Strategic Capacity Withholding by Energy Storage in Electricity Markets

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Abstract—**Although previous work has demonstrated the ability of large energy storage (ES) units to exercise market power by withholding their capacity, it has adopted modeling approaches exhibiting certain limitations and has not analyzed the dependency of the extent of exercised market power on ES operating properties. In this paper, the decision making process of strategic ES is modeled through a bi-level optimization problem; the upper level determines the optimal extent of capacity withholding at different time periods, maximizing the ES profit, while the lower level represents endogenously the market clearing process. This problem is solved after converting it to a Mathematical Program with Equilibrium Constraints (MPEC) and linearizing the latter through suitable techniques. Case studies on a test market quantitatively analyze the extent of capacity withholding and its impact on ES profit and social welfare for different scenarios regarding the power and energy capacity of ES.**

Index Terms—**Electricity markets, energy storage, market power, mathematical program with equilibrium constraints.**

NOMENCLATURE

A. Indices and Sets

t	Index of time periods running from 1 to T
i	Index of producers running from 1 to I
b	Index of generation blocks running from 1 to B
c	Index of demand blocks running from 1 to C

B. Parameters

T	Length of market horizon (hours)
$\lambda_{i,b}^{G}$	Marginal cost of block b of producer i (£/MWh)
$g_{i,b}^{max}$	Maximum power output of block b of producer i (MW)
λ_{t}^{D}	Marginal benefit of block c of demand at time period t (£/MWh)
$d_{t,c}^{max}$	Maximum power consumption of block c of demand at time period t (MW)
s^{max}	Power capacity of ES (MW)
E^{cap}	Energy capacity of ES (MWh)
E^{min}	Minimum energy limit of ES (MWh)
E^{max}	Maximum energy limit of ES (MWh)
E_0	Initial energy level in ES (MWh)
η^{c}	Charging efficiency of ES
η^{d}	Discharging efficiency of ES

C. Variables

k_t	Capacity withholding strategy of ES at time period t
$g_{i,t,b}$	Power output of block b of producer i at time period t (MW)
$d_{t,c}$	Power consumption of block c of demand at time period t (MW)
s_t^{c}	Charging power of ES at time period t (MW)
s_t^{d}	Discharging power of ES at time period t (MW)
E_t	Energy level in ES at the end of period t (MWh)
λ_t	Market clearing price at time period t (£/MWh)

I. INTRODUCTION

After the deregulation of the energy sector, electricity markets are better described in terms of *imperfect* rather than *perfect competition*. In this setting, market participants do not necessarily act as *price takers*. Participants of large size are able to behave strategically and exercise *market power*, i.e. influence the electricity prices and increase their profits beyond the competitive equilibrium levels, through strategic bids and offers [1]. Previous work on imperfect electricity markets has mainly focused on optimizing market strategies of strategic electricity producers [2] and consumers [3].

However, the increasing penetration of energy storage (ES) technologies, driven by their significant value in emerging low-carbon power systems [4], has recently attracted significant research interest in exploring the role of ES in imperfect electricity markets. The first aspect of this research lies in analysing the impact of ES on the extent of market power exercised by strategic producers. Our previous work has demonstrated that ES reduces the ability of exercising 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 for the social efficiency of the market [5].

The second aspect lies in exploring the potential of ES to exercise market power for its own benefit. Previous work has demonstrated the ability of large ES units to exercise market power by withholding their capacity, leading to additional storage profits but loss of social welfare [6]-[8]. However, the modeling approaches adopted in that work exhibit certain limitations. Sioshansi [6]-[7] calculates analytically market equilibria in a simplified two-period market model; this complex analytical calculation cannot be easily extended to realistic market models involving a much larger number of clearing periods. In [8], a Cournot model of imperfect electricity markets is employed, where the impact of strategic storage on market prices is modeled through an inverse demand function. However, the parameters of this function are determined through exogenous data and therefore cannot accurately capture the impacts of the market's generation and demand characteristics on price formation. Finally, none of the above papers analyses the dependency of the extent of market power exercised by strategic storage on its operational characteristics.

