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Load shift incentives for household demand response: A model to evaluate effects from a Danish field experiment

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ABSTRACT

We use a long-term electricity market equilibrium model to assess the impact of variable price products for household electricity customers. The analysed product structures resemble a rebate provided to customers within a field experiment in Southern Denmark. The developed model provides a clearer picture of what to expect from household demand response under spot pricing schemes as compared and simplified product schemes; it also prepares for interpreting the field experiment results. Using preliminary assumptions we estimate both short-term and long-term welfare effects of a shift of customers to an ideal spot pricing scheme and to the simplified rebate product.

KEYWORDS

Dynamic electricity prices, demand response, household consumers, partial equilibrium model, field study.

INTRODUCTION

Background

Danish energy policy aims at a fossil-free electricity supply in 2035 as a stepping stone towards a fossil-free energy system in 2050 [1]. It is widely agreed that wind energy is going to play a major role in this future energy system. In 2020 electricity generation from wind energy should make up 50% of annual consumption [2]. The share was at 39.1% already by 2013 [3].

Large-scale development of intermittent electricity production from renewable sources also requires sufficient flexible capacity to maintain a stable system. With increasing volumes of wind energy new options beyond the traditional flexibility of power producers are required. To address the evolving flexibility challenge the Danish electricity system operator, amongst several other initiatives, aims at a better utilisation of demand-side flexibility [4]. In support of such a development Danish government in 2013 issued a smart grid strategy for the time until 2020 [5].

Although the demand side is just one flexibility option amongst others [6], response from both traditional and new loads (e.g. heat pumps and electric vehicles) will play an increasingly important role in the time to come. Some congestion can only be reliably solved by direct and automatic control of loads, while manual response at times may relieve some of the pressure as well [7]. Household consumers could contribute with both: their new loads for

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heating and transport that can be actively managed, and manual response with a share of their conventional demand.

If demand response is to become significant at household level, we need to know, though, how to make customers adopt flexible technologies and behaviour, and evaluate the costs and benefits this may bring. A large-scale field study has been initialised in Southern Denmark to investigate these questions. The study utilises load-shift incentives based on a rebate product. A unique feature of the ongoing study is, furthermore, that the product structures are analysed with non-monetary incentives as well. Response and benefits depend on the design of the incentives (i.e. tariff structures, environmental benefits as well as other non-monetary incentives), and until the field experiment is finished the actual response from customers is unknown. In this paper we prepare a model framework and test it on preliminary assumptions.

To prepare for interpreting the results and to get a clearer picture of what to expect from household demand response, it is necessary to translate responses to the given incentives into benefits. One of the drivers that need to be examined – although certainly not the only one – is the economic incentive. We use a simple long-term electricity market equilibrium model for that purpose, and we compare situations with and without the new incentive structures. On the way to understanding the effects of demand response on the system and on individual households, a plain economic cost-benefit analysis – as presented here – is an important first step. Eventually, harvesting any economic benefits also relies on removing various barriers within the regulatory framework [8].

Previous research

Cost-benefit analysis of demand response have been conducted in various studies and within different market and regulatory contexts (for an overview see Conchado and Linares [9]). Research in this field takes different directions: While some explain the effects based on economic theory, others take more of a technical approach and optimise demand response actions under a given set of prices and, mostly technical, constraints. As we intend to assess long-term economic impacts it is useful to distinguish previously applied approaches according to the way they model market impacts of demand response. In the following we describe three levels of market impact.

The first level is a price-taker approach: under a given set of prices, find the optimal response, based on either price-elasticities or subject to a set of constraints on timing, volume etc., assuming the response has no impact on prices. The second level, acknowledges the price impact of the optimal response. It can be referred to as the short-run equilibrium approach: find the optimal response given a particular market structure, where structure first of all refers to marginal costs of supply and marginal benefits of demand. At the second level, supply capacities are static, and only their marginal costs are taken into account. The third level integrates fixed costs as well and may be referred to as the long-term equilibrium approach: given the optimal response in short-term equilibrium, find the optimal level of capacity. The equilibrium in both of the last two approaches typically is only partial, i.e. related to the electricity market only.

The price-taker approach is used in a number of demand response analyses [10–16]. It is sometimes based on historical prices or uses models calibrated with historical prices. When focus is on a single project or individual actors' benefits this approach is particularly useful. It may still be useful to analyse system-wide developments or larger groups of actors; in such a

case the validity of the results should be critically evaluated as analysed behaviour may affect price levels.

