Incorporating demand flexibility in strategic generation investment planning

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***Abstract*—The envisaged decarbonization of electricity systems has attracted significant interest around the role and value of demand flexibility. However, the impact of this flexibility on generation investments in the deregulated electricity industry setting remains a largely unexplored area, since previous relevant work neglects the time-coupling nature of demand shifting potentials. This paper addresses this challenge by proposing a strategic generation investment planning model expressing the decision making process of a self-interested generation company and accounting for the time-coupling operational characteristics of demand flexibility. This model is formulated as a multi-period bi-level optimization problem, which is solved after converting it to a Mathematical Program with Equilibrium Constraints (MPEC). Case studies with the proposed model demonstrate that demand flexibility reduces the total generation capacity investment, enhances investments in baseload generation and yields significant economic benefits in terms of total system costs and demand payments.**

***Index Terms*—Bi-level optimization, demand flexibility, electricity markets, generation investment planning.**

I. NOMENCLATURE

A. Indices and Sets

$t \in T$	Index and set of hours
$d \in D$	Index and set of representative days
$i \in I$	Index and set of generation technologies
$I^{MR} \subseteq I$	Subset of must-run generation technologies
V^{LL}	Set of decision variables of lower level problem
V	Set of decision variables of MPEC model

B. Parameters

w_d	Weighting factor of day d
IC_i	Investment cost of generation technology i (£/MW)
l_i^G	Linear operating cost coefficient of generation technology i (£/MW)
q_i^G	Quadratic operating cost coefficient of generation technology i (£/MW^2)
$l_{d,t}^D$	Linear benefit coefficient of demand at day d and hour t (£/MW)
$q_{d,t}^D$	Quadratic benefit coefficient of demand at day d and hour t (£/MW^2)
$d_{d,t}^{max}$	Maximum demand at day d and hour t (MW)
α	Load shifting limit of demand (%)
k	System adequacy coefficient

C. Variables

X_i	Invested capacity of technology i (MW)
$g_{i,d,t}$	Power output of technology i at day d and hour t (MW)
$d_{d,t}$	Power input of demand at day d and hour t (MW)
$d_{d,t}^{sh}$	Change of power input of demand at day d and hour t due to load shifting (MW)
$\lambda_{d,t}$	Market clearing price at day d and hour t (£/MWh)

II. INTRODUCTION

The worldwide deregulation of the electricity industry during the last decades has driven unbundling of vertically integrated monopoly utilities and the introduction of competition in the generation and supply sectors [1]. In this setting, generation investment planning is not anymore carried out by a central regulated utility aiming to maximize social welfare but relies on profit-driven decisions of self-interested generation companies, operating within a competitive electricity market.

A few recent papers [2]–[7] have modeled this strategic generation planning framework under different assumptions and conditions. Authors in [5], [7] take into account transmission network constraints in order to identify the optimal location of generation investments under potential conditions of network congestion. Papers [3]-[7] also consider the potential exercise of market power by the generation companies in the electricity market through strategic offering. Finally, authors in [5]-[7] attempt to capture the uncertainties that generation companies face regarding different parameters (such as demand levels and their competitors' investment and offering strategies) through scenario-based approaches. However, all these studies employ the same fundamental methodology to model strategic generation planning, namely *bi-level optimization*. The popularity of this methodology lies in its ability to comprehensively capture the interactions

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between the strategic investment (and offering) decisions of the generation companies and the competitive clearing of the electricity market at the operational timescale.

In parallel with the deregulation of the electricity industry, environmental and energy security concerns have paved the way for the decarbonization of energy systems through large-scale integration of renewable generation and electrification of transport and heat sectors [8]. However, this paradigm change introduces fundamental techno-economic challenges associated with the high variability and limited controllability of renewable generation as well as the increasing demand peaks associated with transport and heating loads.

In this setting, *flexible demand* technologies, enabling modification of electricity consumption patterns, have lately attracted significant interest by governments, industry and academia [9]-[11]. This interest is justified by the potential of demand flexibility to support system balancing and to limit peak demand levels, improving the cost efficiency of low-carbon electricity systems. This demand flexibility entails two distinct potentials. The first one involves the consumers' price elasticity i.e. the reduction / increase of their overall energy requirements within certain limits, according to the price levels in the electricity market. However, this price elasticity is generally small [12] and the most promising flexibility potential involves redistribution (shifting) of electricity demand in time. In other words, instead of simply avoiding using their loads at high price levels, consumers are more likely to shift the operation of their loads from periods of higher prices to periods of lower prices [12]. Therefore, load reduction during certain periods is accompanied by a *load recovery effect* during preceding or succeeding periods. This shift of energy demand from high- to low-priced periods drives a demand profile flattening effect.