This paper addresses the above challenges. The decision making process of strategic storage is modeled through a *bi-level optimization problem*, where the upper level determines the optimal extent of capacity withholding by strategic storage at different time periods, maximizing the storage profit, while the lower level represents endogenously the market clearing process. This problem is solved after converting it to a *Mathematical Program with Equilibrium Constraints* (MPEC) and linearizing the latter through suitable techniques. A set of case studies on a test market with day-ahead horizon and hourly resolution quantitatively analyze the extent of capacity withholding and its impact on storage profit and social welfare at different time periods and for different scenarios regarding the power rating and energy capacity of strategic storage.

The rest of this paper is organized as follows. Section II models and theoretically demonstrates the ability of strategic storage to exercise market power through capacity withholding. Section III formulates the bi-level optimization model expressing the decision making of strategic storage and presents the equivalent MPEC and Mixed-Integer Linear Program (MILP) formulations. Case studies and illustrative results are presented in Section IV. Finally, Section V discusses conclusions and future extensions of this work.

II. Modelling and Theoretical Analysis of Energy Storage Capacity Withholding

ES can exercise market power through capacity withholding i.e. by reporting lower than its actual power capacity to the market. In order to quantitatively capture the extent of capacity withholding at different time periods, the offered charging and discharging power capacity at period t is given by the actual power capacity multiplied by a factor $(1-k_t)$, where the value of the decision variable $0 \leq k_t \leq 1$ represents the capacity withholding strategy of storage at t. If $k_t = 0$, storage behaves competitively and reveals its actual capacity to the market at t. If $k_t > 0$, storage behaves strategically and reports lower than its actual capacity to the market at t.

Fig. 1 illustrates, in a price-quantity graph, the ability of ES to exercise market power through capacity withholding in a simplified market representation involving only two periods (one peak and one off-peak period) and inelastic demand. The solid curve represents in a simplified fashion the aggregate marginal cost curve of the generation side - characterized by an increasing slope [1] - and vertical dashed lines represent the system demand in different cases; the intersection of the marginal cost curve with a vertical line determines the market clearing price in the respective case. Superscripts c and s denote competitive and strategic behavior of ES respectively, while subscripts 1 and 2 denote off-peak and peak time periods respectively.

As discussed in [5], the operation of competitive ES in the electricity market flattens the (net) demand profile by i) charging and thus increasing demand during off-peak time periods from Q_1 to Q_1^c and ii) discharging and thus reducing demand during peak time periods from Q_2 to Q_2^c. By acting strategically and offering less power capacity to the market, ES limits its flattening effect on the system demand profile, since it i) charges less and thus increases less the demand during off-peak time periods (from Q_1 to Q_1^s) and ii) discharges less and thus reduces less the demand during peak time periods (from Q_2 to Q_2^s).

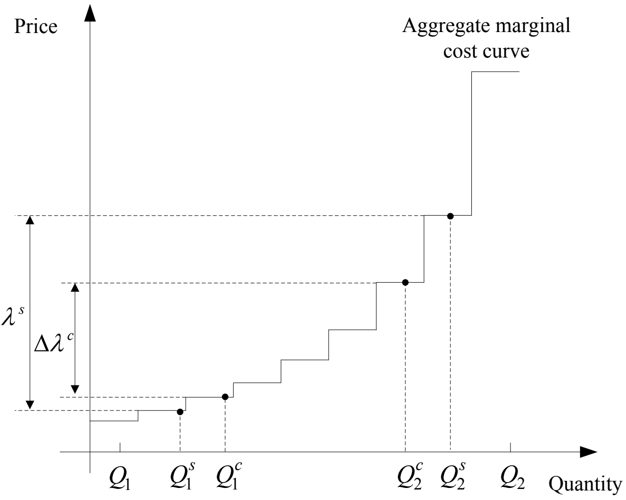

Figure 1. Illustration of market power exercise by ES through capacity withholding

Although this strategic action has a negative effect on social welfare, it can be beneficial for ES. In the example of Fig. 1, assuming a lossless ES for the sake of simplicity (implying that its charging and discharging quantities are equal, i.e. $Q_1^c - Q_1 = Q_2 - Q_2^c$ and $Q_1^s - Q_1 = Q_2 - Q_2^s$), its profit under competitive and strategic behavior is given by $\Delta\lambda^c(Q_2 - Q_2^c)$ and $\Delta\lambda^s(Q_2 - Q_2^s)$ respectively. This strategic action has a positive effect on ES profit, since it increases the price differential between peak and off-peak hours from $\Delta\lambda^c$ to $\Delta\lambda^s$, as demonstrated in Fig. 1. However, it also has a negative effect on ES profit, since it reduces the volume of energy sold by storage ($Q_2 - Q_2^s < Q_2 - Q_2^c$). This mixed effect of capacity withholding on the profit of ES means that the latter needs to optimize its capacity withholding strategies k_t in order to maximize its profit in the market.

