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Working Paper

Decentralized local pricing - improving network usage in a smart-grid environment under limited information

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Decentralized Local Pricing – Improving Network Usage in a Smart-Grid Environment under Limited Information

HEMF Working Paper No. 04/2017

by

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and

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Abstract

With a smart grid environment, flexible load devices and provided local price incentives a more efficient grid usage may be achieved in the future. Bidirectional communication, smart devices and shiftable loads as electric vehicles and heat pumps have the potential to be coordinated with local supply when suitable incentives are provided. This can bring relief especially for distribution grid areas where infeeds from fluctuating renewable energy sources increase.

This paper presents a decentralized local pricing mechanism, aiming at local prices that reflect the current load situation. That is in case of congestion a local price, deviating from the wholesale market price, is determined. With an iterative search algorithm suitable prices can be computed without gathering full-fledged bidding data. Simultaneously self-reinforcing effects are avoided. Further on this concept can be implemented rather easily precisely where and when required so that only areas with grid congestion are affected.

Keywords: Smart Grid, Real-Time Pricing, Network Pricing, Agent-Based Modeling, Price-Elastic Behavior.

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Content

Abstract	I
Content.....	II
1 Introduction	1
2 Methodology.....	3
3 Modeling Environment	7
3.1 The Market Agent.....	8
3.2 Price-elastic Behavior	8
4 Case Study	9
4.1 Reference Case – The Present Wholesale Market.....	10
4.2 Price-elastic Supply	11
4.3 Price-elastic Supply and Demand Response	11
4.4 Results	12
4.5 Performance of the Decentralized Local Pricing Mechanism	13
5 Conclusion.....	15
Acknowledgements	16
References	III

1 Introduction

In recent years, distribution grids in Germany and other countries are facing significant new challenges. The high amount of decentralized and volatile power production, primarily from wind turbines and solar systems, leads to an increasingly complex task to operate the grid and to guarantee system stability.

Today many small-scale renewable energy source (RES) devices have no regulation equipment and typically the current local weather conditions instead of demand are drivers for supply. Further more, the grid infrastructure was designed originally to transport electricity from central large-scale power stations down to lower voltage levels. With local supply, the direction of load flow is inverted more frequently and causes congestion in terms of thermal capacity and voltage restrictions.

Furthermore, the energy consumption behavior is likely to change in the future. Load profiles will change with a broader presence of electric vehicles and electrical heating systems. Critical load situations may arise especially when these devices are used simultaneously. Yet these operations can be executed more flexibly: charging and heating processes can be performed decoupled from utilization due to the storage capacity of batteries and the thermal capacity of buildings. Hence, demand response (DR) from private consumers will gain importance in the near future.

In some places, these changes lead already to constrained networks (see e.g. [1]), but within smart-grid environments an efficient usage of existing networks can be enabled. Grid usage of numerous private consumers, prosumers and small-scale generators could be adjusted in case of congestion, when modified prices indicate the current congestion situation via smart meters. Bidirectional data exchange together with smart components as energy management systems and automated devices would allow a prompt response from network users to specifically modified prices.

The concept of nodal pricing provides a pricing scheme indicating scarcities in the network (cf. e.g. [2], [3], [4] and [5]). Thereby price differences occur when electricity flow has to be reduced due to restricting grid elements. This concept is implemented in electricity markets in the USA and in New Zealand, but so far only at the transmission network level.

In order to implement nodal prices or other forms of local prices in the distribution grid, the availability of local information is more crucial. Local information encompasses notably detailed data on consumption and generation behavior of private households. Gathering such large numbers of data will be facilitated in the future by expansions of intelligent communication infrastructure. Therefore, setting up a market mechanism at the level of small-scale low voltage grids may be challenging. Thereby also the acceptance of individual prices is required from small-

scale grid users. Applications of the nodal pricing concept to the distribution grid are investigated already in e.g. [6], [7], [8] and [9]. Yet, the specific problem of available data and the need for an explicit bidding mechanism are not discussed there.

Local markets as a consequence of congestion within the distribution network are subject of [10]. This theoretical discussion emphasizes that a separation into local markets is efficient only when congestion occurs.

In order to design efficient local markets the demand side has to react more flexible than in conventional electricity markets. Opportunity and consequences of flexible demand - e.g. incentivized by prices - are investigated e.g. in [11], [12], [13]. But suitable price mechanisms to incentivize demand adjustments efficiently are not discussed there. In contrast, e.g. [14] and [15] investigate the issue of generating usage-based prices to coordinate grid users' behavior, but neglect that data affecting the grid are not known by a grid operator in advance.

The problem that the load situation results from the combination of a huge number of grid users but relevant information are not available centrally, is answered variously in the literature: Average grid use is assumed to estimate the load situation e.g. in [16], [17] and [18]. I.e. consequences of individual user behavior are not discussed. In [19], [20], [21], [22], [23] and [24] in contrast the concept of cooperation between grid users is introduced so that data exchange allows an efficient coordination of grid affecting behavior without a system operator's overview. Yet, the precondition of incentives and technical requirements for a fast communication and cooperation are questionable.

Another way to answer the problem of lacking coordinated behavior adjustment in the context of incentivizing prices - it may result in changed but again extreme situations (e.g. congestion caused by supply substituted by congestion caused by consumption) - is chosen in some models and also some German field tests. There the use of selected addresses is made (cf. [25], [26] and [27], [28]). Therewith adjusting responses of participants do not occur at the same time and avalanche effects may be avoided. Yet, the choice of responding users might be unclear, inefficient or discriminating, and it becomes obvious that no proper market price is given in that way.