A short-term equilibrium approach provides a bit more insight into the market dynamics of demand response. Focus typically lies on social welfare impacts. An intuitive outcome often confirmed in such models is the observation of reduced price spikes, and potentially lower prices in general, caused by a more efficient integration of the demand side. Short-term focussed analyses have been carried out, for instance, with a focus on real-time or day-ahead pricing [10,17–20] as well as other incentive-based response schemes [21].

To fully evaluate the impact of policies or regulatory decisions long-term effects should be taken into account. For that reason the short-term approach can be accompanied by an analysis of the long-term equilibrium [22–24]. One could argue that this is the soundest approach from a welfare-economic point of view. One particular formal framework by Borenstein and Holland [25] has been applied several times in different variations, showing how real-time pricing and resulting response of elastic demand generates significant benefits even with limited elasticities. For example, this has been shown for US electricity markets [22,23] and Norway [24]. Similar approaches have also been used to evaluate the impact of wind power on system equilibrium, both with and without demand response [26,27].

A long-term approach results in the construction of an electricity system with optimal generation capacities. Usually this neglects capacity that is already present in a market, assuming that one would divest from overcapacity. As long as the state of the system is not taken into account, the long-term equilibrium found remains somewhat theoretical. Energy system models take a step further. They often require a high level of detail in representing the energy system with existing capacities and cost projections. While they take into account the current market structure, they often have extensive computation requirements. Analyses have, for example, been carried out with a focus on demand response from residential appliances [28], heat pumps [29,30] and electric vehicles [31–33].

In a Danish context, studies on household demand response have mostly been published by authorities, the transmission system operator and business organisations [34–37]. While some of the studies apply an equilibrium approach, long-term effects on capacity are often neglected. In particular manual residential response is mostly modelled as a price-taker.

Research interest

Although the literature is quite extensive on the topic of demand response in electricity, a couple of issues have not yet been fully addressed. We explore the problem of the long-term welfare effect of household demand response in Denmark (a system with large shares of wind power) comparing spot pricing and simplified variable rebate products.

Only few scientific works have been published on impacts in Denmark, although the interplay with the development of wind power is particularly interesting. In a wind-based system the results are expected to be even more distinct and in favour of demand response. Although the wind production may reduce the net need for peak power it has a severe impact on the required capacity mix. As mentioned above, some studies in the Danish context apply a price-taker approach and thus neglect the dynamic effect of residential demand response on long-term market equilibrium.

All of the Danish studies above, as well as many of the international ones, evaluate demand response at retail level using standard day-ahead spot pricing of electricity. While this may be the efficient, and a realistic option, we think that one has to take into account the restrictions of individual consumers in reacting to hourly prices manually. Complexity of contracts may also inhibit adoption [7]. Therefore, we analyse not only the impact of hourly spot pricing schemes, but also investigate the effect of simpler products that are more likely to be adopted by household customers, because the customers are better able to oversee the implications of the products.

The products analysed reflect structures applied in a field experiment amongst Danish electricity consumers. We aim at combining the model with actual results from the experiment at a later stage. The products are similar, but not identical, to critical peak pricing products analysed in a US context [38].

The field experiment also investigates non-monetary incentives, as for some customer segments they potentially represent a more relevant value [39]. If such types of incentives can be translated into elasticities, then the developed model may serve as a basis to evaluate the benefits of such approaches as well. At this stage, however, this is not yet possible.

METHOD

The welfare effect of demand response

In electricity, as in any other market, households consume as long as their marginal benefit exceeds the market price. Yet, to avoid costly real-time metering electricity customers are mostly exposed to flat rates reflecting merely the average price level [40]. As a result observed electricity demand is mostly inflexible in the short term, i.e. inelastic and not responsive to hourly prices.

Actual price elasticity of household electricity consumption may still be different from zero. As has been shown in several studies (see Faruqui and Sergici [41] for an overview), customers show some extent of elasticity also towards short-term changes in electricity prices. But even though demand *is* elastic, as long as the household rate does not change, demand stays the same too. Only if exposed to varying prices one would see varying demand.

On wholesale level electricity prices vary with the marginal costs of the operating production plants. If producers reveal their true costs the price outcome minimises total costs. In an efficient market the demand side should be exposed to these prices and the market would clear where marginal costs equal marginal benefits of the customers as defined by the aggregate demand curve.