III. OPTIMIZING CAPACITY WITHHOLDING STRATEGIES OF ENERGY STORAGE

A. Bi-level Optimization Model

Following the methodology adopted in [2] and [3] for modeling the decision making problem of strategic producers and consumers respectively, the decision making problem of strategic ES is modeled through a bi-level optimization problem, which is formulated as:

(Upper level)

$$\max_{\{k_t\}} \sum_t \lambda_t (s_t^d - s_t^c) \tag{1}$$

subject to:

$$0 \leq k_t \leq 1, \forall t \tag{2}$$

(Lower level)

$$\max_{\{g_{i,t,b}, d_{t,c}, s_t^c, s_t^d, E_t\}} \sum_{t,c} \lambda_{t,c}^D d_{t,c} - \sum_{i,t,b} \lambda_{i,b}^G g_{i,t,b} \tag{3}$$

subject to:

$$\sum_c d_{t,c} + s_t^c - s_t^d - \sum_{i,b} g_{i,t,b} = 0 : \lambda_t, \forall t \tag{4}$$

$$0 \leq g_{i,t,b} \leq g_{i,b}^{max} : \mu_{i,t,b}^-, \mu_{i,t,b}^+, \forall i, \forall t, \forall b \tag{5}$$

$$0 \leq d_{t,c} \leq d_{t,c}^{max} : \nu_{t,c}^-, \nu_{t,c}^+, \forall t, \forall c \tag{6}$$

$$E_t = E_{t-1} + \eta^c s_t^c - s_t^d / \eta^d : \xi_t, \forall t \tag{7}$$

$$E^{min} \leq E_t \leq E^{max} : \pi_t^-, \pi_t^+, \forall t \tag{8}$$

$$0 \leq s_t^c \leq (1 - k_t) s^{max} : \rho_t^-, \rho_t^+, \forall t \tag{9}$$

$$0 \leq s_t^d \leq (1 - k_t) s^{max} : \sigma_t^-, \sigma_t^+, \forall t \tag{10}$$

$$E_0 = E_T : \varphi \tag{11}$$

The upper level (UL) problem determines the optimal capacity withholding strategies k_t maximizing the profit of the ES participant (1). This problem is subject to the limits of the capacity withholding strategies (2) and the lower level (LL) problem (3)-(11). The latter represents the market clearing process, maximizing the social welfare (3), subject to demand-supply balance constraints (4) (the Lagrangian multipliers λ_t of which constitute the market clearing prices), generation and demand limits (5)-(6) and the operational constraints of ES (7)-(11).

These two problems are coupled, since the capacity withholding strategies determined by the UL problem affect constraints (9)-(10) of the LL problem, while the market clearing prices and storage charging / discharging dispatch determined by the LL problem affect the objective function (1) of the UL problem.

B. MPEC Formulation

In order to solve this bi-level optimization problem, the LL problem is replaced by its *Karush-Kuhn-Tucker* (KKT) optimality conditions, which is enabled by the continuity and convexity of the LL problem. This converts the bi-level problem to an MPEC which is formulated as:

$$\max_V \sum_t \lambda_t (s_t^d - s_t^c) \tag{12}$$

where:

$$V = \{k_t, g_{i,t,b}, d_{t,c}, s_t^c, s_t^d, E_t, \lambda_t, \mu_{i,t,b}^-, \mu_{i,t,b}^+, \nu_{t,c}^-, \nu_{t,c}^+, \xi_t, \pi_t^-, \pi_t^+, \rho_t^-, \rho_t^+, \sigma_t^-, \sigma_t^+, \varphi\} \tag{13}$$

subject to:

(2), (4), (7), (11)

$$\lambda_{i,b}^G - \lambda_t - \mu_{i,t,b}^- + \mu_{i,t,b}^+ = 0, \forall i, \forall t, \forall b \tag{14}$$

$$-\lambda_{t,c}^D + \lambda_t - \nu_{t,c}^- + \nu_{t,c}^+ = 0, \forall t, \forall c \tag{15}$$

$$\lambda_t - \rho_t^- + \rho_t^+ - \eta^c \xi_t = 0, \forall t \tag{16}$$

$$-\lambda_t - \sigma_t^- + \sigma_t^+ + \xi_t / \eta^d = 0, \forall t \tag{17}$$

$$-\pi_t^- + \pi_t^+ + \xi_t - \xi_{t+1} = 0, \forall t < T \tag{18}$$

$$-\pi_T^- + \pi_T^+ + \xi_T - \varphi = 0 \tag{19}$$

$$0 \leq \mu_{i,t,b}^- \perp g_{i,t,b} \geq 0, \forall i, \forall t, \forall b \tag{20}$$

$$0 \leq \mu_{i,t,b}^+ \perp \left(g_{i,b}^{max} - g_{i,t,b}\right) \geq 0, \forall i, \forall t, \forall b \tag{21}$$

$$0 \leq \nu_{j,t,c}^- \perp d_{j,t,c} \geq 0, \forall j, \forall t, \forall c \tag{22}$$

$$0 \leq \nu_{j,t,c}^+ \perp \left(d_{j,t,c}^{max} - d_{j,t,c}\right) \geq 0, \forall j, \forall t, \forall c \tag{23}$$

$$0 \leq \pi_t^- \perp (E_t - E^{min}) \geq 0, \forall t \tag{24}$$

$$0 \leq \pi_t^+ \perp (E^{max} - E_t) \geq 0, \forall t \tag{25}$$

$$0 \leq \rho_t^- \perp s_t^c \geq 0, \forall t \tag{26}$$

$$0 \leq \rho_t^+ \perp ((1 - k_t) s^{max} - s_t^c) \geq 0, \forall t \tag{27}$$

$$0 \leq \sigma_t^- \perp s_t^d \geq 0, \forall t \tag{28}$$

$$0 \leq \sigma_t^+ \perp ((1 - k_t) s^{max} - s_t^d) \geq 0, \forall t \tag{29}$$

The set of decision variables (13) includes the decision variables of the UL and the LL problem as well as the Lagrangian multipliers associated with the constraints of the LL problem. The KKT optimality conditions of the LL problem correspond to equations (4), (7), (11), (14)-(29).

C. MILP Formulation

However, this MPEC formulation is non-linear and thus any solution obtained by commercial solvers is not guaranteed to be globally optimal. The objective of this section is to transform this MPEC to a Mixed-Integer Linear Program (MILP) which can be efficiently solved using available commercial solvers. The above MPEC includes two types of non-linearities. The first one involves the bilinear objective function (12). In order to linearize it, we propose an approach making use of some KKT conditions. First of all, by making use of the demand-supply balance constraints (4), the objective function (12) becomes equal to:

$$\sum_{t,c} \lambda_t d_{t,c} - \sum_{i,t,b} \lambda_t g_{i,t,b} \tag{30}$$

By multiplying both sides of (14) by $g_{i,t,b}$, summing for every i, t and b and rearranging some terms we get:

$$\sum_{i,t,b} \lambda_t g_{i,t,b} = \sum_{i,t,b} \left(\lambda_{i,b}^G g_{i,t,b} - \mu_{i,t,b}^- g_{i,t,b} + \mu_{i,t,b}^+ g_{i,t,b}\right) \tag{31}$$

By multiplying both sides of (15) by $d_{t,c}$, summing for every t and c and rearranging some terms we get:

$$\sum_{t,c} \lambda_t d_{t,c} = \sum_{t,c} \left(\lambda_{t,c}^D d_{t,c} + \nu_{t,c}^- d_{t,c} - \nu_{t,c}^+ d_{t,c}\right) \tag{32}$$

By making use of (20) and (21), equation (31) becomes:

$$\sum_{i,t,b}\lambda_t g_{i,t,b} = \sum_{i,t,b}\left(\lambda^G_{i,b} g_{i,t,b} + \mu^+_{i,t,b} g^{max}_{i,b}\right) \tag{33}$$