The motivation behind this work lies in the fact that all the previous works [2]-[7] on strategic generation investment planning model the demand side through a load duration curve that does not incorporate time-coupling characteristics. Therefore, although they can represent its price elasticity, they are inherently unable to capture its time-shifting flexibility potential. As a result, the investigation of the impact of demand flexibility on generation investments in the deregulated electricity industry era remains a largely unexplored area.

This paper makes the first attempt to fill this knowledge gap by incorporating the time-shifting flexibility of the demand side in a strategic generation investment planning modeling framework. The decision making of a strategic generation company is modeled through a *multi-period bi-level optimization problem*. The upper level (UL) problem determines the optimal investment decisions of the generation company so as to maximize its profit, given by the difference between its profit in the electricity market and its investment cost for procuring generation capacity. This UL problem is subject to the lower level (LL) problem which represents endogenously the electricity market clearing process on a daily basis, accounting for the time-coupling operational characteristics of demand flexibility through a generic, technology-agnostic model. This bi-level problem is solved after converting it to a *Mathematical Program with Equilibrium Constraints* (MPEC), and linearizing the latter through suitable techniques.

Case studies with the developed multi-period MPEC model are carried out on a test system with a yearly operation horizon and hourly resolution. The results demonstrate that the time-shifting flexibility of the demand side reduces the total generation capacity investment and enhances investments in baseload compared to peaking generation. Overall, this demand flexibility leads to significant economic benefits in terms of system costs and demand payments.

The rest of this paper is organized as follows. Section III details the developed bi-level optimization and MPEC models. Case studies and quantitative results are presented in Section IV. Finally, Section V discusses conclusions and future extensions of this work.

III. Modeling Strategic Generation Investment Planning with Demand Flexibility

A. Assumptions

For clarity reasons, the main assumptions behind the proposed model are outlined below:

- The model assumes a static planning approach and a yearly operation horizon. In other words, the strategic generation company determines its optimal investment decisions considering a single, future target year. Both investment and operational costs and revenues are calculated at the same yearly basis.

- The strategic generation company can invest in generation capacity of different technologies. Each generation technology is characterized by different investment and operating costs and a subset of the technologies are assumed "must-run" i.e. they must be operating at their full capacity during all times.

- The considered electricity market is a pool-based energy-only market with a day-ahead horizon and hourly resolution, and is cleared by the market operator through the solution of a social welfare maximization problem.

- The strategic generation company submits to the market a quadratic, convex offer curve for each of the different technologies within its generation portfolio. Strategic offering effects are not considered in this work and therefore these offer curves are assumed to represent the actual operating costs of different generation technologies.

- The demand side submits to the market a quadratic, concave bid curve, capturing the effect of price elasticity. In order to capture the temporal diversity of demand characteristics, a set of representative days is examined and the bid parameters vary by day and hour.

- A generic, technology-agnostic model is employed for the representation of the time-shifting flexibility of the demand side [13]. According to this model, demand at each time period can be reduced / increased within certain limits, and demand shifting is energy neutral within the daily market horizon i.e. the total size of demand reductions is equal to the total size of demand increases (load recovery), assuming without loss of generality that demand shifting does not involve energy gains or losses.

B. Bi-level Optimization Formulation

Following the approach employed in [2]-[7], the decision making process of the strategic generation company is modeled through the bi-level optimization model (1)-(11). The UL problem determines the optimal investment decisions maximizing the profit of the generation company and is subject to the LL problem representing the market clearing process.

(Upper level)

$$\max_{\{X_i\}} \sum_d w_d \left[\sum_{i,t}\left(\lambda_{d,t} g_{i,d,t} - \left(l_i^G g_{i,d,t} + q_i^G g_{i,d,t}^2\right)\right)\right] - \sum_i IC_i X_i \quad (1)$$

subject to:

$$X_i \geq 0, \forall i \quad (2)$$

$$\sum_i X_i \geq k\left(d_{d,t} + d_{d,t}^{sh}\right), \forall d, \forall t \quad (3)$$

