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The Impact of Energy Storage on Micro-grid: A Multi-Agent Game Theory Approach

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Abstract It is difficult to balance the power between demand and generation in electrical networks with the rise of distributed energy resources (DERs), especially for the uncertainty of renewable generation. Smart grid concepts have been developed to solve this problem. A set of distributed generation, demand flexibility and energy storage devices are locally managed to minimize the local total generation cost. However, impacts of energy storage on micro-grid has not been explored yet. In this paper, a local smart market based on a multi-agent system is presented to provide for the quantitative evidence of the beneficial impact of flexibility enabled by demand flexibility and energy storage in limiting market power by distributed generation (DG) units. Quantitative analysis is proposed by a bi-level optimization model of the micro-grid setting, accounting for the operational constraints of energy storage. This bi-level problem is solved after converting it into a Mathematical Program with Equilibrium Constraints (MPEC) and linearizing the latter through suitable techniques. Case studies demonstrate the effectiveness of the proposed method.

Keywords: *bi-level optimization, micro-grid, multi-agent system, energy storage, a mathematical program with equilibrium constraints*

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1. Introduction

Several authors consider micro-grid as the evolution of the electrical network [1,2]. They supposed that renewable energies should be distributed in the networks, information technologies should be used for their control, and that flexible demand and storage systems should be necessaries for balancing energy in the grid and avoiding curtailment [3].

The main disadvantage of micro-grid is that it needs more complex distributed control systems. The Multi-Agent Systems (MAS) [4] converge with smart grid because agents are autonomous, share information and can move by information networks. These features make MAS a good candidate to develop control and management systems for smart grids. Several market models for smart grid based on multi-agent have been developed [5,6].

A local market defining the rules to exchange energy among producers and consumers is required. Ramos et al. [7] did a review of local markets from a flexibility view, where the main characteristic of the smart grids is their possibility to offer flexibility in the contracts from the existing wholesale markets, from the creation of a separate platform, and from a reserve market approach.

The mechanisms used to set the price are two: pay-as-cleared pricing and pay-as-bid pricing. In the first method, an auctioneer matches demand and generation, and all participants pay the price of the last technology to enter. Double-sided auctions consist of an auctioneer that collects the offers and bids from all agents and with an auction that determines the winning offers [8,9,10]. The main problem with this method is the course of dimensionality. Some authors [11-16] used simultaneous auctions to solve it. In the second method, buyers submit a price-quantity bid and the sellers paid this price for the amount desired. This method is less used, but it is easier to understand in small communities as a micro-grid. In other methods, the market can be oriented to price when the price determines the amount of energy that every actor will produce or consume [15,16]. And it can be oriented to resources when the price is determined to assign all resources [17,18,19,20,21].

The method presented in this paper has several characteristics that make it different and easy. It is oriented to small communities and non-experts. The price is fixed by pay-as-bid and pay-as-offer pricing method, which it is more beneficial for everyone. The local market allows maintaining differences in prices. And it is an incentive to create micro-grids and improve them. The energy exchange among local agents allows ensuring the competition among generators. This paper provides quantitative evidence of the beneficial impact of flexibility enabled by energy storage in limiting market power by DG units. Quantitative analysis is supported by a bi-level optimization model of the imperfect electricity market setting, whose upper level represents the profit maximization objective of strategic DG units and the lower level represents the local market clearing including the time coupling operational constraints of energy storage. This bi-level problem is solved after converting it to a Mathematical Program with Equilibrium Constraints (MPEC), by replacing the lower level problem by its equivalent Karush-Kuhn Tucker (KKT) optimality conditions. Case studies with this MPEC model on a test market quantitatively demonstrate the benefits of energy storage in reducing the generation profit increase driven by the exercise of market power by generation companies.

The rest of this paper is organized as follows. Section III outlines models of generation and energy storage market participants. Section IV formulates the bi-level optimization problem and the corresponding MPEC problem expressing the decision making of strategic DG units. Case studies and illustrative results are presented in Section V. Finally; Section VI discusses conclusions of this work.