In contrast a pricing mechanism where suitable prices are determined within an iterative process, requiring a minimum of data exchange, is given in [29] and [30]. But the focus is not set to the distribution grid level and the network capacity is not explicitly reflected in the model. Aiming at loss minimization a physically detailed approach to compute node-specific prices is given in [31]. Here grid restrictions are considered and an iterative negotiation process is used. Yet, this approach is rather theoretical and implies specific assumptions (e.g. a quadratic function for line losses).

In this paper we introduce a decentralized local pricing mechanism, which determines price adjustments in the case of congestion situations in the distribution grid. Efficient grid usage is incentivized with increasing or lowering the general price in a certain local grid area because grid usage is adjusted consequently (e.g. via load shifting or reduction of local feed-in). Thereby the pricing mechanism is based on an iterative negotiation process. Only current quantity bids from grid users are required to determine efficient prices, full demand curves are not needed to transmit. That is, gathering and exchange of numerous and particularly private data are not needed. As a consequence this pricing scheme requires no adjustments in case of changed conditions as e.g. varied grid user's equipments or changed numbers of grid users. Additionally the application of this market-clearing mechanism can be implemented precisely with view to the individual grid situation. Thus, implementing in wide network areas with rare congestion situations can be avoided.

The paper is organized as follows: In Chapter 2 the decentralized pricing mechanism is introduced. As a simulation environment, an agent-based model is described in Chapter 3 with local demand and supply agents as well as a market agent. Exemplary applications are presented in Chapter 4 including different settings concerning price-elastic grid users. Chapter 5 concludes.

2 Methodology

From an economical point of view, the lack of transport capacities has to imply the separation of a market into two market places. In the current and future distribution grid congestions due to local supply or large amounts of simultaneous consumption can take place at various locations and are typically not permanent. Hence, there is usually not a certain local market. Yet, a mechanism to reflect the imbalance of the global market and a current isolated grid area can be the same for various congestion situations and even for uncritical grid usage. Here we focus on such a pricing mechanism itself, assuming that a congestion leading to isolated grid areas has been detected (see Fig. 1). The market mechanism provides individual price signals, which reflect the current congestion situation for a local grid area in time steps and locations where such a separation of markets arises. In order to reflect local scarcity the market mechanism computes a markup on the wholesale price. Given an excess feed-in the markup will be negative, for congestion caused by consumption it will be positive.

Particularly an algorithm is needed to determine an adequate magnitude of the markup. Local prices should be efficient but also self-reinforcing effects have to be avoided. E.g. reducing local infeed simultaneously with activation of large amounts of load may result in an inefficient use of the available grid capacity or even overloading in the inverse flow direction, which is obviously not desirable. Therefore the magnitude of price adjustments has to depend on technical network

restrictions as well as on the market participants' behaviors. Especially the possibly time-

