

SHORT-TERM ECONOMICS OF VIRTUAL POWER PLANTS

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ABSTRACT

The Virtual Power Plant (VPP) has gained an increasing interest over the last few years. A VPP is a flexible representation of a portfolio of Distributed Energy Resources (DER: distributed generation, demand response and electricity storage). One of the key activities of a VPP is the delivery of (near-)real-time balancing services. In order to operate such a (near-)real-time coordination activity optimally, the VPP needs to maintain a dynamic merit-order list of all DER participating in the VPP. In order to make optimal decisions based on this list, the merit order needs to be based on the true marginal cost (or marginal benefit in case of demand response) of the individual DER units. The marginal electricity costs of most types of DER are highly dependent on local context and, hence, change over time. From analysis of the short-term bid strategies of various DER units, the existence of a bid strategy spectrum becomes clear. On one end of the spectrum, bidding strategies are based straightforwardly on true marginal cost or benefit. Further along the spectrum, optimal bidding strategies become less dependent on marginal cost levels and more on the price dynamics in the (VPP) market context. These results are relevant for VPP operations both from business and technical perspectives.

INTRODUCTION

The Virtual Power Plant (VPP) has gained an increasing interest over the last few years. A VPP is a flexible representation of a portfolio of Distributed Energy Resources (DER), *i.e.*: distributed generation, demand response and electricity storage [1]. One of the key activities of a VPP is the delivery of (near-) real-time balancing services, *e.g.*: delivering reserve regulating power to the TSO, delivering active network management services to the DSO or minimizing the imbalance costs of a commercial party. In order to operate such a (near-) real-time coordination activity optimally, the VPP is required to maintain a dynamic merit-order list of all DER participating in the VPP [2]. To make optimal decisions based on this list, the merit order needs to be based on the true marginal cost (or marginal benefit in case of demand response) of the individual DER units. The marginal electricity costs of most types of DER are highly dependent on local context and, hence, change over time. For example, the marginal electricity production cost for a CHP is highly dependent on the amount of heat demanded from the unit at a particular time: when the heat demand is high, the marginal cost for the electricity production is low and vice versa. Generally,

VPPs consist of large numbers of relatively small-sized generators, responsive loads and storage units. As shown in the CHP example above, the marginal cost level of the units participating in the VPP may change over time. Hence, the dynamic nature of the VPP merit order list. As we will show later on, there exists a class of DER units for which, under circumstances, the marginal cost level cannot be determined unambiguously.

This paper investigates bid/offer strategies based on marginal cost for flexible DER units in VPPs which use marginal cost mechanisms to establish dynamic merit-order lists. From a micro-economic viewpoint, the DER units are assumed to participate in a competitive market. This assumption holds as generally the number of DER units in a VPP is relatively high and their traded volumes are of the same order of magnitude. A competitive market leaves no room for speculation or gaming, and the best (so called *dominant*) strategy for each participant is to optimize its own utility by truly bidding its marginal cost [3]. These locally-optimal strategies lead to a merit order list that results in an optimal allocation on the global level as well: Those DER which are best fit to respond to a certain event are the first to be selected to do so. In this paper we investigate the mechanisms that determine the momentary marginal costs of distributed generators and the momentary marginal benefits of demand response resources. We show the existence of a bid strategy spectrum and determine the position of particular real-world DER configurations in this spectrum.

DER BIDDING STRATEGIES

For a DER unit to be able to participate in a (near-) real-time balancing service delivered by a VPP, the unit must communicate its momentary marginal cost to the VPP. This information can be delivered in a *bid function* or *demand curve*: defining the DER's electricity demand $d(p)$ for a given price p . An offer to produce a certain amount of electricity against a certain price is expressed by negative $d(p)$ values. As a convention, throughout this paper we refer to these functions as a bid, even when (part of) the functions expresses a production offer.

The software component that determines bid function for a certain DER unit at a given point in time is referred to as *agent*. The bidding strategy of such an agent is a mapping from its context history to a market bid. The context of an agent includes:

- The process controlled by the agent, including the current state of the process and economical parameters like marginal operating costs.

- The market environment in which this agent is situated, including the market mechanism and market prices.

In the extremes, there are two agent types that are forced to base their bid on either of the two context elements described above:

1. Those agents operating a DER unit that has clear and unambiguous levels of marginal costs. In a competitive market, the dominant strategy of these agents is to bid entirely according to their marginal operating cost.
2. Those agents operating a DER unit that does not have unambiguous marginal costs at all. In this case, the bidding strategy can only be based on market parameters, i.e. the market price (history).