By making use of (22) and (23), equation (32) becomes:

$$\sum_{t,c}\lambda_t d_{t,c} = \sum_{t,c}\left(\lambda^D_{t,c} d_{t,c} - \nu^+_{t,c} d^{max}_{t,c}\right) \tag{34}$$

By substituting (33) and (34) into (30), we get the following linear objective function, which replaces the non-linear objective function:

$$\sum_{t,c}\left(\lambda^D_{t,c} d_{t,c} - \nu^+_{t,c} d^{max}_{t,c}\right) - \sum_{i,t,b}\left(\lambda^G_{i,b} g_{i,t,b} + \mu^+_{i,t,b} g^{max}_{i,b}\right) \tag{35}$$

The second non-linearity involves the bilinear terms in the complementarity conditions (20)-(29), which can be expressed in the generic form $0 \leq \mu \perp p \geq 0$, with μ and p representing generic dual and primal terms respectively. The linearization approach proposed in [9] is employed to replace each of these conditions with the set of mixed-integer linear conditions $\mu \geq 0, p \geq 0, \mu \leq \omega M^D, p \leq (1-\omega)M^P$, where ω is an auxiliary binary variable and M^D and M^P are large enough positive constants. The set of decision variables of the MILP formulation includes the set (13) as well as the auxiliary binary variables introduced for linearizing (20)-(29).

IV. CASE STUDIES

The presented case studies analyze the ability of ES to exercise market power through capacity withholding in a test market with day-ahead horizon and hourly resolution, reflecting the general generation and demand characteristics of the GB power system [5]. Different scenarios are examined regarding the power rating and energy capacity of ES, while the assumed values for its other operating parameters are presented in Table I. The MILP formulation has been coded and solved using the optimization software FICO™ Xpress [10] 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 across all examined scenarios was approximately 30s.

TABLE I. ENERGY STORAGE PARAMETERS

Parameter	E^{min}	E^{max}	E_0	η^c	η^d
Value	$0.2E^{cap}$	E^{cap}	$0.25E^{cap}$	0.9	0.9

A. Quantifying the Optimal Extent of Capacity Withholding by Energy Storage

For a scenario with $s^{max} = 6$GW and $E^{cap} = 6$GWh, three cases regarding the behavior of ES in the market are compared: i) competitive behavior, where the capacity withholding strategies are set equal to $k_t = 0, \forall t$, ii) optimized strategic behavior, where the capacity withholding strategies are optimized through the model presented in Section III, and iii) naïve strategic behavior, where the capacity withholding strategies are set equal to an arbitrarily high value (in particular $k_t = 0.8, \forall t$). Fig. 2, Fig. 3 and Table II present the hourly storage charging / discharging dispatch (indicated by negative and positive values respectively), the hourly market clearing prices, and the daily storage profit respectively, under each of the three aforementioned cases.

Under competitive behavior, the energy charged and discharged by ES during off-peak and peak hours respectively is the highest (leading to a flatter net demand profile), but the price differential between peak and off-peak hours is the lowest. Under naïve strategic behavior on the other hand, the energy charged and discharged by ES is the lowest, but the price differential between peak and off-peak hours is the highest. Under optimized strategic behavior, ES determines its capacity withholding strategies based on the optimal trade-off between these two effects. Although this strategy results in lower volumes of charging / discharging energy with respect to the competitive case and lower price differential with respect to the naïve strategic case, it yields the highest total profit for ES (Table II). This result demonstrates the significance of the proposed methodology in optimizing the profit of strategic ES in the market.

