Monetary impact of dynamic pricing and demand response on households: the winners and losers

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***Abstract*—Smart grid paradigm is hailed as the Holy Grail to manage the future electricity consumption in a sustainable manner, and demand response (DR) is a fundamental component in the realization of smart grids. However, DR requires active household participation and in the previous studies monetary benefit is identified as the main motivation for the households to participate. In this paper, we analyze DR on households in terms of the monetary impact. Smart meter data together with data about properties of households are used from 669 households. Dynamic pricing schema and DR model are proposed and utilized in simulations. Self-Organizing Maps (SOM) are applied to identify the household segments that are monetarily affected in the simulations.**

***Index Terms*--demand response, dynamic pricing, households, monetary impact, simulation**

I. Introduction

World electricity consumption reflects reasonable steady growth and Europe follows the trend . The development raises concerns in respect to the widely recognized climate change. In order to foster the sustainable development, numerous countries have established legislation to control CO_2 emissions and improve energy efficiency nationwide. A notable example is the EU's 2020 climate and energy package that requires by the year 2020 [1]:

- 20% reduction in CO_2 emissions,
- 20% increase in the share of renewable resources,
- 20% improvement in energy efficiency

Smart grids are seen as a potential approach to achieve the ambitious '20/20/20' objectives, and demand response (DR) paradigm is a fundamental component in the realization of smart grids. In DR, the demand-side alters its electric use in dynamic fashion for benefit of the electricity grid in large. Such actions can reflect changes in the wholesale price of electricity, or the system reliability during the demand peaks.

Large industrial actors have been active in DR for decades due to the significant monetary benefits they can gain by scheduling electricity-intensive operations in respect to the electricity prices in the wholesale market. Yet, similar incentives have not been available for households due to the infrastructure limitations. However, the rapid penetration of the smart metering systems has enabled (almost) real-time monitoring of the electricity consumption in the households. For instance, in Finland more than 80% of the households are equipped with smart metering technology capable to measure the accumulated electricity consumption for each hour of the day. Thus, the dynamic pricing is technologically possible and such products are expected to appear to the market.

Electricity is a low-interest product in the household market and the customers are not willing to discard the traditional demand-and-supply model. However, supposing the DR introduction is ought to happen in a customer-oriented manner, households need to be motivated enough to participate. Previous studies have indicated that significant monetary benefit is the main motivation for the households to enroll to DR programs [2]. In [3], based on a literature review, it is concluded that little is known about the actual cost savings that DR could pose to households.

In this paper, dynamic pricing and demand response are simulated on households and monetary impact is analyzed. The paper contains two steps:

1) We present a dynamic pricing schema followed by an analysis of the monetary impact it poses to the households.

2) We present a DR model that is used to simulate DR activity in the households in order to analyze the monetary impact that the DR activity yields.

II. Data and Methodology

We simulate dynamic pricing and DR on extensive set of smart meter data, and with help of data about the corresponding households, we identify the households that indicate monetary benefits or losses. The simulations are driven by the electricity wholesale prices.

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Smart meter data (D1) were recorded during the year 2008 by a local energy company Savon Voima Oyj in Northern Savonia, Finland. The electricity consumption was measured in one-hour resolution for each electricity consumption site (metering point). As the focus on households, the rest sites are excluded from the analysis. Additional filtering is done by setting thresholds for the annual consumption: 1000 kWh (min); 30000 kWh (max). Moreover, sites exceeding hourly consumption of 20 kWh more than 40 times during the year are excluded (see Section III for the reasoning).

Properties of the households corresponding to the electricity consumption sites were acquired from questionnaire data (D2). The questionnaire was directed to the household customers of the energy company Savon Voima Oyj and the survey was conducted in the year 2009. Intersection of datasets (D1) and (D2) yields a dataset of 669 households: 438 single-family detached houses, 76 terraced houses, and 148 apartment houses. In this study, the dataset is referred by the name *SAVO669*.

The wholesale electricity price in Nordic countries is determined in *Nord Pool Spot* market. For this study, *Nord Pool Spot* prices in the Finnish market for the year 2008 were acquired. The spot prices are determined in the market for each hour separately.