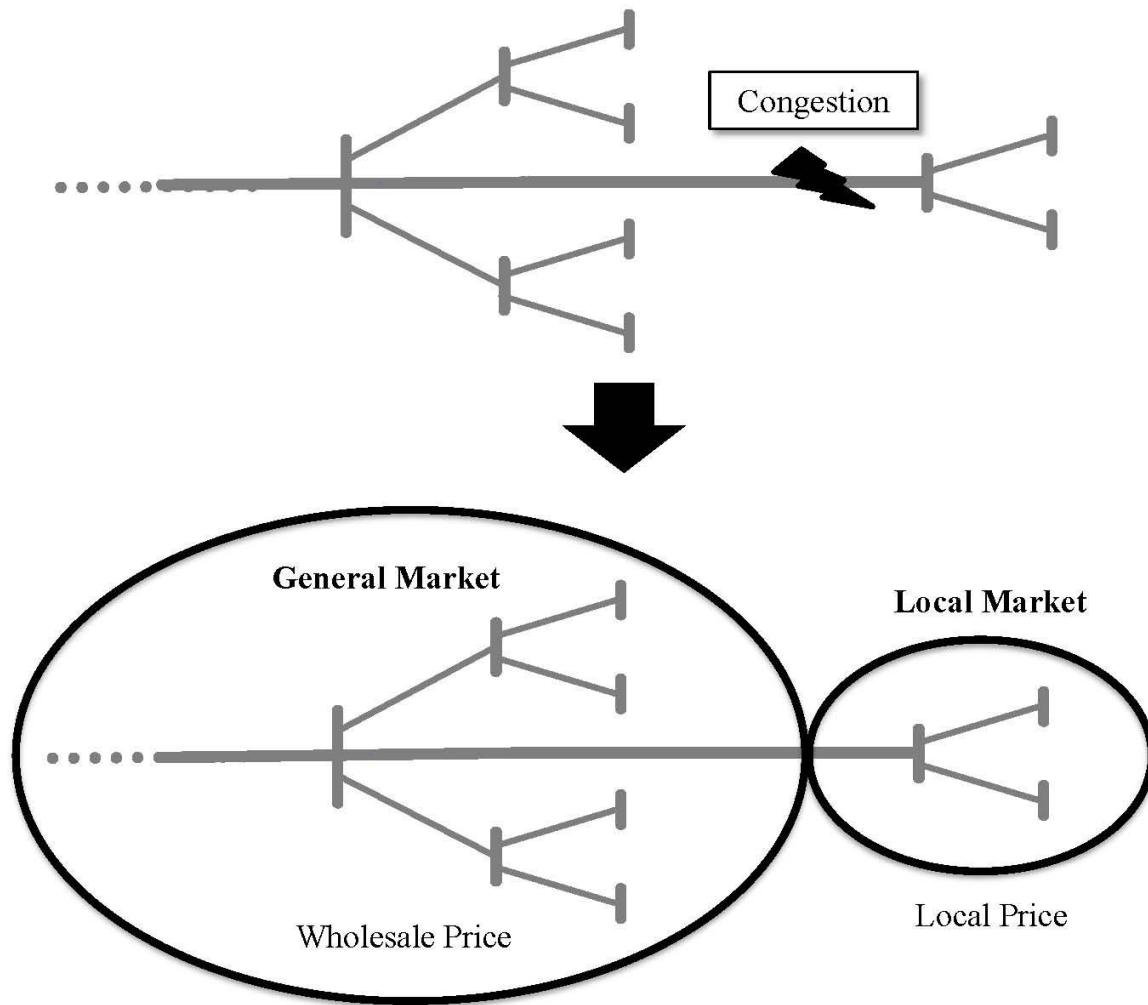


Figure 1: Separated Markets in Case of Congestion

dependent capability and willingness to respond to prices is *prima facie* a private information not known to a central planning coordinator. Therefore a negotiation process based on bidirectional communication is organized by a market coordinator. This includes iterative adjustments of price and quantity bids (see Fig. 2), so that local prices can be determined without centralized optimization and centrally known respond curves. The choice of price adjustments follows the approach of bisection (cf. e.g. [32]). This simple but efficient method requires no further information, as steepness parameters of bidding functions, for an successful convergence. Hence, our approach is effective without making usage of bidding functions and therefore provides a robust mechanism for various conceivable user behaviors. Iterative price bids are computed here with view to (a) resulting quantity bids and corresponding load situations and (b) information achieved with previous price bids. The interval for possible local prices is halved thereby in each time step. In the context of unavailable information repeatedly halving the price interval in question is the quickest way to approximate suitable local prices.

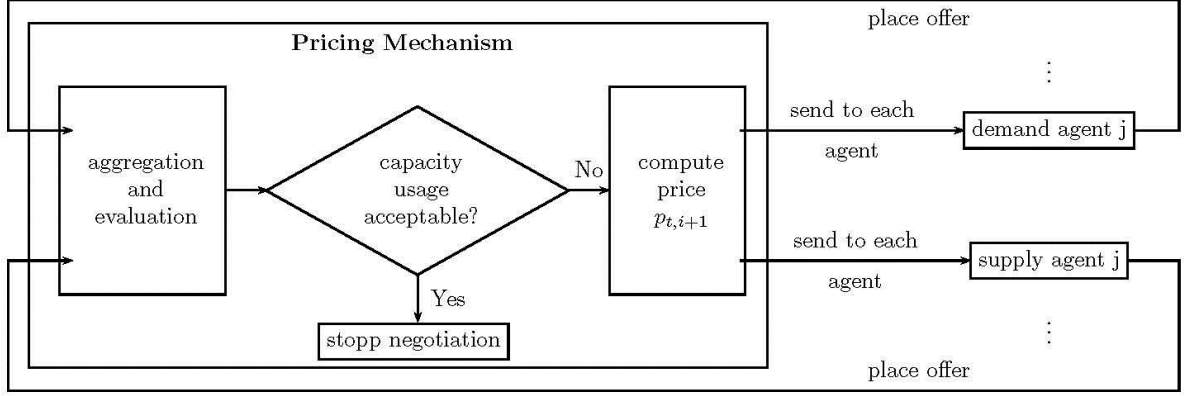


Figure 2: Negotiation Process to determine Decentralized Local Prices

The whole iterative process of the decentralized local pricing mechanism is as follows (see also Fig. 3): In each turn of the bidding process the first step consists of evaluating whether the present local price - being the initial wholesale price $p_{t,0}$ or the previously modified price - is suitable or not. That is the balance of the aggregation of individual power $P_{t,i,k}^{gen}$ and load $P_{t,i,k}^{load}$, bidden in response to the current price, has to be compared to the grid capacity c (t, i, k are indices for time, iteration step and the local grid users respectively). Basically two cases of congestion can occur: a congestion due to excess feed-in or one due to excess demand. The first one is indicated by violations of the following inequation:

$$\sum_k P_{t,i,k}^{gen} - \sum_k P_{t,i,k}^{load} > c \quad (1)$$

But in order to avoid in this situation also adjustments with a greater extend than necessary, a second inequation has to be fulfilled:

$$\sum_k P_{t,i,k}^{gen} - \sum_k P_{t,i,k}^{load} < (1 - \epsilon) \cdot c, \quad (2)$$

where ϵ is a small quantity.

The determination of a target range $[(1 - \epsilon) \cdot c, c]$ after an initial violation ensures as well that an opposite violation is avoided.

Analogously the second case of congestion due to excessive demand is given, when the following inequation is violated:¹

¹ Current grids have been designed and built to serve household demand, therefore congestion due to excessive demand is unlikely as of today. Yet the possibility should be considered, particularly as heat pumps and electric vehicles may lead to increased demand and subsequently congestion in the years to come.

$$\sum_k p_{t,i,k}^{gen} - \sum_k p_{t,i,k}^{load} < -c. \quad (3)$$

Here the inequation

$$\sum_k p_{t,i,k}^{gen} - \sum_k p_{t,i,k}^{load} > -(1 - \epsilon) \cdot c \quad (4)$$

has to be fulfilled, when inefficient overreactions should be prevented.