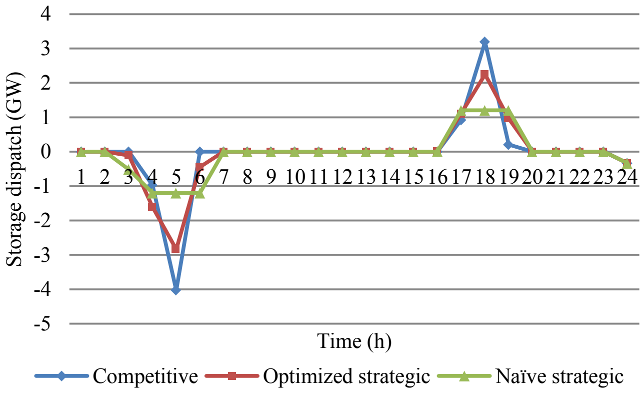

Figure 2. Hourly storage charging / discharging dispatch under different ES behaviors in the market

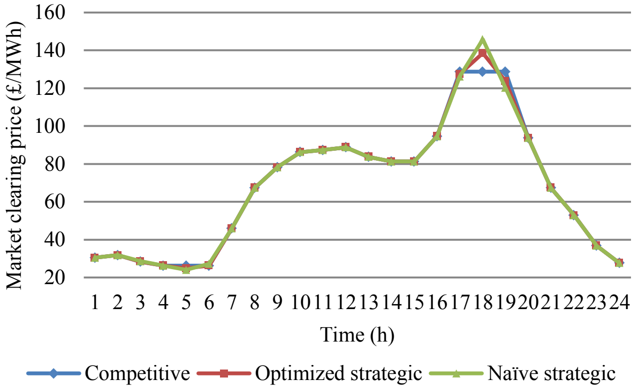

Figure 3. Hourly market clearing prices under different ES behaviors in the market

TABLE II. DAILY PROFIT OF ENERGY STORAGE UNDER DIFFERENT BEHAVIORS IN THE MARKET

Competitive	**Optimized strategic**	**Naïve strategic**
415,694 £/day	434,760 £/day	354,103 £/day

Fig. 4 presents the capacity withholding strategies k_t under optimized strategic behavior. It should be noted that during hours when ES neither charges nor discharges, (mid-peak hours in general, e.g. hours 1-2, 7-16, and 20-23 in Fig. 2), the value of k_t does not affect the ES profit, as verified by additional tests conducted by the authors; thus, Fig. 4 and similar figures in the remainder of this paper do not present any value for k_t in these hours for the sake of clarity. On the other hand, the value of k_t affects the ES profit during (off-peak) hours when ES charges (e.g. hours 3-6 in Fig. 2) and (peak) hours when ES discharges (e.g. hours 17-19 in Fig. 2). The optimal extent of exercised capacity withholding is not the same across all off-peak and peak hours. It is noticed that the hours exhibiting the lowest extent of capacity withholding in the off-peak and the peak time window are hours 5 and 18 respectively. The reason behind this trend is associated with the negative effect of capacity withholding on the volume of energy sold by ES, discussed in Section II. Since ES charges and discharges most of its energy at hours 5 and 18 respectively (Fig. 2), it is motivated to act more truthfully during these hours.

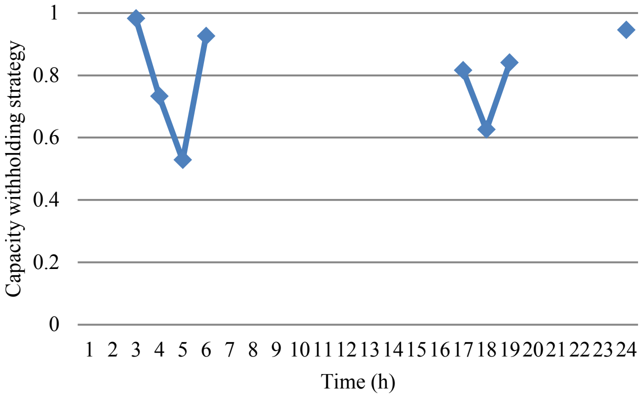

Figure 4. Capacity withholding strategies under optimized strategic ES behavior

D. *Impact of ES Power Rating and Energy Capacity*

Two case studies are investigated in this section. In the first one, the optimal decision making problem of strategic ES has been solved using an ES energy capacity of $E^{cap} =$ 6GWh, and different values for its power rating s^{max}, in order to investigate the impact of the latter on the extent of exercised market power. Fig. 5 presents the optimal capacity withholding strategies k_t for each hour of the day and each power rating scenario. As the (actual) power rating of ES is increased, the value of k_t during peak and off-peak hours also increases. This is because ES needs to enhance the extent of capacity withholding it exercises in order to maintain the peak to off-peak price differential at a high level and maximize its profit.

