

Utilizing End-user Flexibility for Demand Management under Capacity Subscription Tariffs

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Abstract

The Norwegian regulator has proposed a new grid tariff, based on capacity subscription, where the consumer pays an excess fee whenever he exceeds the subscribed level. We compare this tariff with a variant of capacity subscription where demand is physically limited to the subscribed level, but where the limitation is activated only when there is grid congestion. The results show that this can be an attractive option if demand can be flexibly controlled to stay below the subscribed limit, which is increasingly possible. Use of a battery is also attractive, but the investment costs are still much too high.

Flexibility, Batteries, Dynamic tariffs, Capacity subscription, Demand management

Nomenclature

η^{ch}	Charging efficiency of battery.
η^{dis}	Discharging efficiency of battery.
σ_t^{soc}	Battery state of charge [%].
C_P	Cost of capacity [NOK/kW].
C_{tot}	Total customer cost of electricity [NOK].
$C_t^{grid,buy}$	Grid tariff energy cost.
$C_t^{spot,buy}$	Spot price when buying energy [NOK].
$C_t^{spot,sell}$	Spot price when selling energy [NOK].
$C_t^{tax,buy}$	Energy tax [NOK/kWh].

C_t^{VCL}	Value of cut load [NOK/kWh].
C_{VAT}	Value added tax factor.
O^{min}, O^{max}	Min. and max. battery state of charge [%].
$P_{max}^{ch}, P_{max}^{dis}$	Maximum charge and discharge capacity of battery [kW].
P_{sub}	Subscribed capacity [kW].
p_t^{ch}	Charging power of battery [kW].
p_t^{dis}	Discharging power of battery [kW].
p_t^{grid}	Power supplied by or delivered to the grid [kW].
p_t^{load}	Residence load demand [kW].
p_t^{VCL}	Power subject to a VCL cost [kW].
T	Total number of discrete time intervals.
t	Time index [h].

1 Introduction

The Norwegian electricity demand is trending towards more power intensive use where peak demand is increasing relatively more than annual consumption. This brings challenges to especially the distribution grids, where costly reinforcements may be needed for relatively few peak-load hours. Instead of only building new lines, which is costly and often controversial, a potential alternative is to reduce peak demand, especially because the extreme peaks only occur on average a few hours each year. The Norwegian regulator NVE therefore recently proposed a new grid tariff structure based on "static" capacity subscription (CS) [1]. With this tariff, consumers choose and pay for a level of capacity. Below this level, the energy term in the tariff is low, reflecting the marginal grid losses. Above the subscribed level however, the energy term is quite high (10-20 times), to incentivize consumers to stay below this level. The full roll out of hourly metering by end-2018 makes it possible to analyze consumption and make rational choices for the level of capacity.

However, although this system has its merits, it penalizes consumers' use of capacity also when there is no scarcity of grid capacity. We therefore propose to use "dynamic" CS [2] [3] [4], where the capacity limit is activated only when there is a real scarcity in the grid. The capacity limit is physically enforced, and during activations, the consumer must find ways to keep demand below this limit. A reasonable way to do this, is to use control devices that switch off non-essential demand (e.g. water heater, space heating etc.). Ideally, the consumer might experience little or no loss of comfort.

Another option is to use a battery to shift load from high to low demand hours. In this case, electricity consumption would not change, but would be partly taken from the battery when the capacity limit is activated.

In this paper, we assess the effects of CS based tariffs on a large household in Norway. Based on the regulation of the grid companies, their total revenues should not change with the introduction of the new tariff. Therefore, we calibrate the tariff in such a way that the total grid cost for the consumer does not change. We then analyze the effects on the household for three different cases: i) the static CS tariff, ii) the dynamic CS tariff and iii) as ii), but with a battery.

The next section will explain the two variants of the CS tariff. Subsequently, we will present a model of consumer behavior when the capacity limit is activated. This model can be used to calculate optimal subscription, which is explained for both variants in Section 2. Section 3 explains the model, Section 5 gives the results and finally Section 6 gives the conclusions.

2 Capacity based grid tariffs

2.1 Static capacity tariff

The grid tariff proposed by the regulator has four components: a fixed annual cost (NOK), a capacity cost (NOK/kW), an energy cost (NOK/kWh) and an excess demand charge (NOK/kWh). Note that, in addition to the grid tariff, the consumer pays for electricity and taxes. The annual consumer grid cost is calculated as:

$$C_{tot} = C_{fixed} + C_p \cdot P_{sub} + C_{en} \cdot (W - W_{ex}) + C_{ex} \cdot W_{ex} \quad (1)$$

Where C_x 's are the various cost coefficients explained above, P_{sub} is the subscribed capacity, W the annual consumption and W_{ex} the demand in excess of the subscribed capacity. C_{en} should cover the average losses in the grid, and is typically around 0.05 NOK/kWh. Because C_{ex} is significantly higher, the consumer has an incentive to keep demand below the subscribed capacity, P_{sub} .