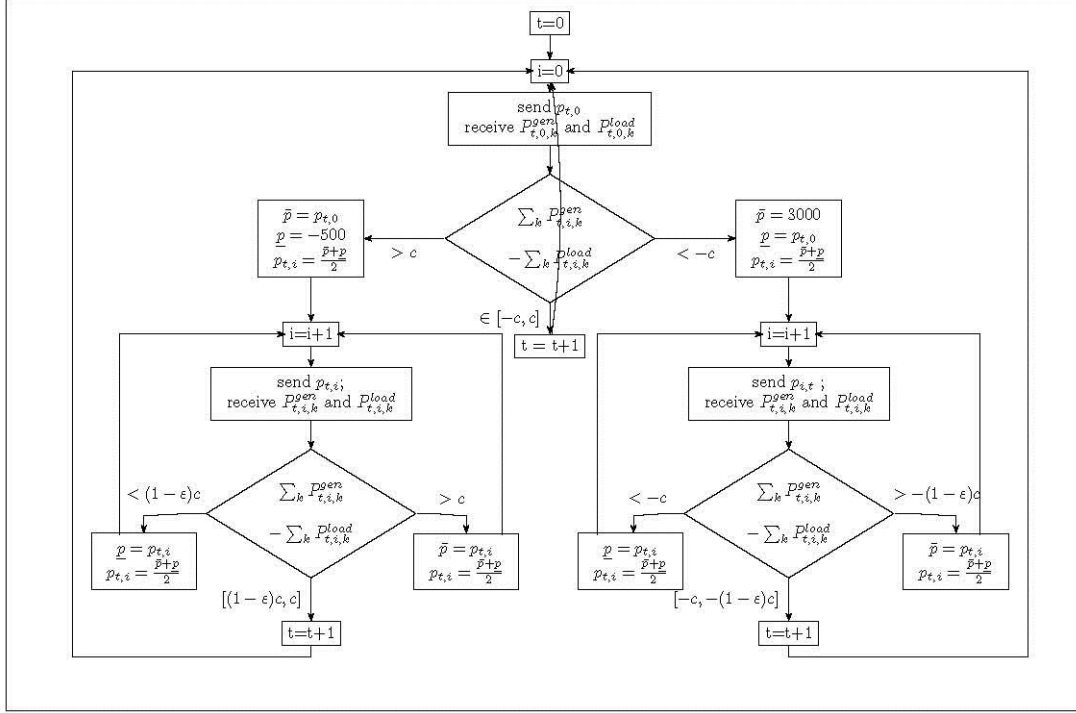


Figure 3: Pricing Algorithm - Process during one Time-Step

According to these possible violations - is there a congestion given or do users change their behavior in succession of a congestion too extremely - the pricing mechanism determines whether a price bid is too high, too low or suitable. The last bid was too high when feed-in reduced by demand exceeds the capacity bound (see (1)), but also when consumption minus generation was reduced too sharply in succession of a congestion caused by demand (see (4)). Likewise the price is too low for the case of capacity overrun due to high demand (see (3)), and again when the capacity is not used by at least $(1 - \epsilon) \cdot c$ succeeding an extreme feed-in situation (see (2)).

Initially, generally valid lower and upper price limits (\bar{p}_0 and \underline{p}_0) are chosen. During each time step these price limits may vary with the bidding process: After stating the current price bid to be too high or too low, it is stored as the current upper resp. lower price limit (\bar{p} resp. \underline{p}) and a new price bid has to be computed. This results according to the bisection method from the average of the highest too low price \underline{p} and the lowest too high price \bar{p} :

$$p_{t,i} = \frac{\bar{p} + p}{2} \quad (5)$$

or

$$p_{t,i} = \frac{\bar{p}_0 + p}{2} \quad (6)$$

or

$$p_{t,i} = \frac{\bar{p} + p_0}{2}. \quad (7)$$

The whole negotiation process is carried out until the market mechanism detects an appropriate network relief according to the users' bids. To be more precise, the final price is given, when

- the congestion was caused by local supply in that time step and

$$\sum_k p_{t,i,k}^{gen} - \sum_k p_{t,i,k}^{load} \in [(1 - \epsilon) \cdot c, c] \quad (8)$$

- or when the current congestion was due to high demand and

$$\sum_k p_{t,i,k}^{gen} - \sum_k p_{t,i,k}^{load} \in [-c, -(1 - \epsilon) \cdot c]. \quad (9)$$

The convergence of this bidding process is guaranteed as demand and supply functions are assumed to be continuous and monotonous.

3 Modeling Environment

To analyze the efficacy and performance of the presented decentralized local pricing mechanism it is implemented within a multi-agent system representing an electricity market and grid (cf. [33], [34]). Here the grid users as well as the conceptual and technical system are represented by agents, namely these are

- local agents (generators and consumers),
- a market agent,
- a network agent,
- weather agents.

This modeling environment enables a flexible simulation of local grids with a specific grid topology and individual grid participants, which are characterized e.g. by their specific location. Here it is used to model a distribution grid at the low voltage level. Thus, generators are mainly RES plants and consumers are private households. Beside the dependence on technical data of specific RES systems the feed-in behavior of generators is mainly affected by local weather conditions. Therefore each instance of a RES agent belongs to a certain type, for example a solar

system agent (PV agent). Further on, each instance of a specific type of agent has individual data, e.g. capacity, location, inclination of solar systems, etc. Weather agents provide information corresponding to the specific location and time for each individual instance of local agents.

A stochastic model determines hourly amounts of consumption for each instance of the household agent, based on typical load profiles.

The network agent is used to represent the grid topology and to compute the load flow after consumption and supply are determined in the market.

3.1 The Market Agent

The market agent may be used to describe the prices obtained from the wholesale market or to model a local market clearing (according to the introduced pricing mechanism). In both cases the wholesale price is set exogenously since the exchange price in a market area like Germany is not affected by the balance of demand and supply within a small-scale network area as investigated here. Without local market clearing the market agent passes the wholesale price on to the local agents.