As discussed in Section II, the exercise of market power by ES increases the price differential between peak and off-peak hours and subsequently its profit, while simultaneously it decreases social welfare when compared to the case it behaves competitively. Fig. 6 presents the impact of ES power rating on the increase of the ES profit and the decrease of the social welfare driven by the exercise of capacity withholding. As the power rating increases from 1GW to 4GW, the increase in ES profit and the decrease in social welfare are both enhanced, because its larger size enables ES to exercise more market power. Under competitive ES behaviour, increasing the ES power rating beyond 4GW cannot further flatten the demand profile and thus does not further change the operation schedule of ES. As a result, the power rating revealed by the ES to the market under strategic behaviour also remains unchanged; this is justified by the fact that the revealed rating, i.e. $(1-k_t)s^{max}$, is identical for $s^{max} =$ 4GW and $s^{max} =$ 5GW at every hour. Therefore, the increase in ES profit and the decrease in social welfare driven by the exercise of market power exhibit a saturation effect for a power rating higher than 4GW (Fig. 6).

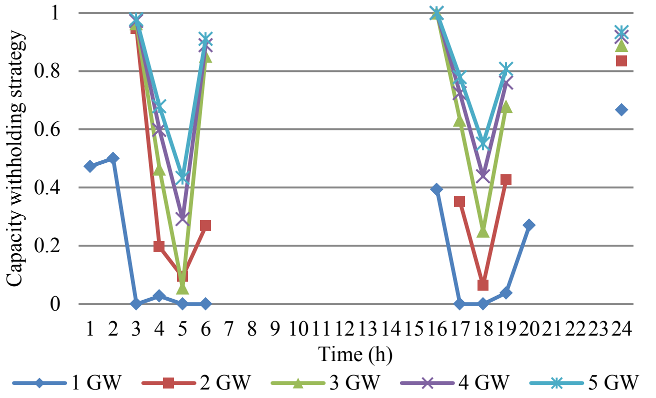

Figure 5. Impact of power rating on optimal capacity withholding strategies of ES

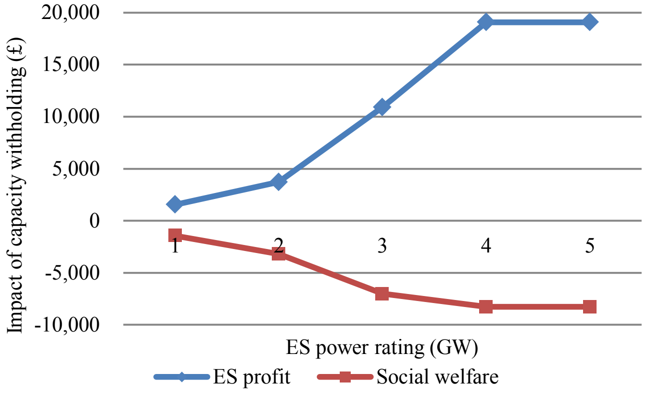

Figure 6. Impact of power rating on increase of ES profit and decrease of social welfare driven by the exercise of capacity withholding

In the second case study, the optimal decision making of strategic ES has been solved using a storage power rating of $s^{max} =$ 6GW, and different values for its energy capacity E^{cap}, in order to investigate the impact of the latter on the extent of exercised market power. Fig. 7 presents the optimal withholding strategies k_t for each hour of the day and each energy capacity scenario. In contrast to the impact of increased power rating examined before, as the energy capacity is increased, the value of k_t decreases. The reason behind this trend is associated with the negative effect of capacity withholding on the volume of energy sold by the ES unit in the market. As its capacity increases, ES is motivated to act more truthfully in order to exploit its higher energy content and sell more energy in the market.

Fig. 8 presents the impact of ES energy capacity on the increase of the ES profit and the decrease of the social welfare driven by the exercise of capacity withholding. As the capacity increases from 6GWh to 54GWh, the increase in

ES profit and decrease in social welfare are both enhanced, because its larger size enables ES to exercise more market power. Under competitive ES behaviour, increasing the ES capacity beyond 54GWh cannot significantly improve the social welfare and therefore does not significantly change the operation schedule of ES. As a result, the revealed power rating under strategic behaviour also remains almost unchanged, as illustrated by Fig. 7, where the curves corresponding to 54GWh and 72GWh almost coincide. Therefore, the increase in ES profit and the decrease in social welfare driven by the exercise of market power exhibit a saturation effect for a capacity higher than 54GWh (Fig. 8).