2.2 Dynamic capacity tariff

Capacity subscription was proposed in [2] for the power market. In [3], the authors also indicated the possibility to use the same model for the grid tariff structure. An essential feature of CS is that demand is limited to the subscribed capacity when there is scarcity in the system (i.e. not enough generation capacity to serve demand), but only then. In such cases, the DSO (or TSO) activates a Load Limiting Device (LLD), effectively limiting demand. In the case of a grid tariff, a lack of grid capacity would be the trigger for activation. In order to make this acceptable for the consumer, it is necessary to have intelligent load

control that keeps demand below the subscribed limit, by switching off non-essential demand like water boiler, freezer, floor heating etc. Here we use the term "dynamic" CS, to distinguish it from the tariff proposed by the Norwegian regulator. The consumer cost is very similar to equation (1) but there is no excess consumption, because demand is limited instead¹.

It is more challenging to determine the optimal subscription level for dynamic CS, because the consumer cost of being constrained must be taken into account. This cost cannot be observed, like the excess demand cost C_{ex} above. In the next Section, we will describe an approach to estimate this cost; once this is defined, it is again straight forward to calculate the optimal subscription.

2.3 Consumer behaviour

By our knowledge, no empirical data for the cost to consumers for having to physically limit demand exist. We therefore use the same approach as in [4], which uses the "Value of Cut Load" (VCL). The idea is that if the consumer loses all power, then the cost is equal to the Value of Lost Load, VoLL, which is equal to the maximum value of VCL. When the power is 100 % available, no load is cut, and $VCL = 0$. Between these extremes, we assume an exponential function [4]:

$$VCL = \frac{VoLL}{1 - e^{-bP_{load}}} (1 - e^{-b(P_{load} - P_{sub})}) \quad (2)$$

The steepness coefficient b describes how fast VCL approaches VoLL as a function of the cut load. The VCL function is shown in Figure 1.

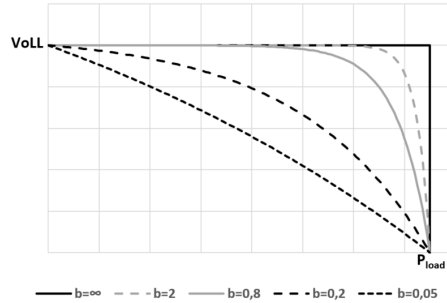


Figure 1: The VCL functions for various values of the steepness coefficient b .

VCL can be viewed as the reduction in consumer surplus caused by the need to limit demand. It is part of the consumer's objective function, but it is not included in the grid company's revenues.

¹It would also be possible to use a "financial" version, which would include payment for excess demand like in the static tariff. The excess cost coefficient would be higher because activation is done only sporadically.

2.4 Activation of the load limiting device

An important aspect of dynamic CS is that the limitation is active only when there is a system scarcity or grid congestion problem. However, this often does not coincide with the times when the consumer exceeds his subscribed capacity. We do not have data for when the grid in our test case is congested, but as a proxy, we use total demand in the region where the household is located. Demand in Norway is very dependent on temperature, and therefore regional demand is a good indicator of grid load. We then assume that the grid is congested a certain share of the time (e.g. 5 %), and use the corresponding highest corresponding regional load hours as the "activation hours". In these hours, the consumer's demand will be limited to the subscribed capacity, but this is an active limitation only if demand exceeds this level. Table 1 illustrates the coincidence between activation and the customer load exceeding the subscribed level for our case study for various relevant numbers of activation hours, depending on the relation between grid capacity and peak demand, cf. Section 4.

Table 1: Overview of coincidence between activation and customer load exceeding subscribed levels.

Annual activations [%]	0.1 %	1 %	2 %	5 %
Annual activations [hours]	9	88	179	438
Demand limitations [hours]	7	39	69	161
Demand limitations	78 %	44 %	39 %	37 %

A low number of activation hours would occur in a strong grid and/or a mild winter, while a higher number is representative for a weaker grid in a cold winter. In our data set, a low number of activations corresponds to a high coincidence, while higher numbers of activations reduces the coincidence.