2. Market Participants Modeling.

A. Strategic Generation Companies

For presentation clarity reasons and without loss of generality, we assume that each generation company owns a single generation unit, in which the quadratic cost function, linear marginal cost function and output limits are as follows:

$$C_{i,t}\left(g_{i,t}\right) = b_i^G g_{i,t} + c_i^G \left(g_{i,t}\right)^2 \tag{1}$$

$$MC_{i,t}\left(g_{i,t}\right) = b_i^G + 2c_i^G g_{i,t} \tag{2}$$

$$0 \le g_{i,t} \le g_i^{max}, \forall t. \tag{3}$$

Strategic generation companies can exercise market power through either submitting offers higher than their actual marginal costs (i.e., economic withholding) [1]. Following the model employed in [4,22,23], the strategic marginal cost function is expressed by Eq.(4), where the value of the decision variable $k_{i,t} \ge 1$ represents the strategic behavior of DG unit i at time period t.

$$SC_{i,t}\left(g_{i,t}\right) = k_{i,t}\left(b_i^G + 2b_i^G g_{i,t}\right). \tag{4}$$

If $k_{i,t} = 1$, DG unit i behaves competitively and reveals its actual marginal costs to the market at t. If $k_{i,t} > 1$, DG unit i behaves strategically and reports higher than its actual marginal costs to the market at t. DG unit i should determine the value of $k_{i,t}$ by accounting for the trade-off between higher market clearing price and lower clearing quantity. More specifically, a higher $k_{i,t}$ will tend to increase the market price at t, but at the same time it will tend to decrease the quantity sold by DG unit i at t, since companies with lower submitted costs may replace i in the merit order and / or the demand side and the energy storage may reduce the demand at t.

B. Energy Storage

Single energy storage e unit in the system is assumed, the operational characteristics of which are expressed by Eq.(5)- Eq.(9). Constraint Eq.(5) expresses the energy balance in the storage unit including charging and discharging losses. Constraint Eq.(6) corresponds to its maximum depth of discharge and state of charge ratings. Constraints Eq.(7)-Eq.(8) represent its power limits. For the sake of simplicity, the storage energy content at the start and the end of the examined temporal horizon are assumed Eq.(9).

$$E_{e,t} = E_{e,t-1} + \eta_e^c s_{e,t}^c - s_{e,t}^d / \eta_e^d, \forall t \tag{5}$$

$$E_e^{min} \le E_{e,t} \le E_e^{max}, \forall t \tag{6}$$

$$0 \le s_{e,t}^c \le s_e^{max}, \forall t \tag{7}$$

$$0 \le s_{e,t}^d \le s_e^{max}, \forall t \tag{8}$$

$$E_{e,0} = E_{e,T}. \tag{9}$$

3. Modeling Non-Competitive Electricity Markets with Demand Shifting and Energy Storage

A. Bi-level Structure

The interaction between distributed generators and the local market operator is structured as Figure 1. The upper-level decision maker of distributed generators submits their strategic offers to the lower level local market operator. The local market operator collects the strategic offers submitted by the upper level distributed generators and other competitive distributed generators as well as the system over demand, then clears the market day-ahead according to the supply-demand curve.

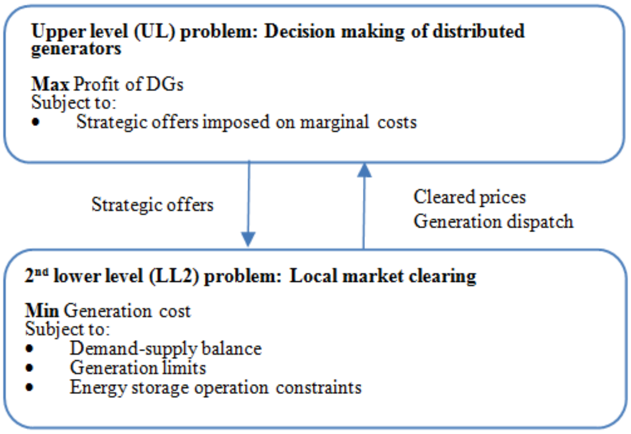


Figure 1. Bi-level structure of strategically distributed generators

B. Bi-level Optimization Model

Following the approach employed in [22,27], the decision making of strategic DG unit is modeled through a bi-level optimization problem. The upper level determines the optimal offering strategies by maximizing the profit of the DG unit and is subject to the lower level problem representing the market clearing process including the operational constraints of energy storage. These two problems are coupled since the offering strategies determined by the upper-level problem affect the objective function of the lower level problem while the market clearing price and generation dispatch determined by the lower level problem affect the objective function of the upper-level problem. The bi-level optimization model representing this monopoly setting is formulated as follows:

(Upper level)

$$\max_{k_{i,t,\omega}} \sum_{i,t,\omega} P_\omega \left[\lambda_{t,\omega} g_{i,t,\omega} - C_{i,t}\left(g_{i,t}\right)\right] \quad (10)$$

Subject to:

$$k_{i,t,\omega} \geq 1, \forall i, \forall t, \forall \omega \quad (11)$$

(Lower level)

$$\min_{\boldsymbol{VL}} \sum_{i,t,\omega} k_{i,t,\omega} C_{i,t}\left(g_{i,t}\right) \quad (12)$$

Where:

$$\begin{aligned} \boldsymbol{VL} = & \left[g_{i,t,\omega}, \forall i, \forall t, \forall \omega\right] \bigcup \left[s^c_{e,t,\omega}, \forall e, \forall t, \forall \omega\right] \\ & \bigcup \left[s^d_{e,t,\omega}, \forall e, \forall t, \forall \omega\right] \bigcup \left[E_{e,t,\omega}, \forall e, \forall t, \forall \omega\right]. \end{aligned} \quad (13)$$

Subject to:

$$\begin{aligned} & \sum_j d_{j,t} + \sum_{e,\omega} (s^c_{e,t,\omega} - s^d_{e,t,\omega}) - \sum_{i,\omega} g_{i,t,\omega} - \sum_{i,\omega} g_{i,t,\omega} \\ & = 0 : \lambda_{t,\omega}, \forall t, \forall \omega \end{aligned} \quad (14)$$

$$0 \leq g_{i,t,\omega} \leq g_i^{max} : \square\mu^-_{i,t,\omega}\ \mu^+_{i,t,\omega}, \forall i, \forall t, \forall \omega \quad (15)$$

$$\begin{aligned} E_{e,t,\omega} = & E_{e,t-1,\omega} + \eta^c_e s^c_{e,t,\omega} \\ & - s^d_{e,t,\omega} / \eta^d_e : \rho_{e,t,\omega}, \forall e, \forall t, \forall \omega \end{aligned} \quad (16)$$

$$E_e^{min} \leq E_{e,t,\omega} \leq \beta E_e^{max} : \sigma^-_{e,t,\omega}, \sigma^+_{e,t,\omega}, \forall e, \forall t, \forall \omega \quad (17)$$

$$0 \leq s^c_{e,t,\omega} \leq s_e^{max} : \varphi^-_{e,t,\omega}, \varphi^+_{e,t,\omega}, \forall e, \forall t, \forall \omega \quad (18)$$

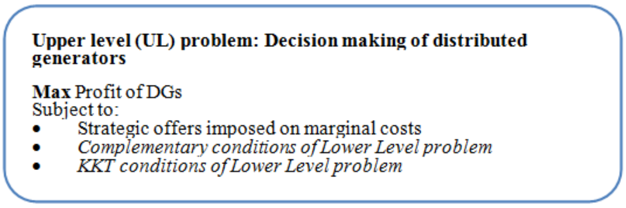
$$0 \leq s^d_{e,t,\omega} \leq s_e^{max} : \chi^-_{e,t,\omega}, \chi^+_{e,t,\omega}, \forall e, \forall t, \forall \omega \quad (19)$$

$$E_{e,0,\omega} = E_{e,T,\omega} : \psi_{e,\omega}, \psi_{e,\omega}, \forall e, \forall \omega. \quad (20)$$

The objective function Eq.(10) of the upper-level problem constitutes the total profit of the DG unit. This problem is subject to the limits of the strategic offer variables Eq.(11) and the lower level problem Eq.(12)-Eq.(20). The latter represents the micro-grid local market clearing process at each time-period, minimizing total generation cost Eq.(12). The constraints subject to demand-supply balance Eq.(14) (the Lagrangian multipliers of which constitute the market clearing prices), generation output limits Eq.(15) and the operational constraints of the energy storage Eq.(26)-Eq.(20), with a fixed demand profile.