(Lower level)

$$\min_{V^{LL}} \sum_{i,d,t}\left(l_i^G g_{i,d,t} + q_i^G g_{i,d,t}^2\right) - \sum_{d,t}\left(l_{d,t}^D d_{d,t} - q_{d,t}^D * d_{d,t}^2\right) \quad (4)$$

where:

$$V^{LL} = \{g_{i,d,t}, d_{d,t}, d_{d,t}^{sh}\} \quad (5)$$

subject to[1]:

$$d_{d,t} + d_{d,t}^{sh} - \sum_i g_{i,d,t} = 0 : \lambda_{d,t}, \forall d, \forall t \quad (6)$$

$$0 \leq g_{i,d,t} \leq X_i : \mu_{i,d,t}^-, \mu_{i,d,t}^+, \forall i \notin I^{MR}, \forall d, \forall t \quad (7)$$

$$g_{i,d,t} = X_i : \xi_{i,d,t}, \forall i \in I^{MR}, \forall d, \forall t \quad (8)$$

$$0 \leq d_{d,t} \leq d_{d,t}^{max} : \nu_{d,t}^-, \nu_{d,t}^+, \forall d, \forall t \quad (9)$$

$$\sum_t d_{d,t}^{sh} = 0 : \varphi_d, \forall d \quad (10)$$

$$-\alpha d_{d,t} \leq d_{d,t}^{sh} \leq \alpha d_{d,t} : \pi_{d,t}^-, \pi_{d,t}^+, \forall d, \forall t \quad (11)$$

The objective function (1) of the UL problem maximizes the profit of the strategic generation company across the yearly horizon, given by the difference between its profit in the electricity market (first term) and its investment cost for procuring generation capacity (second term). This problem is subject to the positivity limits of the investment decisions (2), as well as the adequacy constraints (3), which are imposed by the regulator to ensure that consumers' security of supply requirements are preserved. The UL is also subject to the LL problem (4)-(11) which represents the market clearing process at each representative day, maximizing the social welfare (4), subject to demand-supply balance constraints (6) (the Lagrangian multipliers of which constitute the market clearing prices) as well as the operational constraints of the generation side (7)-(8) and the demand side (9)-(11).

[1] The symbols $\lambda_{d,t}$, $\mu_{i,d,t}^-$, $\mu_{i,d,t}^+$, $\xi_{i,d,t}$, $\nu_{d,t}^-$, $\nu_{d,t}^+$, φ_d, $\pi_{d,t}^-$, $\pi_{d,t}^+$ denote the Lagrangian multipliers associated with the respective constraints.

The time-shifting flexibility of the demand side is expressed by (10)-(11). The variable $d_{d,t}^{sh}$ represents the change of demand with respect to the baseline level $d_{d,t}$ at day d and hour t due to load shifting, taking negative / positive values when demand is moved away from / towards t. Constraint (10) ensures that demand shifting is energy neutral within the daily market horizon (Section III-A). Constraint (11) expresses the limits of demand change at each period due to load shifting as a ratio α $(0 \leq \alpha \leq 1)$ of the baseline demand; $\alpha = 0$ implies that the demand does not exhibit any time-shifting flexibility, while $\alpha = 1$ implies that the whole demand can be shifted in time.

C. 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 a single-level MPEC which is formulated as:

$$\max_{V} \sum_d w_d \left[\sum_{i,t}\left(\lambda_{d,t} g_{i,d,t} - \left(l_i^G g_{i,d,t} + q_i^G g_{i,d,t}^2\right)\right)\right] - \sum_i IC_i X_i \quad (12)$$

where:

$$V = \{X_i, V^{LL}, \lambda_{d,t}, \mu_{i,d,t}^-, \mu_{i,d,t}^+, \xi_{i,d,t}, \nu_{d,t}^-, \nu_{d,t}^+, \varphi_d, \pi_{d,t}^-, \pi_{d,t}^+\} \quad (13)$$

subject to:

(2)-(3), (6), (8), (10)

$$l_i^G + 2q_i^G g_{i,d,t} - \lambda_{d,t} - \mu_{i,d,t}^- + \mu_{i,d,t}^+ = 0, \forall i \notin I^{MR}, \forall d, \forall t \quad (14)$$

$$l_i^G + 2q_i^G g_{i,d,t} - \lambda_{d,t} + \xi_{i,d,t} = 0, \forall i \in I^{MR}, \forall d, \forall t \quad (15)$$

$$\lambda_{d,t} - \nu_{d,t}^- + \nu_{d,t}^+ - \alpha\pi_{d,t}^- - \alpha\pi_{d,t}^+ - l_{d,t}^D + 2q_{d,t}^D d_{d,t} = 0, \forall d, \forall t \quad (16)$$

$$\lambda_{d,t} + \varphi_d - \pi_{d,t}^- + \pi_{d,t}^+ = 0, \forall d, \forall t \quad (17)$$