3 Model

Without a battery it is straight forward to calculate the consumer cost for both tariff variants, using equations (1) and (2). The optimization task is finding the optimal subscription level, which is an easy task in the case of perfect foresight, as we have assumed in this paper². With a battery however, it is necessary to determine the optimal operation of the battery in order to keep demand below the subscribed level and in addition to optimally utilize variations in spot prices.

²In reality, determining the optimal subscription is a stochastic problem, as the temperatures and therefore the number of activations in the coming year are unknown. this is outside the scope of this paper, but an interesting topic for future research.

3.1 Dynamic Programming Model

The objective function aims to reduce the cost of energy bought from the grid. The battery can be used to leverage spot prices in the market and at the same time navigating around consumption peaks that exceed the capacity subscription limit. Thus, the (dis)charging power P_{bat} is decided for every hour to minimize the cost from 1 to T . In our case study the algorithm optimizes for 8760 hours³. The optimization is based on grids of nodes, where different possible energy levels (SOCs) for every time step in T are calculated. The goal is to find the path of SOC that result in the lowest possible price for the given input. The dynamic programming is developed from [5].

3.2 Optimal battery operation

By utilizing dynamic programming, the algorithm calculates the price for every single charge and discharge possibility, when the spot price, grid tariff, load and PV production is known. With C_{tot} being the annual customer cost, the optimization objective function is presented in Eq. (3).

$$\min C_{tot} = \sum_{t \in T} [(C_t^{spot,buy} + C_t^{grid,buy} + C_t^{tax,buy}) C^{VAT} p_t^{buy} + C_t^{VCL} p_t^{VCL} - C_t^{spot,sell} p_t^{sell}] + P_{sub} C_P C_{VAT} \quad (3)$$

$$p_t^{buy} - p_t^{sell} = p_t^{load} + p_t^{ch} - p_t^{dis} \quad (4)$$

$$\sigma_t^{soc} = \sigma_{t-1}^{soc} + p_t^{ch} * \eta^{ch} - \frac{p_t^{dis}}{\eta^{dis}}, t \in T \quad (5)$$

$$O^{min} \leq \sigma_t^{soc} \leq O^{max}, t \in T \quad (6)$$

$$p_t^{ch} \leq P_{max}^{ch}, t \in T \quad (7)$$

$$p_t^{dis} \leq P_{max}^{dis}, t \in T \quad (8)$$

Equation (4) describes the system's power balance, where the net exchange with the grid equals the load plus the battery charging power minus the discharging power. Equation (5) is the battery storage balance equation, depending on the charging and discharging power, modified with their respective efficiencies. Equation (6) limits the SOC between its min and max values, while (7) and (8) limit the charging and discharging power.

³The battery can fully charge and discharge in 2 hours. Hence, decisions are made based on information for the next 2 hours, although the simulation is run for the whole year when executed.

4 Case Studies

Three case studies are performed. In the first case study, we investigate a static capacity subscription tariff where the customer pays the excess demand charge when he exceeds the capacity limit. In the second case study, a dynamic capacity subscription tariff is used, where the customer is restricted to the capacity limit whenever there is scarcity in the grid, thus resulting in activation certain hours during the year, cf Section 2. The third case study also uses the dynamic tariff variant, but a battery is used to deliver power during hours where demand surpasses the capacity limit. In other words, the capacity limit constraint is satisfied, as the excess power is taken from the battery. In this case, the consumer use of electricity is not affected by the limit. The hour-to-hour battery operation is optimized utilizing the dynamic programming optimization method, which also results in some cost reductions from arbitrage between high and low prices, cf Table 3. Grid tariff cost coefficients are shown in Table 2.

Table 2: Grid tariff cost coefficients.

Cost element	Cost
Cost of capacity [NOK/kW/month]	90
Fixed cost [NOK/month]	-
Grid energy cost [NOK/kWh]	0.05
Grid excess energy cost [NOK/kWh] (static only)	1.00
Energy tax [NOK/kWh]	0.124
Green certificate fee [NOK/kWh]	0.0369
Retailer margin [NOK/kWh]	0.025
VAT [%]	25

All case studies are performed on a large residence with electrical heating, located in Trondheim, Norway, with a cold climate. Annual consumption is 43 000 kWhs, corresponding to an average demand of 4.94 kWh/h. The maximum power was 15.0 kWh/h. Simulations are done with spot prices from the Nord-pool market for 2015 as shown in Fig. 3⁴. The load duration curve is shown in Fig. 2. Especially note the very short duration of demand above 10 kW.