A market with flat average retail pricing fails to reach efficient wholesale prices that correspond to actual marginal benefits [42]. Given their elasticity, customers that see only an average retail price consume too much during high wholesale price periods and too little during low wholesale price periods. The production, and thus supply costs, would either be higher than the actual consumer benefit, or production capacity is left idle although a higher benefit could be achieved by producing more. If exposed to the actual market price, demand would adjust and ensure the optimal quantity to be produced. Moving from customers on a flat rate and not reacting, to customers exposed to actual wholesale prices and becoming able to react, will therefore result in a positive welfare effect.

The relevant measure for a change in welfare is the net-change in consumer and producer surplus [43]. In order to estimate these we construct an hourly model of supply and demand and compare the outcomes of different retail price regimes.

The long-term impact of demand response on capacity

The above description of the welfare effect of demand response addresses only the short-run effect of response, that is, what happens given a certain structure of supply. Optimality is thus found only considering marginal costs of production.

In the long run, however, it is possible for producers to adjust their capacities. New entrants may join the market, or capacity may be shut down. This process continues until capacity reaches a new long-term equilibrium. In this situation, adding additional capacity would result in overall losses, while reducing capacity would result in profits attracting new entrants and a capacity increase.

Optimal electricity market production capacities can be determined considering their fixed and variable costs. Constructing so called screening curves is one concept of determining the optimal amounts based on a fixed load duration curve [40]. Having flexible demand complicates the process a bit, as every addition of capacity may alter the short-term equilibrium and thus the resulting prices that form the basis for long-term revenues.

Intuitively, the impact of demand response with real-time pricing will be to reduce the use of expensive peak capacity. This makes it overall less costly to supply customers. Also one gets a higher utilisation of low-marginal cost plants, which generates a higher contribution to their fixed costs. This situation, however, cannot go on for long, as peak generators would not be able to cover their fixed costs, while other generators might generate profits. Some peak generators would have to leave the market. While other generators may as well join, the structure of supply would still change and result in market prices at new levels. In particular, the intuitive results of reduced peak prices will be affected due to the adjustment in capacity.

A further complication in the Danish system is the development of wind power capacity and its impact on the revenues of all other generators. The initial tendency of an introduction of wind production at practically zero marginal cost is to reduce the frequency and level of price peaks, thus lowering overall prices. An impact often referred to as the merit-order effect [44]. However, capacity that is not able to cover fixed costs at such reduced price levels will have to leave the market resulting in a backlash of prices until a new long-term equilibrium is reached.

One might assume that if both wind and demand response affect peak prices in the short term similarly, then the effect on long-run capacity would be similar as well, and thus lead to an amplification of the effects. Demand response, however, is flexible as opposed to wind production. Therefore some of the backlash effect can be expected to be compensated by responsive demand, and may be another argument in favour of demand response in a wind based system.

Modelling approach

The described theoretical framework is implemented in a closed market model, i.e. without interconnections to other systems. At first the model generates a short-term equilibrium based on a given set of production capacities and demand. The short-term equilibrium condition to be fulfilled is that marginal cost equals marginal benefit in each of the simulated hours such

that volume supplied equals the volume asked for at the market clearing price. To find the equilibrium we need a model of demand and supply curves. These are marginal cost and benefit functions based on the characteristics of supply and demand.

On the demand side the determining factor is the price elasticity of demand. It may be defined in several ways depending on the underlying model of individual utility [45]. Moreover one has to distinguish between elasticity of demand due to price changes of the good itself (own-price elasticity) and of other goods (cross-price elasticity). Here we focus on own-price elasticity.

A traditional good has a decreasing marginal utility to consumers, that is, an additional unit consumed will provide less benefit to the consumer as compared to the previous unit. The absolute effect of a price change will therefore be different depending on the price level previous to the change; i.e. the demand curve is not linear. We use constant elasticities defined as the percentage change of quantity Q given a percentage change of the price P to take this into account [46]:

$$\varepsilon = \frac{dQ}{dP} \frac{P}{Q} \quad (1)$$

Our focus lies on the short-term elasticity of electricity demand, which is expressed in adjustments along a demand curve that is static within the time horizon analysed. Sometimes this is referred to as the real-time price elasticity [47]. We do not consider structural changes in electricity demand changes that may occur if the long-term price level encourages new investments in appliances producing a permanent change of the short-term demand curve.