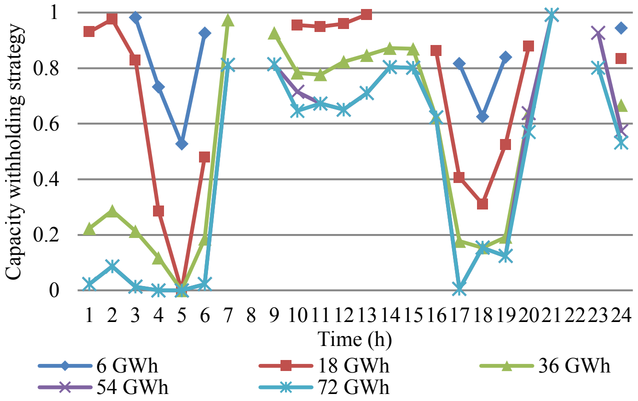

Figure 7. Impact of energy capacity on optimal capacity withholding strategies of ES

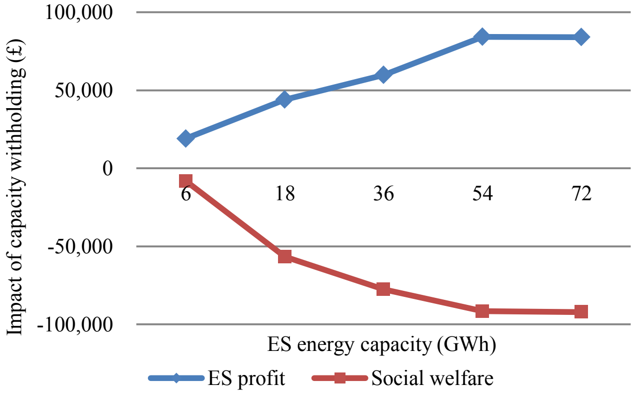

Figure 8. Impact of energy capacity on increase of ES profit and decrease of social welfare driven by the exercise of capacity withholding

V. CONCLUSIONS

In order to avoid the limitations of previous modeling approaches analyzing the market power potential of ES in electricity markets, this paper has developed a bi-level optimization model of the decision making process of strategic storage. This problem is solved after converting it to an MPEC and linearizing the latter through suitable techniques. Theoretical analysis in a simplified two-period market as well as case studies with the developed optimization model on a test market with day-ahead horizon and hourly resolution demonstrate that ES needs to optimize the extent of exercised capacity withholding, in order to achieve the best trade-off between the positive effect of capacity withholding on peak to off-peak price differentials and its negative effect on the volume of energy sold by storage. Due to this negative effect, the optimal extent of capacity withholding is different at different periods of the market horizon, being lower during periods when ES charges and discharges higher energy.

Case studies have analyzed the impact of the size of ES in terms of its power rating and energy capacity on the extent of exercised capacity withholding and the resulting increase in ES profit and decrease in social welfare. A higher power rating increases the extent of exercised capacity withholding as ES attempts to maintain the peak to off-peak price differential at a high level. On the other hand, a higher energy capacity reduces the extent of capacity withholding as ES is motivated to act more truthfully in order to exploit its higher energy content and sell more energy. Nevertheless, both a higher power rating and a higher energy capacity increase the additional profit made by storage and the social welfare loss (with respect to the case where ES acts competitively), since they increase the ability of storage to affect market prices. This trend however exhibits a saturation effect, as increasing power rating and energy capacity beyond a certain level does not affect the market outcome under neither competitive nor strategic storage behavior.

Future work aims at enhancing the presented model in two directions. First of all, uncertainties faced by strategic storage participants regarding generation and demand conditions in the market will be incorporated in the developed model and stochastic optimization principles will be employed for its solution. Secondly, the presented model assumes that a single strategic storage participant exists in the market and the generation and demand participants behave competitively. In order to explore the role of ES in a more realistic oligopolistic market setting, future work will incorporate multiple strategic storage participants as well as strategic producers and consumers and will determine the market equilibria resulting from their interaction.

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