With local market clearing the iterative negotiation process starts, when a congestion situation is detected as described above. Further on, the market agent states that a new time-step can be simulated when a local price is determined or when the separation of a local market is not required currently.

In order to gain an efficient grid usage incentivized by local prices a price elastic behavior of the local agents is required here. The specific shaping of demand and supply function has no impact on the pricing mechanism and its convergence in general. The price-elastic behavior for generators and consumers as it is modeled in this sample is described in the following chapter.

3.2 Price-elastic Behavior

Within smart-grid environments and with provided real-time prices a priceelastic behavior may be implemented for small-scaled generators as well as for consumers. That is actual generation and consumption patterns may deviate from the originally scheduled ones depending on the actual prices. For generation systems we can assume a simple choice between feed-in and curtailment, with the marginal generation cost as threshold value. In contrast there is less empirical evidence available on price-elastic demand behavior for private households. Most available studies are using data from field tests with limited size (e.g. [27], [35]). Yet we may expect with smart household equipment both a reduction of consumption and demand increase (as a reaction to low prices).

We model both kinds of price responsive behavior as smoothened step functions applying a sigmoid function: RES systems can generate electricity with zero operation costs so that the step

from zero to full available capacity feed-in is given at a price limit of zero. The currently available feed-in potential $P_{t,0,k}^{gen}$ is dependent on weather conditions and technical system data. It is determined in each time-step and corresponds to the feed-in level without price response. We then define a price-quantity relation for each time-step and RES agent through a sigmoid function (see Fig. 4a):

$$P_{t,i,k}^{gen} = P_{t,0,k}^{gen} \cdot \frac{1}{1 + e^{-\beta_{gen} \cdot p_{t,i}}}$$

Thereby $\beta_{gen} > 0$ is a parameter to model steepness, for β_{gen} tending towards infinity the price-response is approaching a step function.

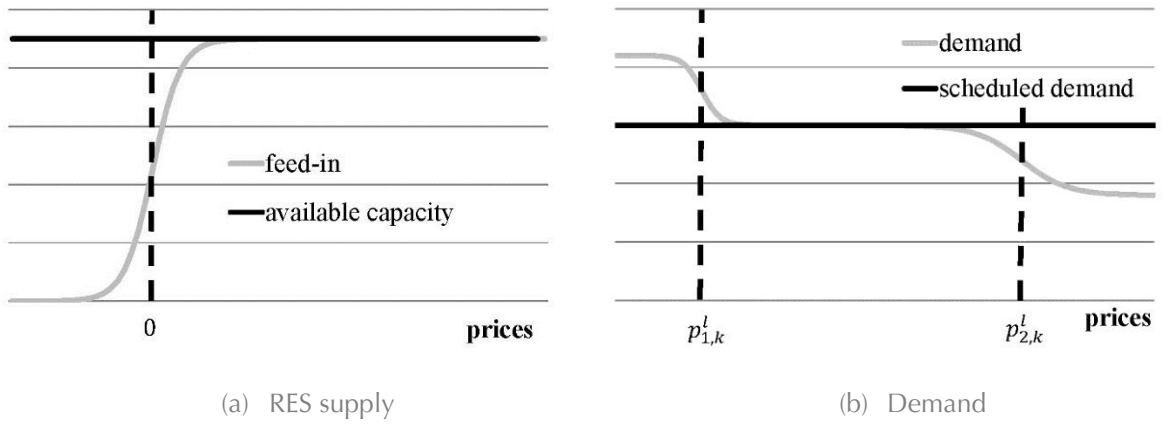


Figure 4: Price-elastic Response

For households the scheduled demand $P_{t,0,k}^{load}$ is taken as starting point. It is computed using a stochastic model and taking into account the time and type of day (there is a distinction between weekdays, Saturdays and Sundays) (cf. [33]). Further on it is assumed that demand response is possible in both directions within certain limits l_{red} and l_{exp} . This yields the relationship:

$$P_{t,i,k}^{load} = P_{t,0,k}^{load} \cdot \left(1 + l_{exp} \left(1 - \frac{1}{1 + e^{-\beta_1 \cdot (p_{t,i} - p_{1,k}^l)}} \right) - l_{red} \cdot \frac{1}{1 + e^{-\beta_2 \cdot (p_{t,i} - p_{2,k}^l)}} \right),$$

where $p_{1,k}^l < p_{2,k}^l$ are price limits corresponding to thresholds for behavioral changes: When prices increase above $p_{2,k}^l$, then consumption is decreased. But when prices fall below $p_{1,k}^l$, then additional electric loads are activated, $\beta_1, \beta_2 > 0$ are again steepness parameters (see Fig. 4b).²

4 Case Study

The proposed methodology is applied to a real low voltage distribution system in Germany. It consists of 38 nodes (including the substation), with 31 households connected to the network and 7 solar

² Note that further components of household retail tariffs such as levies, taxes and grid charges are not modeled here. Yet, a detailed representation of these costs would just mean to adjust the price thresholds accordingly.

systems with an aggregated nominal capacity of about 200 kW. As input data for weather conditions and the wholesale market we use data from 2011. As especially the feed-in from solar installations is of interest we focus on some summerdays.

Overload situations are detected with focus to lines, which are linked to the transformer. Thus, the coupling point between low voltage and medium voltage grid is chosen as the critical location for congestion and price differences. To reflect future developments and possible congestion situations we assume doubled amounts of local supply and consumption. The current carrying capacity with 0.27 A per substation-linked line is not altered in our sample. These simple and theoretic assumptions are a suitable backdrop to analyze the functionality of the introduced pricing mechanism. With constant network capacity but increased solar system capacity, network overload may especially occur during daytime around noon.