Self-Organizing Maps (SOM) are applied in this analysis as the primary tool. SOM is a well-known and effective neural network method that maps complex non-linear relationships of the multidimensional data onto 2D/3D space while retaining the original topological relations. Thus, SOM provides us a convenient tool to analyze the complex data in a visual manner.

III. DYNAMIC PRICING SCHEMA FOR RETAIL AND DISTRIBUTION MARKET

In Finland, the electricity pricing schema for households has traditionally been such that DO and ES charge customers based on the total consumption with a fixed €/kWh rate. However, the introduction of smart metering has also enabled the option for dynamic pricing, yet such products are rare in the Finnish market, and well-established pricing schemas do not exist.

The business logic of dynamic pricing fundamentally differs in DO and ES market. ES gains profit by maximizing the amount of electricity sold in relation to the purchasing and/or production costs at the time. Dynamic pricing of ES can be based on the wholesale prices with a certain margin [4]. The wholesale price in Nordic countries is determined in *Nord Pool Spot* market. Fig. 1 illustrates the spot prices in respect to the total consumption within the dataset *SAVO669* during the year 2008. Fig. 2 illustrates the spot prices in respect to the mean ES and DO prices (without taxes) in the Finnish market during the year 2008.

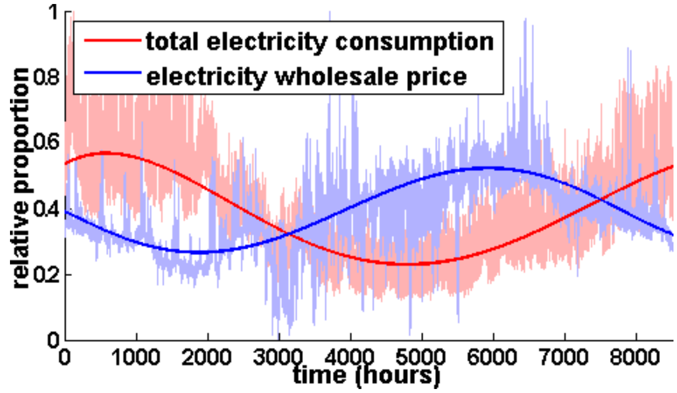

Figure 1. Wholesale prices in respect to total consumption (normalized)

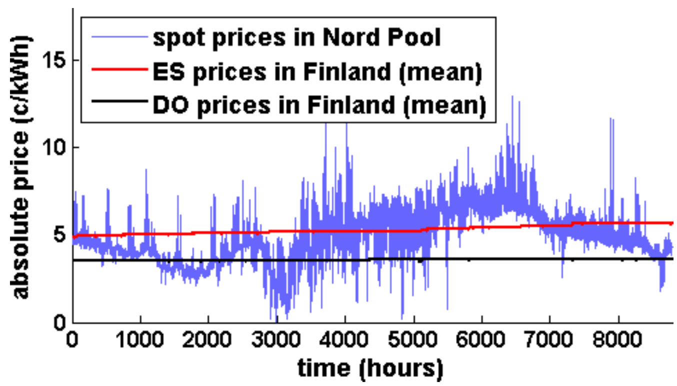

Figure 2. Wholesale prices in respect to ES/DO prices in Finnish market

On the contrary, the amount of energy carried in the grid does not generate significant costs to DO [5]. The costs come from the grid infrastructure maintenance and development to support the increasing demand in terms of peak power. Therefore, the traditional pricing schema that is based on the energy consumption does not match with the factual operating costs. A desirable option presented in the literature is bandwidth-based billing [5]. That is, the customer purchases electricity bandwidth that corresponds to his annual peak demand of electricity. Limited numbers of overflows are allowed, though.

The dynamic pricing schema utilized in this paper is summarized in Table 1 and Table 2. The suggested schema takes into account interests of both ES and DO by using spot prices as the base for the ES prices and the bandwidth for the DO prices. Traditional static pricing schema is shown as a reference. The static prices are deduced from the mean ones in the market of the year 2008 (Fig. 2). The structure for bandwidth options in Table 2 follows the schema presented in [5]. Margin for spot prices and €/kW ratio in bandwidth prices are adjusted so that the monetary returns for both, DO and ES, remains unaffected on the set of households we are concerning, that is, *SAVO669*.