C. MPEC Formulation

To solve the above-given bi-level optimization problem, the lower level problem is replaced by its KKT optimality conditions, which is enabled by the continuity and convexity of the lower level problem.



Upper level (UL) problem: Decision making of distributed generators

Max Profit of DGs
Subject to:
- Strategic offers imposed on marginal costs
- *Complementary conditions of Lower Level problem*
- *KKT conditions of Lower Level problem*

Figure 2. Bi-level structure of strategically distributed generators

This converts the bi-level problem into a Mathematical Program with Equilibrium Constraints (MPEC). The MPEC is formulated as follows:

$$\max_{\boldsymbol{V}} \sum_{i,t,\omega} P_\omega \left[\lambda_{t,\omega} g_{i,t,\omega} - C_{i,t}\left(g_{i,t}\right)\right] \quad (21)$$

Where:

$$\begin{aligned} \boldsymbol{V} = & \left[k_{i,t,\omega}, \forall i, \forall t, \forall \omega\right] \bigcup \left[g_{i,t,\omega}, \forall i, \forall t, \forall \omega\right] \\ & \bigcup \left[s^c_{e,t,\omega}, \forall e, \forall t, \forall \omega\right] \bigcup \left[s^d_{e,t,\omega}, \forall e, \forall t, \forall \omega\right] \\ & \bigcup \left[E_{e,t,\omega}, \forall t\right] \bigcup \left[\lambda_{t,\omega}, \forall t, \forall \omega\right] \\ & \bigcup \left[\mu^-_{i,t,\omega}, \mu^+_{i,t,\omega}, \forall i, \forall t, \forall \omega\right] \\ & \bigcup \left[\rho_{e,t,\omega}, \forall e, \forall t, \forall \omega\right] \\ & \bigcup \left[\sigma^-_{e,t,\omega}, \sigma^+_{e,t,\omega}, \forall e, \forall t, \forall \omega\right] \\ & \bigcup \left[\varphi^-_{e,t,\omega}, \varphi^+_{e,t,\omega}, \forall e, \forall t, \forall \omega\right] \\ & \bigcup \left[\chi^-_{e,t,\omega}, \chi^+_{e,t,\omega}, \forall e, \forall t, \forall \omega\right] \\ & \bigcup \left[\psi_{e,\omega}, \forall e, \forall \omega\right]. \end{aligned} \quad (22)$$

Subject to:

$$k_{i,t,\omega} \geq 1, \forall i, \forall t, \forall \omega \quad (23)$$

$$\begin{aligned} & k_{i,t,\omega} MC_{i,t}\left(g_{i,t}\right) - \lambda_{t,\omega} - \mu^-_{i,t,\omega} + \mu^+_{i,t,\omega} \\ & = 0, \forall i, \forall t, \forall \omega \end{aligned} \quad (24)$$

$$\begin{aligned} & \lambda_{t,\omega} - \eta^c_e \rho_{e,t,\omega} - \varphi^-_{e,t,\omega} + \varphi^+_{e,t,\omega} \\ & = 0, \forall e, \forall t, \forall \omega \end{aligned} \quad (25)$$

$$-\lambda_{t,\omega} + \rho_{e,t,\omega}/\eta^d_e - \chi^-_{e,t,\omega} + \chi^+_{e,t,\omega} = 0, \forall e, \forall t, \forall \omega \quad (26)$$

$$\rho_{e,t,\omega} - \rho_{e,t+1,\omega} - \sigma^-_{e,t,\omega} + \sigma^+_{e,t,\omega} = 0, \forall e, \forall t < T, \forall \omega \quad (27)$$

$$\rho_{e,T,\omega} - \sigma^-_{e,T,\omega} + \sigma^+_{e,T,\omega} - \sigma^+_{e,T,\omega} = 0, \forall e, \forall \omega \quad (28)$$

$$E_{e,t,\omega} = E_{e,t-1,\omega} + \eta^c_e s^c_{e,t,\omega} - s^d_{e,t,\omega}/\eta^d_e, \forall e, \forall t, \forall \omega \quad (29)$$