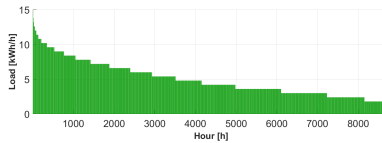


Figure 2: Residence load duration curve.

⁴The average price in 2015 was 0.19 NOK/kWh, with a variance of 0.0047. This the lowest average price since 2005, and is about 60 % of the price in 2016.

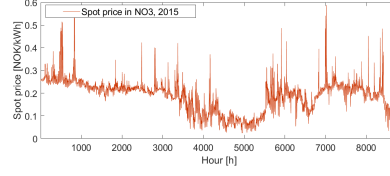


Figure 3: Overview of spot prices 2015.

5 Results

5.1 Static capacity subscription tariff

Fig. 4 shows the annual grid tariff costs under different subscription levels. The optimal subscription level in the static capacity subscription tariff case study is 7.5 kW, where the grid costs are 11 977 NOK. When exceeding the 9 kW subscription level, excess demand cost is negligible, which is due to the small amount of energy consumed above this level, cf Fig. 2. On the other hand, excess demand cost increases steeply when subscribing to less than 7 kW.

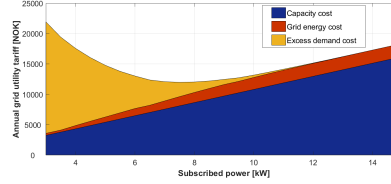


Figure 4: Annual customer grid cost under different subscription levels, static tariff.

The optimum is quite flat, implicating that any subscription between 7.0 - 9.0 kW leads to close to equal costs, showing that the grid tariff structure decided by the Norwegian regulator NVE is somewhat robust for the choice of subscription level. For lower subscription levels cost increases sharply. Instead of buying more capacity, consumers could procure a smart control home system which automatically switches off or reschedules flexible loads after a pre-described priority list. The profitability of this depends on the investment costs and ease of installation.

5.2 Dynamic capacity subscription tariff

With the introduction of dynamic capacity subscription tariffs, the annual customer grid cost looks similar. When choosing a capacity limit there is a tradeoff between the cost of capacity and the inconvenience cost, represented by the cost of cut load (CCL). Fig. 5 shows how the cost of cut load changes depending on

amount of activated hours.

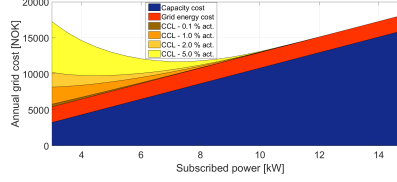


Figure 5: Annual customer grid cost under different activation limits, dynamic tariff.

The figure shows that the optimum subscribed capacity depends strongly on the amount of activations. In the case of 5 %, the optimum is 7.5 kW. Here, the grid costs are 10 250 NOK⁵. In addition, it can be observed that it makes little sense to subscribe to more than 9 kW, as the cost of cut load is very small above this limit due to the relatively low number of hours where activation coincides with excess demand. If a subscription at the average consumption of roughly 5 kW or less is chosen, it can be seen that the cost of cut load depends greatly on the amount of activated hours. Should there be only 0.1 % activated hours, the cost of cut load is small. However, with 5 % activated hours, the cost of cut load becomes more than 5000 NOK with a 5 kW subscription. In reality, this means fairly large limitations to heating capacity during cold days where activation could last several hours. The choice of subscription level should thus not be based on only one reference year (as we have done here).

A potential problem with this grid tariff structure is the consequence of speculation among customers. As Fig. 5 shows, the optimal subscribed capacity is 1 kW, given that there is < 1.0 % activated hours during the year (88 hours). Thus, customers could gamble for a mild winter and hope for a low amount of activated hours in order to reduce costs. In case of a cold winter, this could be a problem for the customer if his residence cannot be heated for several days of cold weather. A potential solution to this could be to set a minimum subscribed limit for household consumers, related to their average consumption.

5.3 Dynamic capacity subscription tariff with battery

With the introduction of a battery, power can be provided during activated hours in order to avoid load limitation of actual consumption. In essence, the customer's load which exceeds subscription limit during activation hours should be covered by the battery. Depending on the amount of activations and activation durations, the subscribed capacity could potentially be reduced. Table 3

⁵Note that this does not include the cost of cut load, i.e. the customer inconvenience of demand being limited in the activation hours.

shows the **minimum** battery size⁶ that is required in order to avoid any load curtailment given different subscription limits.

Table 3: Required battery sizes for different subscription levels.