Results concerning the users behavior are illustrated in aggregation for the whole observed network, while those concerning network conditions are displayed exemplarily for a node at the end of one line with connected PV system. This is due to the fact that most critical situations arise in distant nodes with connected generators.

We present a reference case, where local congestion do not affect prices, and further on, two cases with local price determination. Here initially only price-elastic behavior of generators is assumed. Afterwards additionally demand behavior is simulated to be flexible.

4.1 Reference Case – The Present Wholesale Market

The reference case represents a wholesale market as it is common in many European electricity markets.

Here the behavior of local agents is price-inelastic: Private households are not affected by price fluctuations as these are not reflected within typical retail contracts and flexible electrical devices are presently not wide-spread. The corresponding household agents act therefore without adjusting their scheduled consumption pattern.

Distributed generators are only solar systems. Again the behavior of the operators is assumed to be price-inelastic. This behavior is consistent with the one of operators of solar systems who are remunerated by a flat feed-in tariff as it is paid to small-scale solar systems e.g. in Germany even after the legislative amendment of the renewable law (EEG) 2014.

Since the global wholesale price is given exogenously here, the market agent's task is to read out the current price from a database and pass it on to the local agents.

4.2 Price-elastic Supply

In case of simulation of the pricing mechanism local generators are modeled with price-elastic behavior. I.e. the remuneration of RES devices by flat feed-in tariffs are replaced by a remuneration based on local prices here and the PV agents behavior is simulated according to the price-elastic behavior described in Chapter 3.2 with parameter $\beta_{gen} = 0.5$.

The market agent carries out the local market-clearing mechanism. Initial upper and lower price limits and the coefficient ϵ , which defines the acceptable line load in succession of a congestion situation, are chosen as listed in Table 1.

Table 1: Parameters

Price-elastic Supply	
\underline{p}_0	-500 €/MWh
\overline{p}_0	3000 €/MWh
ϵ	0.1
β_{gen}	0.5
Demand Response	
β_1	0.5
β_2	0.2
$p_{1,k}^l$	20 €/MWh
$p_{2,k}^l$	90 €/MWh
l_{red}	40 %
l_{exp}	40 %

Household agents do not act price-elastic in this case, in order to investigate the situation with local incentives when no automation appliances or smart meter devices are given in typical households.

4.3 Price-elastic Supply and Demand Response

The same scenario is analyzed with a variation concerning the household agents behavior. It is plausible that flexible electric devices and a smart environment enable a price-elastic demand behavior in the future. Thus, beside the PV agents also the household agents adjust their consumption in response to prices as introduced in Chapter 3.2. Relevant parameters are listed in Table 1. Concerning PV agents and the market agent the assumptions laid down in Chapter 4.2 hold.

4.4 Results

The results are illustrated in Fig. 5. Prices, aggregated feed-in, aggregated demand and the voltage state of a distant node with connected PV system are given. Thereby black lines each indicate the reference case, dark grey lines the case of price-elastic supply and the light grey lines the one, where additionally DR is assumed.

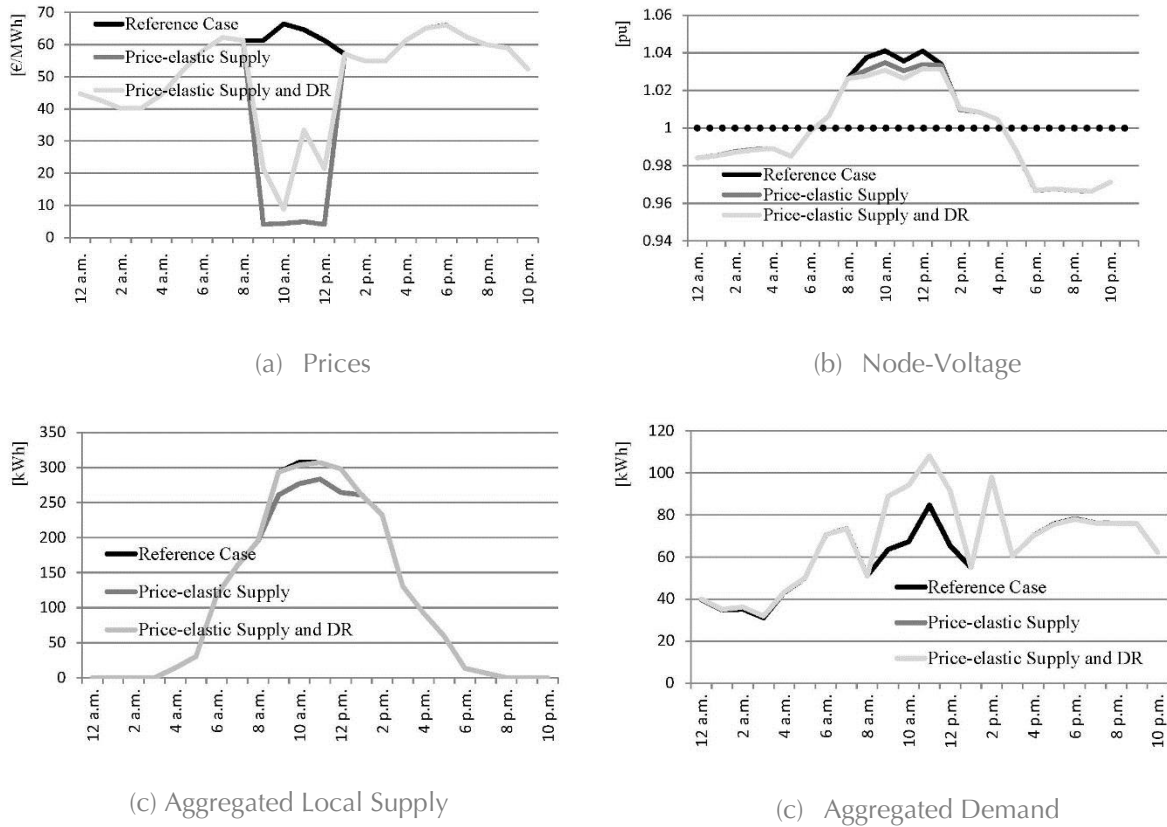


Figure 5: Results

In the first case the prices comply with wholesale prices as the possibility of deviating local prices is not considered here (see Fig. 5a). The curve of aggregated feed-in from solar installations (see black line in Fig. 5c, which is nearly equivalent to the light grey one) shows a typical intra-day profile according to the local solar radiation. With increasing local solar feed-in voltage is quite high with deviations of more than 4% (see Fig. 5b).³