$$E_{e,0,\omega} = E_{e,T,\omega}, \forall e, \forall \omega \quad (30)$$

$$0 \leq \mu^-_{i,t,\omega} \perp g_{i,t,\omega} \geq 0, \forall i, \forall t, \forall b, \forall \omega \quad (31)$$

$$0 \leq \mu^+_{i,t,\omega} \perp \left(g_i^{max} - g_{i,t,\omega}\right) \geq 0, \forall i, \forall t, \forall \omega \quad (32)$$

$$0 \leq \sigma^-_{e,t,\omega} \perp \left(E_{e,t,\omega} - E_e^{min}\right) \geq 0, \forall e, \forall t, \forall \omega \quad (33)$$

$$0 \leq \sigma^+_{e,t,\omega} \perp \left(E_e^{max} - E_{e,t,\omega}\right) \geq 0, \forall e, \forall t, \forall \omega \quad (34)$$

$$0 \leq \varphi^-_{e,t,\omega} \perp s^c_{e,t,\omega} \geq 0, \forall e, \forall t, \forall \omega \quad (35)$$

$$0 \leq \varphi^+_{e,t,\omega} \perp \left(s_e^{max} - s^c_{e,t,\omega}\right) \geq 0, \forall e, \forall t, \forall \omega \quad (36)$$

$$0 \leq \chi^-_{e,t,\omega} \perp s^d_{e,t,\omega} \geq 0, \forall e, \forall t, \forall \omega \quad (37)$$

$$0 \leq \chi^+_{e,t,\omega} \perp \left(s_e^{max} - s^d_{e,t,\omega}\right) \geq 0, \forall e, \forall t, \forall \omega. \quad (38)$$

The set of decision variables Eq.(22) includes the decision variables of the upper level and the lower level problem as well as the Lagrangian multipliers associated with the constraints of, the lower level problem. The KKT optimality conditions of the lower level problem correspond to equations Eq.(31)-Eq.(38).

4. Case Studies

A. Test Data and Implementation

The examined studies demonstrate the impact of energy storage on the market power exercised by generation companies in a test market with the day-ahead horizon, hourly resolution and generation/demand data reflecting the general properties of a micro-grid system.

The micro-grid system includes 7 DG units, the cost coefficients and maximum output limits of which are given in Table 1. Figure 3 presents the demand profile $d_{j,t}$, which follow the daily pattern of consumers' activities. We assume that the expected power output of renewable generation in the micro-grid is 10% of the system baseline demand, and following the normal distribution with 10 equal-probability scenarios, presented in Figure 4.

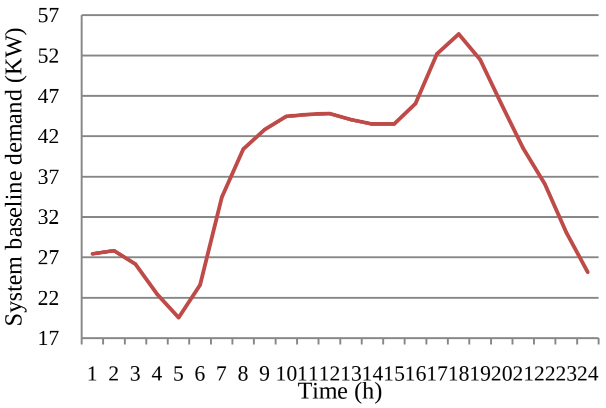


Figure 3. Hourly values of system baseline demand

Table 1. DG Unit Parameters

DG unit *i*	1	2	3	4	5	6	7
b_i^G (£/KW)	10	15	23	35	50	70	100
c_i^G (£/KW^2)	0.0001	0.0006	0.0014	0.0026	0.0042	0.0065	0.001
g_i^{max} (KW)	13,170	11,520	7,560	6,670	6,500	5,760	5,500

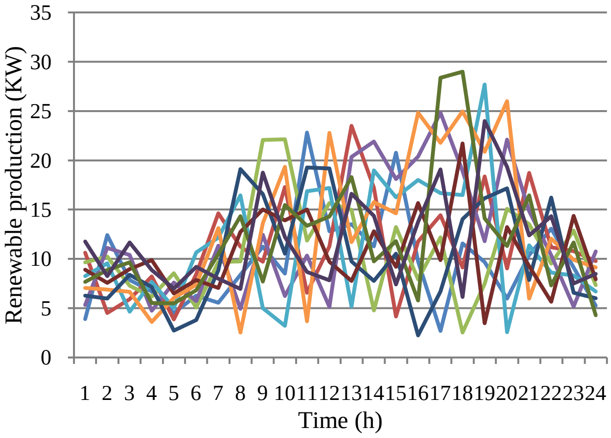


Figure 4. Wind production with uncertainties

In order to analyze the impact of energy storage, different scenarios are examined regarding the size of energy storage, as expressed by its capacity E^{cap} as a percentage β of the daily energy demand. The assumed values of the rest of the energy storage operational parameters are given in Table 2.