Subscribed power [kW]	5	6	7	7.5	8	9
Required battery size [kWh]	60	48	36	30	24	12
CCL saved, 1 % act. [NOK]	1314	851	506	371	258	104
CCL saved, 5 % act. [NOK]	5451	3445	1989	1 444	1005	416
Energy cost reduced [NOK]	354	329	259	217	171	65

The last row shows the savings in energy costs obtained by using the battery for arbitrage between high and low energy prices. In addition, it is observed that the battery size required to reduce the subscribed capacity by 1 kW in the interval of 5-9 kW is 12 kWh. It turns out that in this particular case, one very cold day with many hours of activation necessitates a rather large battery, also for the lowest level of activation. Hence, activation level does not affect the minimum battery size needed to cover excess load. The table also shows that the annual energy costs that the battery saves are low, which makes a weak economic case for the secondary use of the battery, which is arbitrage between fluctuating prices. This is caused by the general low price level and relatively small price variations in 2015, cf. Fig. 3.

An interesting approach which is not studied in detail, is a solution where an EV is connected, being able to provide power during activation hours if necessary. The EV battery would in essence have the functionality of a home battery with limited availability. As EV batteries have high capacity from the nature of their primary objective, most peaks could be covered by the battery. Still, a necessary assumption is that the EV battery is available when load exceeds subscribed capacity (during activation). This could be true in many cases where residents mostly travel by car, hence resulting in high demand only when the EV battery is at disposal. In homes where residents are home although the car is not available, this is a less interesting solution.

5.4 Comparison of case studies

To compare the case studies, Table 4 shows the costs. Given 5 % activation, 7.5 kW was the optimal subscribed capacity in the dynamic tariff case study. This is the same result as in the static tariff. The table hence shows the annual customer costs for the three case studies given 7.5 kW subscribed capacity.

We see that grid costs are about 15 % lower for the dynamic tariff cases. When the grid energy and the excess grid energy costs are added in the static tariff case, they make up significantly more than the grid energy costs in the

⁶The chosen P/E factor is 1, which means that the relation between power and energy in the battery is 1. I.e. a 20 kWh battery can deliver a maximum power of 20 kW.

Table 4: Price comparison for optimal subscribed capacity (7.5 kW) for all case studies.

Case Study	Static	Dynamic	Dynamic with battery
Grid costs	11 977	10 250	10 290
Capacity cost	8 100	8 100	8 100
Grid energy cost	1 514	2 150	2 190
Grid excess energy cost	2 363	-	-
Energy cost	11 830	11 721	11 504
Energy tax	5 370	5 331	5 432
VAT	7 347	6 825	6 806
Total	36 524	34 127	34 032
Cut load	-	1 444	-
Total incl. cut load	36 524	35 571	34 032

dynamic tariff cases. The energy costs are slightly lower for the dynamic cases, due to either load limitation or due to battery arbitrage. The energy tax is lower in the dynamic tariff case due to load limitation, but higher in the battery case as the residence might buy more energy from the grid and sell it later, where energy tax is not "refunded".

From the table it is observed that the energy costs drop very little ($<2\%$) when a battery is added, whereas 1444 NOK of CCL is saved. Although the battery avoids the inconvenience of load limitation, the economic value of this is small compared to its investment cost of approx. 5000 NOK/kWh⁷ in this case study. A battery is therefore not an economically viable choice before battery costs are significantly lower than today.

Altogether, the dynamic battery case is the cheapest when the battery costs are not considered.

6 Conclusion

In this paper we analyze a newly proposed subscription based grid tariff in Norway, and compare it with a dynamic capacity subscription tariff. In the proposed tariff, the consumer pays a high excess fee for demand exceeding the subscribed limit, while in the dynamic variant, demand is physically limited to the subscribed capacity. However, this limit is only activated when there is actual grid congestion. This tariff is analyzed in two settings. In the first setting, the consumer is assumed somehow to stay below the subscribed limit. The inconvenience this causes is modeled by a "cost of cut load". In the second setting, a battery is used to stay below the limit.

⁷The Norwegian market for home batteries is new, and hence has few choices which are priced fairly high.

Without considering the investment cost of the battery, the lowest cost is obtained for the battery alternative. However, when the investment cost is included, this alternative is very expensive. If an EV battery could be used, however, this could be an attractive option, but it would require that the EV is there whenever the load limitation is activated.

Even without a battery, the dynamic variant is attractive for the consumer if a flexible solution is installed to keep demand below the subscribed limit, which becomes an increasingly relevant option. The upside for the consumer is that demand is constrained only relatively few hours each year, while the excess fee in the static variant is paid all year.

Further research could focus on optimal subscription under uncertainty and analyze larger groups of consumers instead of only one as in the present study.

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