As said, these cases are the extremes of a spectrum and hence, there is a group of agents whose bidding strategy is somewhere in between these extreme cases. In the next subsections we will give examples of these extreme and median cases.

Fully marginal-cost based

An example of a bidding strategy entirely based on the marginal cost level is that of a fuelled electricity generator set, for instance a gas generator set. The marginal cost for a given period of operation depends on the fuel price, the efficiency of the generator and the running-history dependent maintenance costs. Furthermore, each startup of such a generator causes additional costs for maintenance and fuel. The dominant strategy in this case is bidding a price equal to the marginal operation cost.

The bidding strategy is a function of the following parameters:

p_f	[ct/m ³]	Fuel price
r_g	[Wh/m ³]	Generator fuel rate
P_g	[W]	Generator electrical power
m_r	[ct/h]	Maintenance cost rate
c_s	[ct]	Additional start-up maintenance cost
f_s	[m ³]	Additional start-up fuel rate

The marginal cost for operating the generator for a time period of Δt are:

$$c_{m,r}(\Delta t) = \left(\frac{P_g p_f}{r_g} + m_r \right) \Delta t \quad (1)$$

$$c_{m,s}(\Delta t) = c_{m,r}(\Delta t) + c_s + f_s p_f \quad (2)$$

where $c_{m,r}(\Delta t)$ is the marginal cost when the generator is already running at the start of the Δt time period, and $c_{m,s}(\Delta t)$ when it has to be started up.

Then, the optimal bidding function is given by:

$$d(p) = \begin{cases} 0 & \text{if } p < c_m \\ -P_g & \text{Otherwise} \end{cases} \quad (3)$$

where c_m equals either $c_{m,r}$ or $c_{m,s}$ depending on the running state of the generator. Note that, by definition, $d(p)$ is negative in case of supply, hence the minus sign before the P_g term.

Note: This bidding strategy depends entirely on the cost parameters of the generator. The market price history does not play a role in this strategy.

Fully price history based

At the other extreme is the bidding strategy of an electricity storage facility. Systems like batteries, flywheels and pumped storage, charging from the electricity grid at one time and discharging to it at another. Here, the aim of the agent is to buy electricity in periods of low prices, store it and resell in periods of high prices. Here, the notion of what defines the “high price” or “low price” is crucial in the agent’s bidding strategy. Maximizing the agent’s utility comes down to determining the charge/discharge price that yields the best profit. This *optimal price set* is entirely dependent on the dynamic price characteristics of the market environment plus the time needed for a full charge or discharge.

Charging and discharging a storage device is subject to *round-trip energy losses*. Note that, for the operation of a storage system to be profitable in the long run, the margin between the buy price and the resell price must exceed the costs for these losses. However, these costs do not influence the optimal price levels themselves.

Therefore, the agent requires some kind of function \mathcal{E} that yields estimates of the optimal charge and discharge prices given the current price history and the charging/discharging time:

$$\langle \bar{p}_c, \bar{p}_d \rangle = \mathcal{E}(H_p, T_s) \quad (4)$$

$$T_s = C_s / P_s \quad (5)$$

where:

P_s	[W]	Storage charging/discharging power
C_s	[Wh]	Storage capacity
T_s	[h]	Storage charging/discharging time
H_p	[ct]	Price history vector

Based on these estimated price levels the bidding function is given by:

$$d(p) = \begin{cases} P_s & \text{if } p < \bar{p}_c \\ -P_s & \text{if } p > \bar{p}_d \\ 0 & \text{Otherwise} \end{cases} \quad (6)$$

The long-run profit is highly dependent on the quality of the estimator \mathcal{E} , which must operate in dynamic market environments whose characteristics will be unknown at design time for most cases.