Table 2. Energy Storage Parameters

Parameter	E^{min}	E^{max}	E_0	s^{max}	η^c	η^d
Value	$0.2E^{cap}$	βE^{cap}	$0.25E^{cap}$	$0.5E^{cap}/1\text{h}$	0.9	0.9

The MILP problem has been coded and solved using the optimization software FICO^{TM} Xpress [28] on a computer with a 6-core 3.47 GHz Intel(R) Xeon(R) X5690 processor and 192 GB of RAM. The average computational time required for solving the MILP problem across all the examined scenarios was around 10s.

B. Impact of Energy Storage

The exercise of market power by the generation side increases its profit while it decreases the utility of the demand side. Figure 5 presents the system demand with different energy storage capacity scenarios. It can be found that as the capacity increases, more and more energy is stored during the peak periods with low price and discharged during the periods with high prices, leading to a flatter system demand.

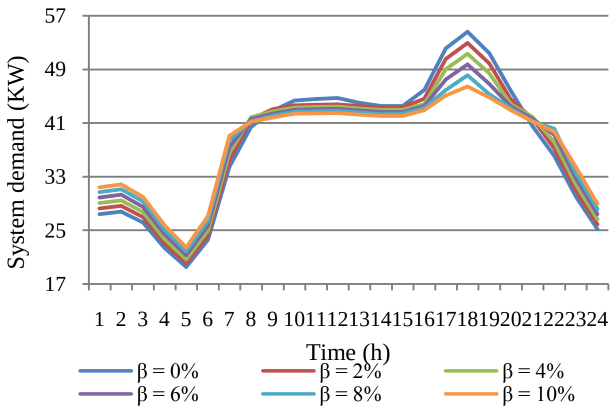


Figure 5. Hourly system demand for different energy storage scenarios

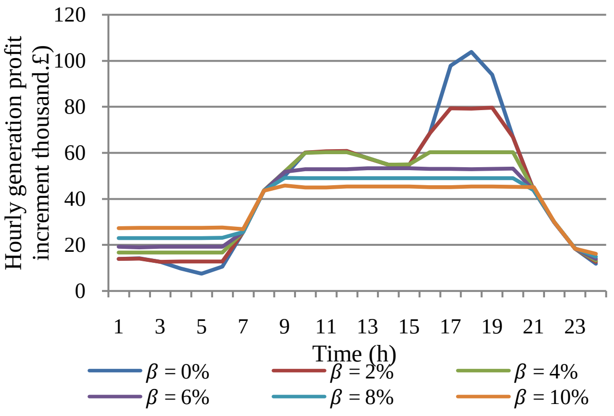


Figure 6. Hourly generation profit increment drove by the exercise of market power for different energy storage scenarios

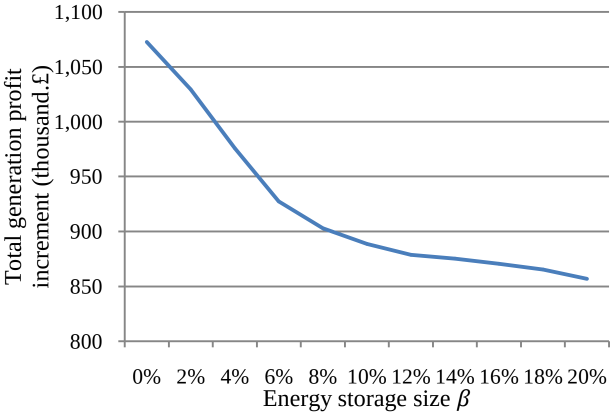


Figure 7. Total generation profit increment and demand utility decrement drove by the exercise of market power for different energy storage scenarios