Table 1. Dynamic pricing schema

	DSO	**ES**
Static pricing	3.6 c/kWh	5.3 c/kWh
Dynamic pricing	bandwidth	Nord Pool Spot + margin

Table 2. Bandwidth options

Bandwidth (kW)	5	8	10	13	15	18	20
Max. overflows	10	15	20	25	30	35	40
Price (€/month)	20	32	40	52	6	72	80

IV. Monetary impact of dynamic pricing on households

In this section, we evaluate impact of the dynamic pricing schema (Section III) on households in terms of annual electricity costs. Let us define:

$$NH = \{h \in households \mid P_d - P_s \leq 0\}$$
$$PH = \{h \in households \mid P_d - P_s > 0\}, \quad (1)$$

where P_d denotes the annual cost of electricity if the dynamic pricing is applied, and P_s denotes the annual cost of electricity if the static pricing is applied.

To clarify, Definition (1) states that by *NH* we refer households that gain monetary benefits and by *PH* households that encounter monetary losses.

Table 3 and Fig. 3 are summing up the distribution of *NH* and *PH* in relation to all households. The results indicate that the dynamic pricing schema can have significant impact on the annual electricity costs in individual households: ~150 euros on average. In *NH*, the distribution of the annual monetary benefit is somewhat normal hitting mean at -13%. However, in *PH*, the distribution of the annual monetary losses indicates exponential tendency. That is, minor losses are very likely but major ones are also possible - several households fall in the segment that would triple its annual electricity costs. As the scale in *NH* and *PH* differs by a magnitude of 10 but the medians does not, this indicates that in *NH* the total electricity consumption is greatly higher than in *PH*.

The monetary impact of dynamic pricing in respect to additional household properties is analyzed by constructing a SOM. The results are presented in Fig. 4. The maps in the second and third row describe the distributions of type of housing and heating systems, respectively, in binary-scale: yes/no (1/0). For the other maps, relevant continuous-scale is used.

SOM confirms the earlier assumption: relative difference in the annual cost correlates with the annual electricity consumption. That is, the higher the energy consumption, the more likely the household gains monetary benefit by the dynamic electricity pricing, and vice versa.

Table 3. Statistics of NH and PS

	NH	*PS*
proportion (%)	46	54
mean($P_d - P_s$) (€)	-119.70	175.65
mean(($P_d - P_s$)/P_s) (%)	-1.26	0.51
median($P_d - P_s$) (€)	-117.40	145.80
median(($P_d - P_s$)/P_s) (%)	-1.29	0.39