In case of price-elastic behaving generators, the market agent identifies a grid overload for each hour during the hours from 10 a.m. to 1 p.m.. Feed-in from solar systems is too high, so local prices have to be reduced in order to make feed-in less profitable. Nevertheless a complete shut-down is not beneficial for grid usage as well, therefore the bidding process of the market agent ends up with prices of about 4 to 5 €/MWh (see dark grey lines in Fig. 5a). In consequence

³ E.g. in Germany the allowed deviation of 10% is typically allocated to low and medium voltage level with 6 and 4% (cf. [36]).

aggregated feed-in from PV agents is reduced as it is illustrated in Fig. 5c in comparison to the current available potential - which corresponds to a feed-in of the reference case. Due to this relief the highest voltage values are reduced and are closer to the normal level with a maximum deviation of 3.5% (see Fig. 5b).

When additionally demand is assumed to be price-elastic, then prices are reduced throughout the period of grid overload from 10 a.m. to 1.p.m. again (see light grey lines in Fig. 5a). In this case, local prices are consequently higher in comparison to the one without DR. E.g. at noon, a reduction to 33.39 €/MWh implies a suitable network relief. Feed-in reduction from solar systems is nearly not incentivised. Firstly, demand is increased during these hours. Thus, solar feed-in corresponds roughly to the one in the reference case, while the adjustments of demand can be observed in Fig. 5d. Intensifying electricity consumption in times of high distributed feed-in can relieve the congestion situation as well. Similarly to the case with shut-down of local generators a reduction of voltage deviations is realized here (see Fig. 5b). The deviations of voltage amounts are even more reduced than in the case without DR: The maximum deviation now is 3%.

One main result therefor is that additional flexibility in the system lead to lower fluctuations in local prices: As households are willing to adjust their behavior earlier than local suppliers in this sample, local prices of about 10 €/MWh to 35 €/MWh are the results of the pricing mechanism, while in the case without DR local prices of about 5 €/MWh are required (see light and dark grey lines in Fig. 5a).

In fact the interrelation of local prices on the one hand, and the opportunity to adjust behavior as well as the current load situation on the other hand, becomes clear in this example: At 12 p.m. a minimal reduction of local prices is suitable as demand is anyhow high and therefore the load situation in spite of high local feed-in is less critical. In contrast a significantly lower price is required at 11 a.m., when available upward demand flexibility is not sufficient and so generation has to be reduced, too. That feed-in from RES agents is adjusted in that single hour can be seen in Fig. 6.

4.5 Performance of the Decentralized Local Pricing Mechanism

As the decentralized local pricing mechanism is based on a negotiation process, which avoids gathering a multitude of supply curve data, the simulation time is likely to increase in time steps with congestion. But at most ten iterations are required in the first case with local market clearing (see 4.2). Compared to the reference case, where a time step takes about 0.4 - 0.5 seconds, the simulation time of a single time-step with iterative market clearing is at most a factor of 1.8 higher.

For the case where additionally DR is assumed (4.3) the simulation performance is not degraded. The number of required iterations is at most eight and the longest run time is a factor of 1.9 higher compared to the case without local prices.