Figure 6 present the increment of the generation side's hourly profit driven by the exercise of market power, i.e. the difference between the profit obtained under strategic generation behavior (as determined by the solution of the MPEC problem Eq.(21)-Eq.(38)) and the profit obtained under competitive generation behavior (as determined by the solution of the market clearing problem Eq.(12)-Eq.(20) with $k_{i,t,\omega} = 1, \forall i, \forall t, \forall \omega$), for different scenarios of energy storage capacity. The energy storage reduces the hourly generation profit increment during peak hours and increases it during off-peak hours, with the former reduction being significantly higher than the latter increase. These effects are enhanced as the size of energy storage is increased. Due to the fact that the positive impact of energy storage during peak hours is more significant than its negative impact during off-peak hours, the total (daily) generation profit increment driven by the exercise of market power are significantly reduced as the size of energy storage is increased, as illustrated in Figure 7. This result means that deployment of energy storage reduces the generation profit made by the exercise of market power, and allows consumers to more efficiently preserve their economic surplus against generation companies' strategic behavior.

5. Conclusions and Future Work

This paper has provided for the theoretical and quantitative evidence of the beneficial impact of energy storage in limiting market power by strategic generation companies. Theoretical explanation of this impact has been presented through a simple price-quantity graph, demonstrating that storage reduces the extent of exercised market power at peak periods and increases it at off-peak periods, with the former reduction dominating the latter increase and resulting in an overall positive impact. Quantitative analysis has been supported by a bi-level optimization model of imperfect electricity markets, accounting for the time-coupling operational constraints of energy storage and solved by converting it to an MPEC. Case studies with this MPEC model on a test market with the day ahead horizon and hourly resolution have quantitatively demonstrated the benefits of storage in limiting market power. Increasing storage capacity has been shown to reduce the generation profit made by the exercise of market power, and allow consumers to more effectively preserve their economic surplus against generation companies' strategic behavior.

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Conflict of Interest

The authors indicate no potential conflicts of interest.

Nomenclature

A. Indices

t	Index of time periods, running from 1 to T
i	Index of DG units, running from 1 to I
b	Index of generation blocks, running from 1 to B
j	Index of consumers, running from 1 to J
e	Index of energy storage units, running from 1 to E
ω	Index of uncertainty scenarios, running from 1 to W

B. Parameters

l_i^G	Linear cost coefficient of generation company i (£/MW)
q_i^G	Quadratic cost coefficient of generation company i (£/MW^2)
g_i^{max}	Maximum power output limit of generation company i (MW)
$d_{j,t}$	Power input of consumer j at time period t (MW)
s_e^{max}	Power limit of energy storage e (MW)
E_e^{cap}	Capacity of energy storage e (MWh)
E_e^{min}	Minimum energy limit of energy storage e (MWh)
E_e^{max}	Maximum energy limit of energy storage e (MWh)
E_e^0	Initial energy level in energy storage e (MWh)
η_e^c	Charging efficiency of energy storage e
η_e^d	Discharging efficiency of energy storage e
$g_{i,t,\omega}$	Power output of distributed renewable units i at time period t for uncertainty scenario ω (MW)
P_ω	Probability for uncertainty scenario ω

C. Variables

$k_{i,t,\omega}$	Strategic offer variable of DG units i at time period t for uncertainty scenario ω
$g_{i,t,\omega}$	Power output of DG units i at time period t for uncertainty scenario ω (MW)
$s_{e,t,\omega}^c$	Charging power of energy storage e at time period t for uncertainty scenario ω (MW)
$s_{e,t,\omega}^d$	Discharging power of energy storage e at time period t for uncertainty scenario ω (MW)
$E_{e,t,\omega}$	Energy level in energy storage e at the end of time period t for uncertainty scenario ω (MW)
$\lambda_{t,\omega}$	Market clearing price at time period t for uncertainty scenario ω (£/MW)

D. Functions

$C_{i,t}$	Cost of block b of DG units i at time period t (£)
$MC_{i,t}$	Marginal cost of block b of DG units i at time period t (£/MW)
$SC_{i,t}$	Strategic marginal cost of block b of DG units i at time period t (£/MW)

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