Our constant-elasticity demand curves have the form:

$$D_t = D_{0,t} \left(\frac{P_t}{P_0} \right)^\varepsilon \quad (2)$$

With

- D_t : Demand in hour t
- $D_{0,t}$: Base line demand in hour t
- P_t : Price in hour t
- P_0 : Anchor price
- ε : Price elasticity

The marginal benefit function is derived from the demand function that incorporates both the demand from customers on a flat-rate tariff and customers on a variable tariff such that:

$$D_t = D_{0,t} \left(\alpha \left(\frac{P_t}{P_0} \right)^\varepsilon + (1 - \alpha) \left(\frac{P_f}{P_0} \right)^\varepsilon \right) \quad (3)$$

With additional parameters:

- α : Share of customers on variable prices
- P_f : Flat-rate price

Rearranging for the price P_t to find the inverse demand function [48], provides us with the aggregate marginal benefit function:

$$MB = P_0 \left(\frac{1}{\alpha} \left(\frac{D_t}{D_{0,t}} - (1 - \alpha) \left(\frac{P_f}{P_0} \right)^\varepsilon \right) \right)^{\frac{1}{\varepsilon}} \quad (4)$$

Ensuring that $D_t > D_{0,t}(1 - \alpha) \left(\frac{P_f}{P_0} \right)^\varepsilon$, i.e. total demand can never be less than the demand of flat-rate customers.

If a share of customers is exposed to spot prices total demand follows this curve. For increased elasticity ε and increased share of customers on variable prices α market demand becomes more elastic. Figure 1 illustrates the shape of the demand curves at different adoption levels of variable prices. While P_0 is a fixed anchor price, D_0 changes on an hourly basis. P_0 should be set such that it reflects the efficient level of the flat-rate tariff in the reference case. In this case the model yields the load curve $D_{0,t}$ with a 100% share of flat-rate customers.

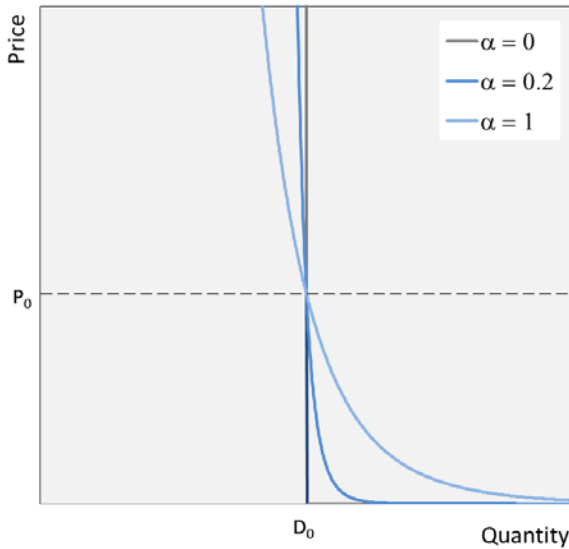


Figure 1: Aggregate demand curve for different shares of variable price customers

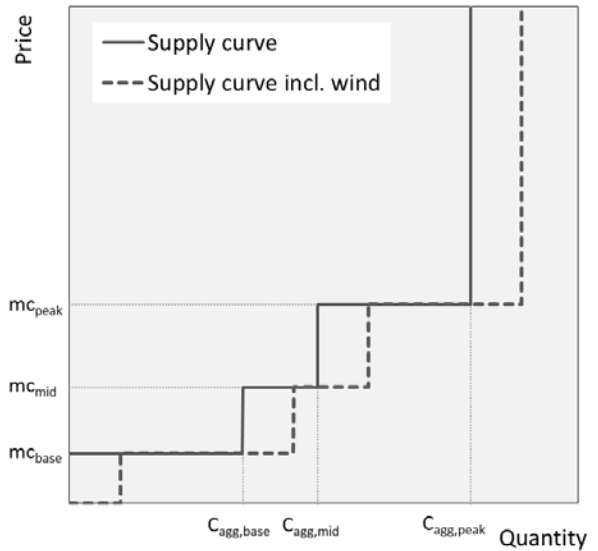


Figure 2: Stylised supply curves with and without wind production

To model generation we use a step-wise supply curve. Supply is based on three generic technologies: base load, mid-merit, and peak load capacity. The short-term marginal cost function is a piecewise linear function such that:

$$MC = \begin{cases} mc_{base}, & \text{for } Q < C_{agg,base} \\ k(Q - C_{agg,base}) + mc_{base}, & \text{for } C_{agg,base} \leq Q < C_{agg,base} + \frac{mc_{mid} - mc_{base}}{k} \\ mc_{mid}, & \text{for } C_{agg,base} + \frac{mc_{mid} - mc_{base}}{k} \leq Q < C_{agg,mid} \\ k(Q - C_{agg,mid}) + mc_{mid}, & \text{for } C_{agg,mid} \leq Q < C_{agg,mid} + \frac{mc_{peak} - mc_{mid}}{k} \\ mc_{peak}, & \text{for } C_{agg,mid} + \frac{mc_{peak} - mc_{mid}}{k} \leq Q < C_{agg,peak} \\ k(Q - C_{agg,peak}) + mc_{peak}, & \text{for } Q \geq C_{agg,peak} \end{cases} \quad (5)$$

With

Q : Quantity supplied
 $C_{agg,base/mid/peak}$: Aggregated installed capacity
 $mC_{base/mid/peak}$: Marginal costs
 k : Slope at steps

A computational difficulty occurs at the shift of one technology to the next, as well as when demand exceeds supply capacity. In theory the factor k , representing the slope between steps, has an infinite value. In order to be able to determine equilibrium prices at any point, and to ensure that the market clears in every case, we avoid fully vertical curves by applying steep slopes. Practically, the slopes are vertical; they enable us, however, to determine finite price spikes without having to set a price cap. We can interpret the minor additional capacity as emergency generation that may be utilised during short periods of time [40].

Calculating a short-term equilibrium applying the above supply and demand curves results in a set of hourly prices that, in combination with their respective cost structures, determines producers' revenues. On the other hand, these prices are the basis for the retail rate customers are charged.

To establish a long-run equilibrium producers leave and enter the market until all profits go to zero. This includes profits to retailers. Consumers will therefore pay a price that exactly covers whole-sale procurement costs of their suppliers.

As a benchmark we first establish an equilibrium without customer response; that is, all customers are on a constant flat-rate tariff with no incentive to change their behaviour. By switching shares of customers to variable prices, demand in all of the hours changes according to the price elasticity of demand.

A change in consumption affects producer revenues. In order to fulfil the equilibrium condition of zero profits will therefore require to adjust capacities until we reach a new long-term equilibrium state.

Following this procedure makes it possible to assess the impact of the customers' response reacting upon a constant price elasticity. This will not exactly resemble the real world, but it provides us with an initial estimation of the economic demand response potential by deriving the relative supply costs and welfare estimates at different long-term equilibria (i.e. with and without the variable pricing scheme).

Simplified retail products

In order to better reflect the expected impact from household demand response we adjust the price structures that customers are exposed to. As stated above simplified product structures might be more realistic to be adopted by households. Furthermore, even though a customer may adopt and be exposed to hourly prices, other restrictions may prevent an optimal response pattern.

The product used in this step reflects a structure used in a field experiment conducted at the time of writing. The experiment applies a premium paid for shifted volumes (i.e. a rebate).

The complication with a time-shift rebate relates to that we want to reward only volumes shifted – payments for all other volumes stay the same.

To settle such a product we need to establish a baseline that we can measure the shift against. In principle using cross-price elasticities would be an option to model the demand in one time period dependent on the demand in another and vice versa. However, we can simplify the problem by concentrating on one of the time periods only, and use the ordinary own-price elasticity in combination with the marginal value. We can as well use the own-price elasticity in the other period to adjust demand in the opposite direction. In practice this is a useful approach, because we are most interested in one of the periods – typically the peak – when there is a risk of insufficient supply.

Modelling the appropriate price level is another issue. As the program is defined as a rebate for every unit shifted (either upwards or downwards), this needs to be reflected in the price. We must assume that the price otherwise is the flat rate. We also assume a fixed rebate as a percentage of the flat rate.

The aim of the price structure in our case is to be able to dynamically react upon system conditions. Therefore the rebate will depend on the difference between the average price and the price during a predefined critical period. Now if spot prices show a sufficiently large price difference between the critical program period and the remainder of the day, then the rebate gets triggered. That means, during the rebate period the customer has to pay the flat rate for the full volume consumed minus the rebate times the difference between his consumption and the baseline.