$$0 \leq g_{i,d,t} \perp \mu_{i,d,t}^- \geq 0, \forall i \notin I^{MR}, \forall d, \forall t \quad (18)$$

$$0 \leq (X_i - g_{i,d,t}) \perp \mu_{i,d,t}^+ \geq 0, \forall i \notin I^{MR}, \forall d, \forall t \quad (19)$$

$$0 \leq d_{d,t} \perp \nu_{d,t}^- \geq 0, \forall d, \forall t \quad (20)$$

$$0 \leq (d_{d,t}^{max} - d_{d,t}) \perp \nu_{d,t}^+ \geq 0, \forall d, \forall t \quad (21)$$

$$0 \leq (d_{d,t}^{sh} + \alpha d_{d,t}) \perp \pi_{d,t}^- \geq 0, \forall d, \forall t \quad (22)$$

$$0 \leq \left(\alpha d_{d,t} - d_{d,t}^{sh}\right) \perp \pi_{d,t}^+ \geq 0, \forall d, \forall t \quad (23)$$

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 (14)-(23).

This MPEC formulation is characterized by several non-linearities, including bilinear terms in the objective function (12) and the complementarity slackness conditions (18)-(23). In order to avoid global optimality issues associated with non-linear formulations, this MPEC is transformed to a *mixed-integer quadratic problem* (MIQP), which can be efficiently solved to global optimality using commercial branch-and-cut solvers. For space limitations reasons, this transformation is not presented here, but adopts the linearization approaches presented in previous relevant works [13]-[14].

IV. Case Studies

A. Test Data and Implementation

The examined studies aim at quantitatively analyzing the impacts of the time-shifting flexibility of the demand side on the investment decisions of a strategic generation company. For this reason, different scenarios regarding the extent of this flexibility (as expressed by parameter α) are examined.

The strategic generation company can invest in three different technologies, namely nuclear, combined cycle gas turbines (CCGT) and open cycle gas turbines (OCGT). Nuclear generation is assumed "must-run". The assumed values of the investment and operating costs of these technologies are presented in Table I. Four typical days representing the four seasons of the year are used, and the respective baseline demand profiles are obtained from [15].

TABLE I. Investment and Operating Costs of Generation Technologies

Technology	Nuclear	CCGT	OCGT
IC_i (£/MW)	500,000	200,000	100,000
l_i^G (£/MW)	10	35	70
q_i^G (£/MW^2)	0.0001	0.0026	0.0065

The developed MIQP model has been implemented and solved using the optimization software FICO™ Xpress [16] on a computer with a 6-core 3.50 GHz Intel(R) Xeon(R) E5-1650 processor and 32 GB of RAM. The average computational time required for solving this MIQP across all the examined scenarios was around 350s.

B. Results

Fig. 1 and 2 present the system demand and market price profiles corresponding to one of the representative days for different time-shifting flexibility scenarios.

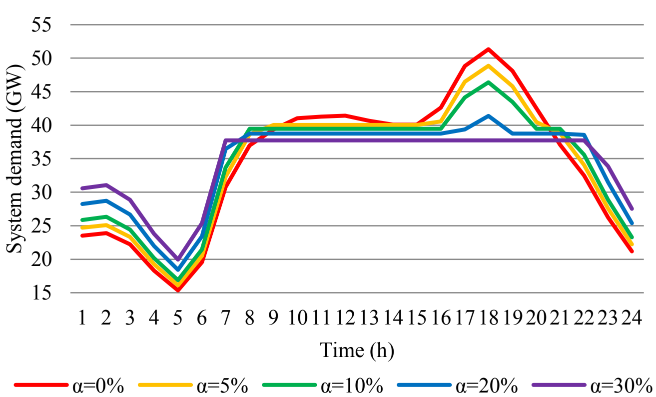

Figure 1. Hourly system demand for different demand flexibility scenarios.

As previously discussed, this flexibility drives flattening of the demand profile by reducing demand during peak time periods and increasing it during off-peak time periods, although the daily energy consumption remains the same given the energy neutrality constraint (10). This drives a similar flattening effect on the price profile; however, the price reduction during peak periods is greater than the price increase during off-peak periods due to the quadratic nature of the generators' operating cost curves (Section III-A).