Mixed strategy

This case is based on configurations found in installations supplying heat to residential areas. These systems typically consist of a combination of one or more CHPs plus one or more traditional gas heaters and a heat storage buffer. Here, we assume that the installation has one CHP and one heater. The marginal cost levels depend on the following parameters:

η_{chp}^t	[]	Thermal efficiency of the CHP
η_{chp}^e	[]	Electrical efficiency of the CHP
η_{htr}	[]	Thermal efficiency of the heater
p_g	[ct]	Gas price
H_c	[kJ/m ³]	Gas combustion heat
T_{max}	[°C]	Upper limit heat buffer temperature
T_{min}	[°C]	Lower limit heat buffer temperature

The heat demanded by the residential area is subtracted directly from the heat buffer. The local control goal of the CHP/heater combination is to keep the inner temperature of the buffer, T , between thermal limits T_{max} and T_{min} . Hence, the buffer level is defined as:

$$L_B = \frac{T - T_{min}}{T_{max} - T_{min}} \quad (7)$$

To prevent the buffer from over or under heating, three levels are defined at which special control actions are to be taken:

- L_H : High buffer level: just below the fill level of 100%. Above this level both the CHP and the heater must be switched off to prevent overheating. CHP operation is only possible in combination with heat dump, if that is technically possible (and ethically acceptable).
- L_L : Low buffer level: the level under which either the heater or the CHP must be switched on to prevent under heating.
- L_{LE} : Low emergency level: just above 0%. Below this level both heater and CHP must be switched on.

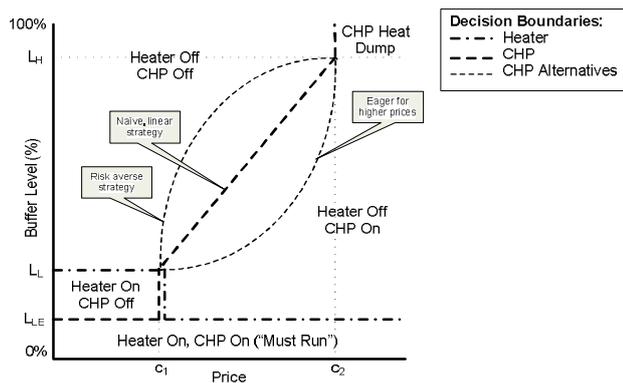


Figure 1: Bid strategy of a Heater/CHP combination as found in heat network systems delivering heat to residential areas. The strategy is well-defined below c_1 , the marginal cost for CHP-produced electricity when heat demand is high, and above c_2 , the CHP’s marginal electricity cost when there is no heat demand at all.

These levels define four different operation modes (see Figure 1):

1. Below L_{LE} the high heat demand is the dominant factor in the operation of the installation. This is a must-run situation for both CHP and heater, regardless of the electricity price.
2. Between L_{LE} and L_L there is a heat demand that could be met by either the heater or the CHP. Hence, there is a choice of producing this heat using the heater or the CHP. In the latter case, the operating costs will be higher (as the thermal efficiency of the heater will typically be higher than that of the CHP), with additional electricity production in return. While the heat demand is covered by the CHP, the marginal cost of the additional electricity production is equal to:

$$c_1 = c_{chp}^t - c_{htr}^t \quad (8)$$

where c_{chp}^t is the marginal cost for heat produced by

the CHP regardless the value of the co-produced electricity, and c_{htr}^t is the marginal cost for the heater-produced heat:

$$c_{chp}^t = \frac{p_g}{H_c} \eta_{chp}^t \quad (9)$$

$$c_{htr}^t = \frac{p_g}{H_c} \eta_{htr}^t \quad (10)$$

The CHP is operated when the market price for electricity is higher than c_1 , otherwise the heater is operated.

3. Above buffer level L_H , there is no heat demand. Hence, there is a choice to run the CHP and dump the produced heat. Even if the installation is not technically capable to discard CHP-produced heat, the marginal cost level of this option is of interest as it provides one of the strategy boundaries of the forth operation mode. During CHP operation, just for electricity production, the marginal cost for the electricity equals to:

$$c_2 = \frac{p_g}{H_c} \eta_{chp}^e \quad (11)$$

If the market price is above c_2 , it is profitable to run the CHP, even when the produced heat is discarded.

4. In the region between L_L and L_H , there is a high level of freedom to let the CHP run dependent on the electricity price. At both boundaries of this region, the bidding strategy is well defined: at level L_L it is profitable to produce whenever $p > c_1$, while at level L_H it is profitable to produce whenever $p > c_2$. The ‘ignorant’ strategy would be to connect these two points linearly. However, dependent on both the dynamic price characteristics of the market and the used risk profile different trajectories are possible. In Figure 1, two alternative strategies are shown. The risk-averse strategy tries to avoid must-run situations for both CHP and heater by taking the chance to fill the buffer whenever it is profitable to run the CHP. The other alternative strategy waits for higher prices to operate the CHP, with a higher risk of missing profit opportunities and ending in the must-run regions for heater and CHP.