The relevant marginal benefit for the customers depends on whether they are provided with an incentive to increase or to reduce consumption. If spot prices during the rebate period are higher than average, customers should reduce their consumption and the relevant marginal price will be the flat rate plus the rebate. In the opposite case the relevant marginal price is the flat rate minus the rebate.

Assumptions

We apply the model using preliminary inputs to derive illustrative results. As a starting point we use historic demand profiles and wind profiles. These determine base case prices and costs.

We use fixed and variable costs for three stylised thermal generation technologies as shown in Table 1. As the baseline demand we use the aggregate 2012 consumption of all Danish customers not settled on an hourly basis [49]; that is, customers with an annual consumption of less than 100 MWh. The price elasticity of demand is a crucial input. We use -0.1 as a starting point in line with previous publications [9,47,50].

Table 1: Input costs of stylised generation technologies

		<i>Base load</i>	<i>Mid merit</i>	<i>Peak load</i>
Annual fixed cost	EUR/MW	150,000	75,000	50,000
Variable cost	EUR/MWh	15	35	60

The parameters of the rebate pricing scheme are defined to reflect values used in the field experiment. During the experiment customers will only be asked to shift volumes relative to a

time window of three hours. Shifted volumes generate a rebate of 50% of the retail price. A signal to customers is triggered whenever the price level within the defined time window differs from the daily average price with more than 10%. This threshold is built in to ensure that the response generates sufficient value at wholesale level. While the rebate is fixed, the wholesale price differences vary every day; so this is a parameter that needs to be optimised by the retailer eventually.

RESULTS

With our approach we calculate both the short-term and the long-term equilibrium. This provides us with the possibility of comparing both these effects of demand response.

We first look at a spot pricing scheme for retail customers. In the modelled market setting this is the ideal pricing option and thus yields the most favourable results. The effect of two different levels of adoption of such a scheme is shown in Figure 3. For most of the year demand increases, while it decreases only during a shorter peak period.

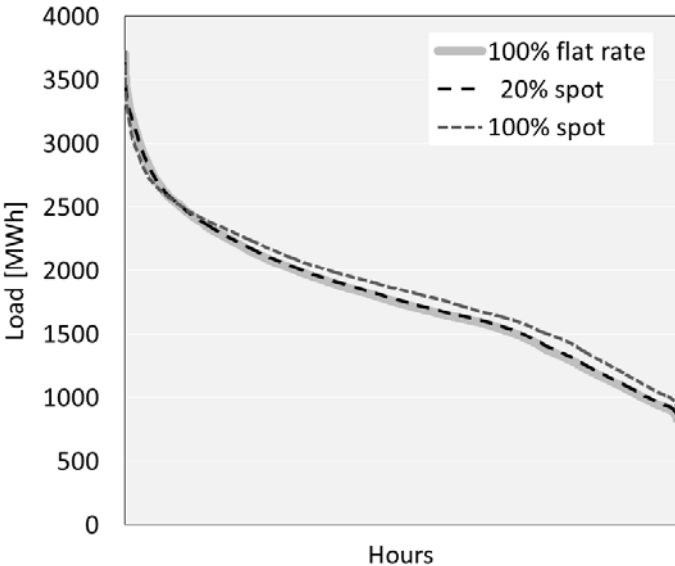


Figure 3: Long-term equilibrium load duration curves

The welfare effect of the analysed incentives is determined by the change in consumer and producer surpluses. With traditional price elasticities of demand, the demand curve is not linear and it is therefore not possible to determine an absolute value for the consumer benefit. What we can measure, however, is the change in consumer surplus from an option with all costumers on fixed prices to the new option with variable prices.

As shown by Borenstein and Holland [25] the change in welfare caused by a switch of customers to variable prices depends on the change in consumer surplus while generator and retailer profits stay the same. The producer surplus is defined by the difference between costs and revenues. In long-term equilibrium revenues exactly cover fixed costs and the surplus is at zero. Due to retail market competition retailer profits will be driven down to zero as well.

To derive the welfare effect we can therefore use the following expression per time step t :

$$\Delta W_t = \alpha D_{0,t} \frac{P_0 - P_t \left(\frac{P_t}{P_0}\right)^\varepsilon}{\varepsilon + 1} + (\alpha - 1) D_{0,t} \frac{P_0 - P_f \left(\frac{P_f}{P_0}\right)^\varepsilon}{\varepsilon + 1} \quad (6)$$

Although not a welfare indicator, the direct cost impact on consumers is an immediate concern of policy makers and it is therefore relevant to extract from the results. It is not just relevant here to look at the responsive customers, but also to include the conservative customers in the analysis of effects.