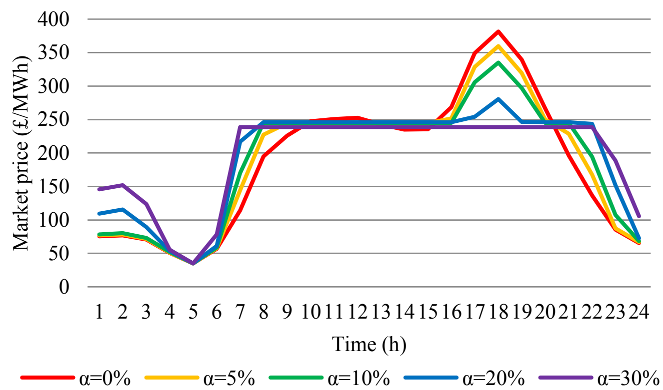

Figure 2. Hourly market price for different demand flexibility scenarios.

Fig. 3 presents the optimal investment decisions of the generation company for different demand flexibility scenarios. First of all, demand flexibility reduces the total capacity investment since it limits the peak demand levels in the system (Fig. 1). Furthermore, by flattening the demand profile, demand flexibility enhances the cost efficiency of nuclear generation which is characterized by higher investment and lower operating costs. As a result, the amount of nuclear capacity is increased while the amount of CCGT and OCGT capacity is reduced.

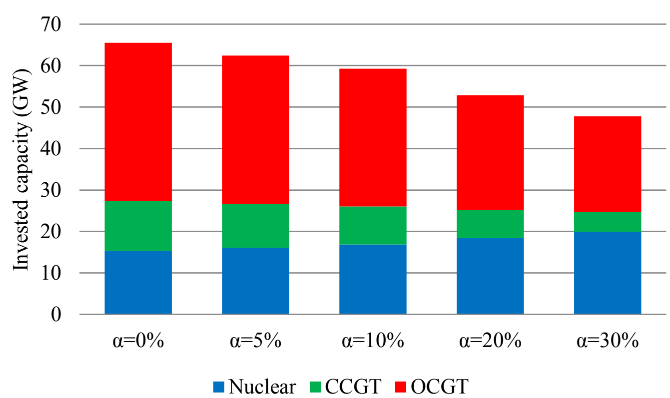

Figure 3. Investment decisions of strategic generation company for different demand flexibility scenarios.

Table II presents the reduction of the total system cost (including both investment and operating costs) and the total electricity payment of the demand side (given by the sum of products of demand and price across the year) brought by different levels of demand flexibility with respect to the base case $\alpha = 0$. The system cost savings are mainly driven by the reduction of the total capacity investment as well as the reduced need to run CCGT and OCGT generators with high operating costs. The demand payment savings are driven by the combination of two effects: a) the demand during periods with reduced prices (peak periods) is higher than the demand during periods with increased prices (off-peak periods) and b) the price reduction during peak periods is greater than the price increase during off-peak periods.

TABLE II. SAVINGS IN TOTAL SYSTEM COST AND DEMAND PAYMENT FOR DIFFERENT DEMAND FLEXIBILITY SCENARIOS

	$\alpha = 5\%$	$\alpha = 10\%$	$\alpha = 20\%$	$\alpha = 30\%$
System cost	2.4%	4.7%	8.6%	11.5%
Demand payment	0.9%	1.8%	3.1%	4.1%

V. CONCLUSIONS AND FUTURE WORK

This paper has proposed a strategic generation investment planning model incorporating the time-shifting flexibility of the demand side that has been neglected by previous relevant works. This model expresses the decision making of a strategic generation company and is formulated as a multi-period bi-level optimization problem, accounting for the time-coupling operational characteristics of demand flexibility at the lower level. This problem is solved after converting it to an MPEC and subsequently to a MIQP.

Case studies have demonstrated that the time-shifting flexibility of the demand side reduces the total generation capacity investment and enhances investments in baseload generation, since it limits peak demand levels and flattens the demand profile. Furthermore, this reduction of the total capacity investment and the reduced need to run mid-merit and peaking generation results in significant system cost savings. Finally, this flexibility brings considerable savings for the consumers since it reduces electricity prices during peak periods.

For the sake of simplicity, the proposed model optimizes the investment decisions of a single generation company. However, in a realistic setting, multiple strategic companies interact in the electricity market, maximizing their individual profits. Therefore, future work aims at extending the presented model to an equilibrium programming model capturing these complex interactions and providing more elaborate insights on the role and value of demand flexibility.

Furthermore, this work, as well as previous relevant works, has focused on investments in conventional generation technologies only. Driven by the envisaged decarbonization of electricity generation, future work aims at incorporating renewable technologies in the investment options and investigating the impacts of demand flexibility on the integration of such technologies in the system.

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