase 0+	Limited reduction 0-	Increased +	**Increased** +

V. DISCUSSIONS

This paper presents the results from the analyses calculating the consequences of alternative grid tariffs, when changing from energy based to capacity based tariffs. Using capacity based tariffs the customers will pay according to how they affect the distribution grid.

With the four different energy tariffs (T1-T4), the customers mainly pay according to their volume of electricity consumption, and only to a limited degree related to when the electricity is used. The calculations show small variations related to load profile (C1-C5) with the different energy tariffs – for both the building types (B1-B2).

The calculations for the alternative capacity based tariffs (T5-T8) show a reallocation of costs. The main trends show that the customers with a peak load during the night (C1) get reduced costs for all the tariff alternatives (T5-T8). Customers with low utilization time of the grid (C5) get an increased costs when changing to capacity based tariff, but the increase are dependent on both when the peak load periods occurs and the duration of these periods.

For the customers with peak load in the afternoon (C3), there are some minor reductions with the different power grid tariffs, but the reduction depends on the definition of peak load periods. For customers with load profiles C2 and C4 the calculations show not that clear results.

VI. CONCLUSIONS

This work analyses hourly data from residential customers that are selected according to their building types (B1-B2) and load profiles (C1-C5). The work concludes that when changing to a capacity based tariff, customers with highest load consumption during night (C1) get a cost reduction and customers with a low utilization time of the grid (C5) get an increase in the costs. Minor changes are visible for the other typical load profiles.

Further research are needed to get more detailed information about the typical load and how this affect the tariff costs for the typical customers. When selecting customers within a group, there might be a risk that these customers do not represent the "typical" customer.

Further work should also focus on how to define peak load periods. The duration of peak load periods, and when they occur, have impact on the costs related to the different power grid tariffs (T4-T8). A time component should be included in the power tariff, if the power grid tariff should stimulate to load reduction at a specific time of the day.

VII. ACKNOWLEDGMENT

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