It is particularly relevant here to distinguish between short-term and long-term effects. In the short-term customers will be able to significantly reduce their bill by reducing their peak consumption and potentially shifting it to lower-priced hours. Table 2 shows clearly how the customers may immediately gain from responding to variable prices. It is not even required for all customers to switch in order to find substantial gains of around 25% on both costs and consumer surplus. A small change in demand at peak times will have a large price effect and this should also result in much lower prices for passive flat-rate customers.

Table 2: Short-term effects of spot pricing

	<i>Costs</i>		<i>Average retail price</i>		<i>Change in welfare</i>	
	Total	Flat	Variable	Total	Absolute	Relative to original costs
	EUR	EUR/MWh	EUR/MWh	EUR/MWh	EUR	%
100% flat pricing	635,202,914	40.38	NA	40.38	0	0.00%
20% spot pricing	491,350,478	30.45	29.57	30.27	159,836,039	25.16%
100% spot pricing	483,604,857	NA	29.4	29.4	168,442,285	26.52%

The reduction in peak prices has an impact on the revenue of peak suppliers. They will not earn a sufficient return to pay for the fixed costs. Thus one must expect capacity to be reduced, which in turn increases prices. These adjustment processes have to be taken into account in the longer run as they significantly reduce expected gains.

The effect of capacity adjustments in the long run are striking. As can be seen in Table 3 supply costs to customers in a long run equilibrium with all customers reacting to spot prices, at the given elasticity, results in a change in consumer surplus of about 7.55% – significantly lower than what could be expected if only looking at the new short term equilibrium.

Table 3: Long-term effects of spot pricing

	<i>Costs</i>		<i>Average retail price</i>		<i>Change in welfare</i>	
	Total	Flat	Variable	Total	Absolute	Relative to original costs
	EUR	EUR/MWh	EUR/MWh	EUR/MWh	EUR	%
100% flat pricing	635,202,914	40.38	NA	40.38	0	0.00%
20% spot pricing	623,626,381	40.46	34.73	39.27	12,862,814	2.02%
100% spot pricing	592,035,616	NA	36.05	36.05	47,963,665	7.55%

A central result of previous analyses is that a switch of customers to real-time pricing makes all customers better off. It has been formally shown how the flat rate to remaining retail customers decreases to prevent retailer profits in the long-run equilibrium [25]. The intuitive explanation of this result is that the efficient retail rate is equal to the volume-weighted

average wholesale prices. Customers on variable pricing schemes reduce peak prices, at times when demand is usually high. Our results show, however, that in a system with high shares of variable production this argument does not hold necessarily. While demand response customers still reduce price peaks, such peaks must not in any case coincide with highest demands. Therefore it may be the case that retailer costs to supply flat-rate customers are not reduced in the expected way.

Another effect worth noting is that while in the short term a small share of responsive customers is sufficient to generate substantial savings, further increases become more important in the longer run. The difference between 20% and 100% on variable pricing is more significant in the long-term than in the short-term results.

Although decreased, the long-term results are still significant. Moving from this ideal scheme to simplified pricing will have to reduce the effect. The question is, though, whether the reduction is within an acceptable range.

Unfortunately the rebate pricing scheme as used in the field experiment only covers a daily three-hour period. Therefore effects are rather limited and it is difficult to draw final conclusions. What can be observed from Table 4 is a substantial reduction of the economic effect already in the short term.

A long-term equilibrium is not easily established for the rebate pricing scheme. As for other averaging variable-pricing schemes, like for example time-of-use pricing, convergence is not guaranteed [22]; a definite equilibrium has not been determined. However, already from the short-term figures it can be concluded that the gain in consumer surplus should be sufficient to more than compensate for the welfare losses on the production side. So the rebate schemes can be expected to have a positive welfare effect in the long run as well.