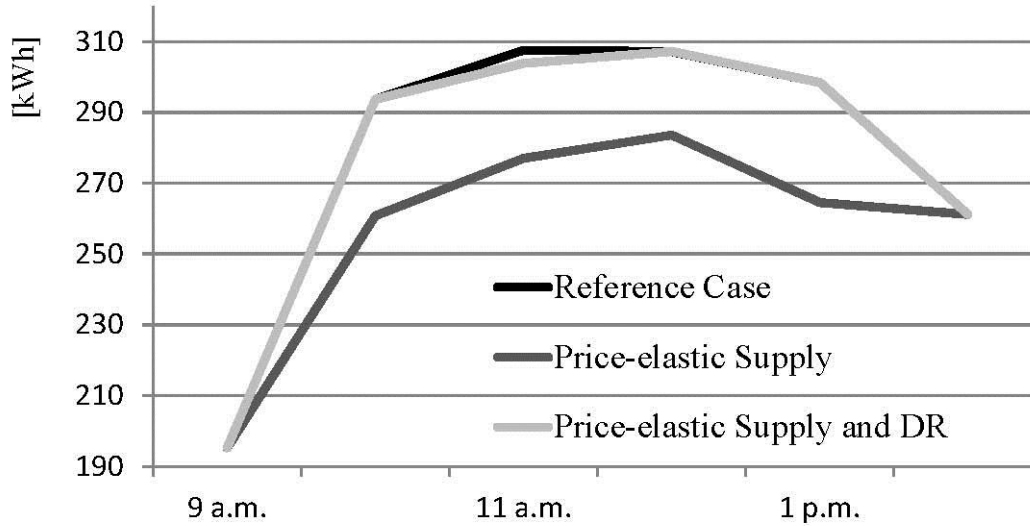


Figure 6: Detail of Aggregated Supply

Taking a closer look at the negotiation process, we exemplarily describe the process in the case without DR in more detail for the hour at noon (see also Fig. 7). The initial wholesale price $p_{t,0}$ of more than 60 €/MWh comes along with too high solar feed-in, so that the market agent adds a negative surcharge and passes the resulting price $p_{t,1}$ of approximately -220 €/MWh to the agents (which results from the average of $p_{t,0}$ and the initial lower price limit of - 500 €/MWh). Consequently local feed-in would be completely curtailed then. So further on price bids increase again in order to use the available potential with more than 90%. Yet, a price of 27 €/MWh (price $p_{t,4}$) is again too high and leads to excess feed-in. The following reduction to nearly 9 €/MWh does not improve the predicted grid situation so that the prices decrease once more. Finally the adjustment from nearly 0 €/MWh to price bid $p_{t,7}$ of approximately 4.5 €/MWh induces both, a congestion relief and still a high amount of feed-in from renewable energy sources.

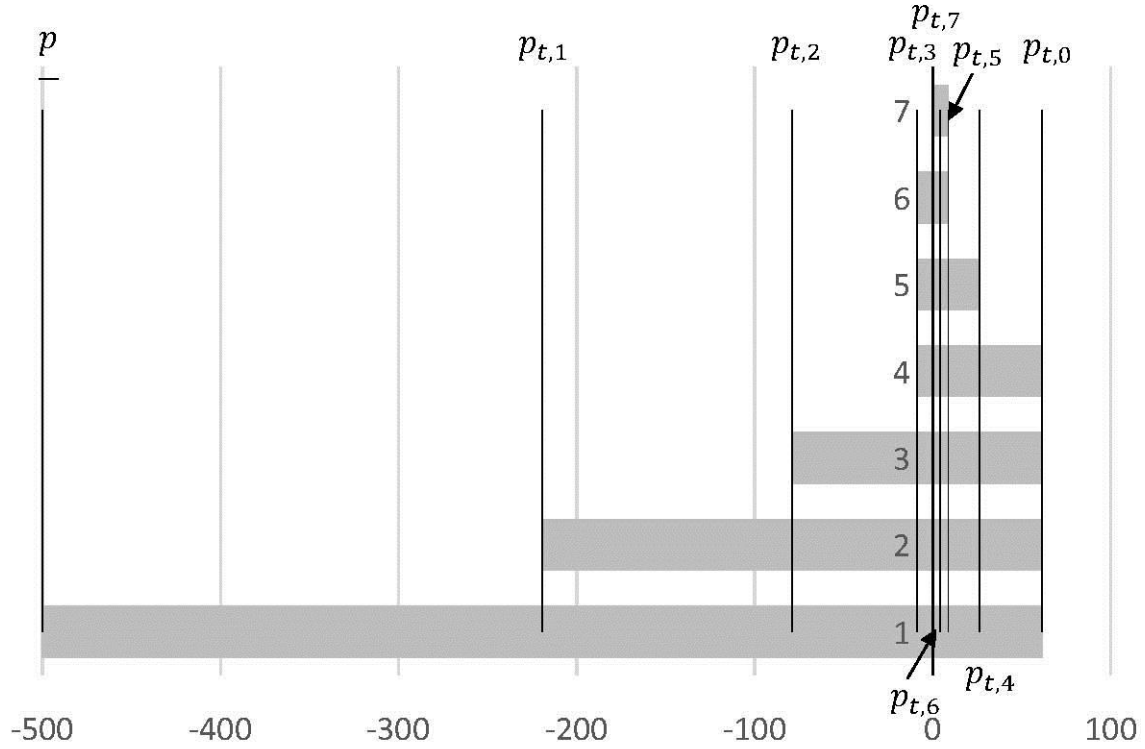


Figure 7: Exemplary Price Bid Process with Final Price $p_{t,7}$

5 Conclusion

The contribution of this paper is the introduction of a decentralized local pricing mechanism to determine suitable real-time prices aiming at an efficient grid usage in the context of smart environments. It is shown how local prices can coordinate local suppliers and potentially also private consumers in the context of the physical grid restrictions. Individual preferences, current personal circumstances and meteorological conditions are considered. Self-reinforcing effects are avoided.

The chosen iterative search algorithm is a computationally simple scheme which ensures a high performance in the context of unknown participants' responses and therefore unknown effectiveness of prices. This kind of iterative search procedure gives the opportunity to determine local prices without gathering and storing specific bidding curves - what would be a large quantity of data and even critical in the sense of privacy. Another advantage of the concept of this market-clearing mechanism is that there is no adjustment required when the context varies, e.g. when the households' equipment change. Additionally, this mechanism can be implemented precisely when and where it is needed. In areas of sufficient grid capacity a separate local pricing mechanism is not efficient. With the presented concept a costly and permanent market splitting is not required.

Further on, the presented test case has shown that appropriate adjustments of grid usage can help to relieve congestion situations. Concerning the resulting grid situation it does not matter whether an excess of decentralized energy generation is responded with feed-in curtailment or with consumption increases. In contrast, it does make a difference in terms of prices: Integrating DR into the system leads to less price adjustments in comparison to a situation where only distributed suppliers respond to price signals. As diverse types of grid users have distinct price limits for rearrangements it is worthwhile to make use of all available flexibility in the system.

It is to state that the investigated test case is rather a theoretical one. In order to analyze the introduced pricing mechanism beyond its mere functionality, more test cases as well as a more detailed look on available consumer flexibility is required. Another issue to keep in mind for a real implementation is to detect possible winners and losers of such novel market mechanisms.

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