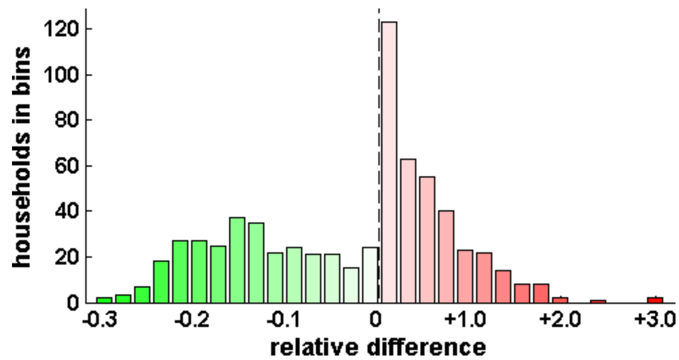

Figure 3. Distribution of NH and PH

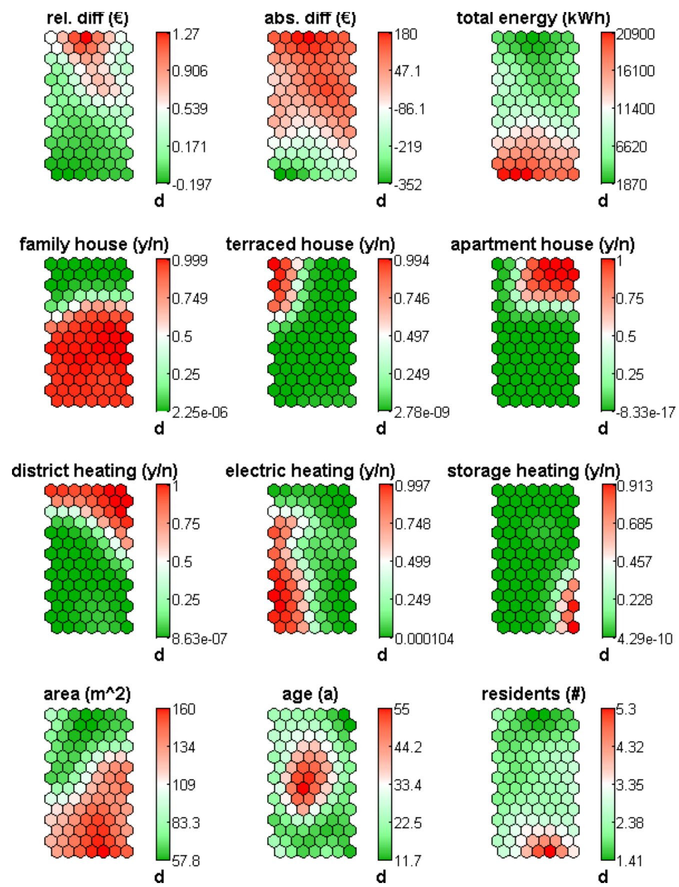

Figure 4. SOM: dynamic pricing and household properties

Households in *NH* can be described as:

- high electricity consumption
- single-family detached house
- electricity-driven heating
- larger area (> 100 m^2)
- higher number of residents (> 2)

On the contrary, households in *PH* can be described as:

- low electricity consumption
- apartment or terraced house
- district heating
- smaller area (< 100 m^2)
- lower number of residents (< 2)

Age of building does not seem to correlate directly with the monetary impact of dynamic pricing. However, it can be seen to boost the extremes in the case of younger buildings (< 20 years old).

V. Simple Demand Response Model for Simulation Purposes

In order to analyze the monetary DR potential that lies in different customers segments, we construct a simple DR model. In the literature, it is suggested that ES could act as the DR operator in the Finnish electricity market implying that the DR signals are based on the wholesale spot prices [9]. Hence, we construct DR model (2) to be utilized in the subsequent simulations:

$$
\begin{aligned}
&d^H := \arg\max_i \frac{P_i + P_{i+1} + \cdots + P_{i+k}}{k+1}, \\
&\quad i = 1, 2, \ldots, 24 - k \\
&D^H := \{d^H, d^H + 1, \ldots, d^H + k\} \\
&D^L := \{1, 2, \ldots, 24\} \backslash D^H \\
&E_{D^H} := (1 - \alpha) E_{D^H} \\
&E_{D^L} := E_{D^L} + \frac{\sum \alpha E_{D^H}}{24 - k - 1},
\end{aligned}
\tag{2}
$$

where *P* denotes the vector with 24 values indicating hourly electricity prices in the wholesale market for a given day, *E* denotes the vector with 24 values indicating hourly electricity consumption for a given day and household, α denotes a scalar that defines the DR potential (in percentage), and *k* denotes a scalar that defines the duration of DR action (in hours). In addition, d^H is the index for the first high-spot hour, D^H and D^L are set of indices for the *k* sequential high-spot hours, respectively, and $E_D{}^H$ together with $E_D{}^L$ denotes the indices in *E* defined by D^H and D^L, respectively.

In the model (2) we assume that DR action takes place during the high-spot hours of the day. The high-spot hours are defined to be the *k* sequential hours when the average spot price reaches its maximum. Moreover, we assume that the consumption decreases α during the high-spot hours and the unallocated energy distributes equally to the remaining hours of the day; that is, energy efficiency remains unaffected. The DR action by the model (2) is illustrated in Fig. 5.

In this study, we set $\alpha = 0.3$ and $k = 3$. The choice is done arbitrary but it attempts to capture the DR potential that could be achieved in the initial stage of DR. That is, alteration in electricity consumption is modest enough to be easily achieved. Moreover, the choice of α and k corresponds the DR potential that is captured in the real DR trials previously [6].