Table 4: Short-term effect of rebate pricing scheme

	<i>Costs</i>		<i>Average retail price</i>			<i>Change in welfare</i>	
	Total	Flat	Variable	Total	Absolute	Relative to original costs	
	EUR	EUR/MWh	EUR/MWh	EUR/MWh	EUR	%	
100% flat pricing	635,202,914	40.38	NA	40.38	0	0.00%	
20% rebate pricing	634,940,794	40.38	40.28	40.36	294,766	0.05%	
100% rebate pricing	634,223,629	NA	40.30	40.30	1,474,055	0.23%	

DISCUSSION

The model presented above provides indications of how demand response affects welfare in a system with high shares of wind power. To keep the model flexible and enable testing of different pricing structures we limited its complexity and left out a couple of conditions. In the following we briefly discuss how these may affect results.

The model uses a simplified representation of production capacities, only incorporating the major categories of plants. Using a more detailed model of plants may provide more accurate numerical results. The general conclusions, however, would stay the same. In practice generators would have more technical restrictions limiting their flexibility. In Denmark, for example, combined heat and power production is an important factor. Such restrictions of plant flexibility are expected to add to the value of demand response.

The most substantial concern may be that we look at a closed economy and don't allow for other sources of flexibility to react upon prices. This would clearly reduce the economic benefit of these kinds of pricing schemes, because the flat-rate benchmark will not have such extreme price spikes as we see them in the model. It could still be argued that for political reasons from a national perspective production capacities should still be held available, even though peak demand is covered by interconnection capacities with neighbouring countries. The capacity will then be idle at peak times and would not gain scarcity rents as in the model. They would still have to be financed, though, so the costs would have to be covered by consumers. In that case however, demand response could not directly avoid the costs.

One might as well object that the model is based on hourly values. While it may be possible to increase the time granularity of the model this also needs to take into account the special characteristics of electricity markets at such time scales. Modelling the technical restrictions at this level is considered of limited relevance for the analysis at hand, though. It could be considered to include a reserve to handle short-term deviations below the hour. As long as customers are inelastic below the one-hour timeframe this will constitute a fixed cost, and thus not be relevant for the results. If one suggests that household demand response is able to provide regulating power it would be relevant to include such aspects in a model. It would require automation of some of the households' equipment. This may be an option, but would require a different kind of modelling.

An issue that is a clear limitation is that we only take into account the system as a whole. As stated above, grid congestions may very well occur locally. These have a different cost structure and would have a quite different impact on the analysis. This should be very much in favour of demand response, though.

CONCLUSION

Flexibility of the demand side is an element that is prominently placed in the political debate on smart energy systems. Our calculations show that it can be a helpful and valuable strategy. It is important, however, to keep in mind the extent of what small consumers are able to contribute with manually. The ideal case with elastic demand reacting to real-time price signals is likely to be limited to automatically controllable loads that can be shifted without any loss of comfort to the consumer. Traditional household demand, although subject to some elasticity, is more likely to contribute via simplified signals like the ones used in the aforementioned field experiment.

The illustrative results above show that, although the ideal case produces significant benefits of around 7% in a new long-term equilibrium, the effects of the simplified structures are clearly limited. Simplification may be necessary to enable the adoption of new variable tariff schemes. But it may as well make a promising instrument less effective. The design of the applied rebate structure can certainly be improved. Deliberate contract design for demand response considering both adoption and effectiveness will be essential for households to make a significant contribution to power system flexibility.

The model also shows that short-term gains can be large; but policy-makers should note that these gains are merely temporary. The timing of long-term over short-term effects is an interesting aspect that requires further research. Harvesting the short-term gains could become an interesting incentive for first-movers if the long-term dynamics are relatively slow. In an

interconnected system the advantage of flexible demand in one market may still be substantial as long as the remaining markets stay inflexible.

The method we used is based on a formal economic model of demand. One might object that this does not properly reflect the behaviour of household electricity customers. The initiated field experiment will address some of these behavioural issues. In future work we aim at incorporating the economics of such effects in a similar setting. By coupling the model with results from the field experiments we expect to derive welfare effects from different levels of incentives, and could propose appropriate product design.

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NOMENCLATURE

D_t :	Demand in hour t
$D_{0,t}$:	Base line demand in hour t
P_t :	Price in hour t
P_0 :	Anchor price
ε :	Price elasticity
α :	Share of customers on variable prices
P_f :	Flat-rate price
Q :	Quantity supplied
$C_{agg,base/mid/peak}$:	Aggregated installed capacity
$mc_{base/mid/peak}$:	Marginal costs
k :	Slope at steps
ΔW_t :	Change in welfare

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