BID STRATEGY SPECTRUM

As becomes apparent, there exists a spectrum of DER bidding strategies. On one end of the spectrum, bidding strategies are based straightforwardly on true marginal cost or benefit. Along the spectrum, optimal bidding strategies become less dependent on marginal cost levels and more on the price dynamics in the (VPP) market context. As may be clear from the description of the CHP/Gas Heater combination, price-dynamics based strategies are not unambiguously defined but are dependent on a desired risk level.

In Figure 2, the relative positions of a number of DER units are shown. Below, we discuss briefly the spectrum position of units not described previously.

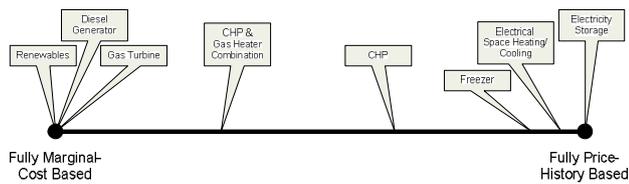


Figure 2- Bid Strategy Spectrum for Distributed Energy Resources based on momentary marginal cost levels.

- **Renewables:** Generators of renewable power, such as wind turbines and photo-voltaic solar systems, typically have low marginal costs associated with them, as these consist mainly of maintenance costs. Fuel costs, the main marginal cost component for most other generation types, are essentially absent here. Therefore, the dominant strategy of renewables is to generate at any going electricity price. This positions them at the marginal-cost based extreme of the spectrum.
- **CHP & Gas Heater Combination:** The bidding strategy of this configuration is partly based on clear marginal-cost levels and partly on price dynamics, as described in the analysis above. As the two marginal costs (8) and (11) define an important part of the strategy, this DER type is positioned in the left-hand side of the spectrum in Figure 2.
- **CHP with heat buffer:** In high-price situations, the bidding strategy of a solitaire CHP is similar to that of the CHP/Heater combination. The marginal cost for CHP produced electricity in the (theoretical) heat-dump case (c_2 in Figure 1) is applicable here as well. However, the low-price behavior is dependent on the value attached (by the user) to a reliable heat supply and the risk level one allows for occasionally not being able to cover the heat demand entirely. Minimizing this risk is highly dependent on the prevailing price-dynamic characteristics. Hence, the position of CHPs in the right-hand side of the spectrum.
- **Direct Electrical Space Heating or Cooling:** Modern building constructions show relatively high degrees of thermal inertness. This can give some degree of freedom in the operation of systems for space heating and cooling, but is dependent on the current temperature and the temperature desired by the user. As field experiences learn, it is possible to shift cooling or heating periods forward or backward in time without infringing user comfort [4]. Here, the agent strategy goal is to provide the desired comfort level against minimal electricity costs, shifting cooling/heating actions towards low-priced periods as much as possible. Comparable to the strategy for storage units, the notion of what 'low prices' actually are is crucial for a successful strategy. This locates this DER type directly in the price-history based end of the spectrum. However, as experiences with demand response programs aiming at influencing user behavior learn, most users are willing to offer some comfort in order to

avoid periods of high tariffs. Due to this, we position Direct Electrical Space Heating or Cooling just left of the spectrum end.

- **Freezer:** The case of a freezer is similar to that of that of space heating/cooling described above, hence the position near the price-history based end of the spectrum. As a minor difference, for this instance, the cost of 'lost service' is known as this equals to the total value of the stored food items.

CONCLUSION AND DISCUSSION

A bid strategy spectrum exists for DER units being part of a VPP delivering (near-) real-time balancing services. On one end of the spectrum, bidding strategies are based straightforwardly on true marginal cost or benefit. On the other spectrum end, optimal bidding strategies are dependent on the price dynamics in the (VPP) market context and the desired maximum risk level.

These results are relevant both from business economic and technical perspectives:

- **Business economic relevance:** our results contribute to the understanding of the business economics of Virtual Power Plants. A good understanding of marginal cost mechanisms of DER units participating in a VPP gives better insight to the profitability factors of the VPP.
- **Technical relevance:** the technical challenge is to design VPPs that find an optimal division of work in a given cluster of distributed generators and demand response resources under all circumstances. As shown, the merit order in a VPP is highly dependent on the local context at the DER units in the VPP's cluster. Insight in these dependencies is necessary to design optimal VPPs.

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