Fig. 6 presents the distribution of the high-peak hours D^H in the year 2008. Nord Pool Spot prices are used as the reference. The typical morning and evening hour peaks are very distinct on the histogram and the distribution is unequal. Thus, the households whose consumption does not follow the trend will not gain monetary benefit if DR signals are defined by the high-spot hours.

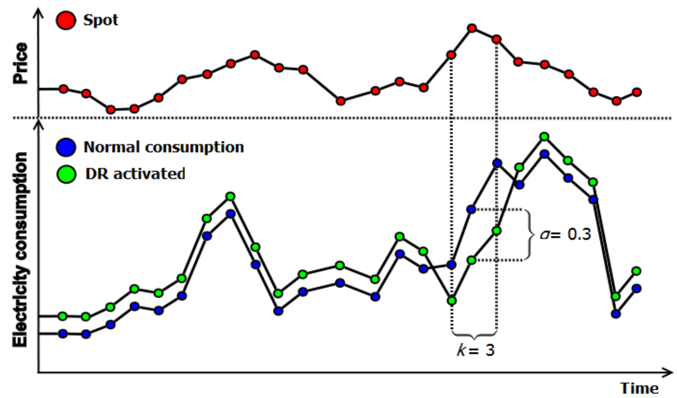

Figure 5. Example of the DR model

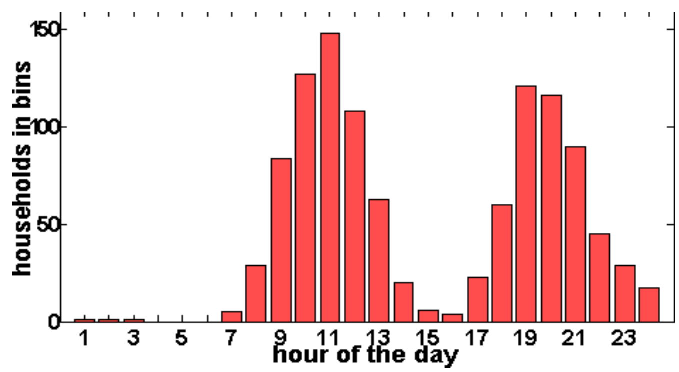

Figure 6. Distribution of high-spot hours

VI. Monetary Impact of Dynamic Pricing on Households

In this section, demand response by the model (2) is simulated and results are analyzed to identify the household segment that indicates high DR potential in terms of cost savings. DR activity was simulated by including all the households in *SAVO669* dataset, totaling 669 households. Simulation was carried out by giving coverage for entire year 2008, that is, DR by the model (Section VI) activated every day on the high-spot hours.

The magnitude of the monetary impact on individual households is illustrated in Fig. 7. The histogram represents the number of households that fall in groups that belong to the same range in relative annual cost difference. Reference costs are the ones discussed in Section V, that is, dynamic pricing is introduced to the system but no DR activity is expected. The result indicates that high proportion (> 95%) of the households could gain only minor savings (< 5%) by the DR activity. A few percent of the households could gain considerable savings (20%-30%) and this segment is likely to have high motivation to be active in DR introduction. However, low portion of the households (~3%) is also expected to suffer from the DR activity - the annual cost of electricity increases up-to 30 % by following the model.

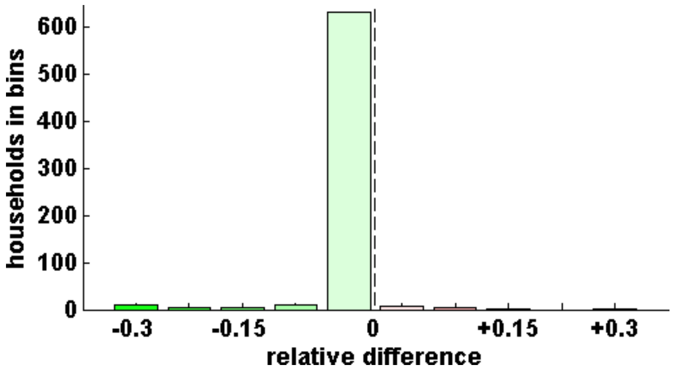

Figure 7. Annual cost effect of demand response

The monetary impact of DR in households is further analyzed in respect to various properties of the households; SOM is presented in Fig. 8. The results (*nDR/DR* versus *sta/dyn*) indicate that households with high DR potential in monetary terms are among those whose electricity cost increases due to the dynamic pricing. However, the extremes do not overlap, that is, the greatest monetary losses by dynamic pricing do not imply highest DR potential. The same applies for low DR potential in monetary terms. Households having high DR potential can be described as:

- rather low electricity consumption (<5000 kWh/a)
- apartment house
- district heating
- smaller area (< 80 m^2)
- newer building (< 10 years old)
- lower number of residents (< 3)

I. Conclusion

In this paper, we analyzed dynamic electricity pricing and demand response (DR) from the household's point of view. In the previous studies, the expected savings in electricity costs are identified as the main motivation for the households' DR participation. Thus, in this paper, data-driven approach was taken to model the monetary impact that introduction of the dynamic pricing and DR would present to the households. In order to simulate the impact on different cases, we presented a dynamic pricing schema taking into account benefits of electricity supplier and distribution network operator, and a simple DR model that captures the time-optimal DR activity in respect to electricity wholesale prices.

The results indicated that the dynamic pricing of electricity can deliver significant changes in annual electricity costs for the households. In particular, high monetary losses were discovered in our simulations. Moreover, the households that consume lot of electricity, gained highest monetary benefit by the dynamic pricing, and vice versa. In that respect, the dynamic pricing as an incentive to improve energy efficiency, seems questionable. In addition, DR simulations by the presented DR model indicated only minor cost savings in the households. This raises the question, would such DR activity be an interesting option for the majority of households. The minor household segment that indicated high DR potential in

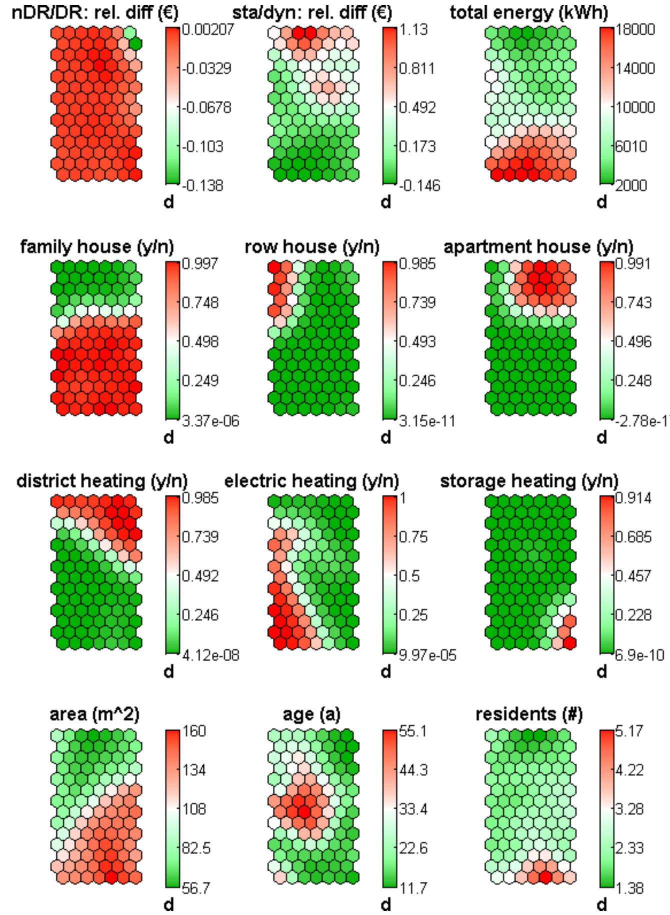

Figure 8. SOM: monetary DR potential and household properties

monetary terms identified to be the apartment houses equipped with district heating and having rather low electricity consumption in general.

In the future research, extensive set of dynamic pricing schemas and DR models are evaluated and analyzed from household's point of view, but also concerning the other stakeholders. In particular, interests of distribution operator (DO) are covered by analyzing the peak power in the grid in various DR scenarios.

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