Market-oriented Decision Making in Power Generation Investment

Maria Kanta, a Evangelos G. Tsimopoulos, a Christos N. Dimitriadis, a Michael C. Georgiadis a,\*

*aDepartment of Chemical Engineering, Aristotle University of Thessaloniki, University Campus, Thessaloniki, 54124, Greece*

*mgeorg@auth.gr*

Abstract

In recent times, owning a Gas-Fired Power Plant (GFPP) is considered an appealing choice for investors in the power sector. GFPPs offer flexibility, to compensate for the stochastic nature of renewable energy sources, and high production efficiency. This work considers a bi-level model for optimizing investment decisions of a producer participating in both electricity and natural gas markets. The investor endeavors to maximize his profit and acts as a strategic player in the electricity market and as a non-strategic player in the gas market. That implies that he can exercise market power in the electricity market. However, he cannot manipulate gas prices. A Carbon Emission Trading Scheme (CETS) is incorporated towards a low-carbon economy. The bi-level algorithm is initially recast into a Mathematical Program with Equilibrium Constraints (MPEC) and is further transformed into a Mixed Integer Linear Program (MILP) by utilizing the Karush-Kuhn-Tucker (KKT) optimality conditions, a binary expansion method and the strong duality theory. The model's application to a modified Pennsylvania-New Jersey- Maryland (PJM) 5-bus power system and a single-node gas system captures the contrasting impact of emission allowance trading and gas prices on investments in GFPPs. The results indicate that CETS implementation moderates profit loss, resulting from rising gas prices, while increasing carbon prices elevate the importance of GFPPs over high-emission non-GFPP units.

**Keywords**: bi-level optimization, strategic offering, electricity market, natural gas market, carbon emission trading

* 1. Introduction

To mitigate climate change, high-emissive power units are replaced with environmentally cautious ones. Thus, GFPPs constitute an economically attractive investment option. Approaches for the optimal coordination of natural gas and power markets have been presented in the open literature (Dimitriadis et al., 2021). Dimitriadis et al. (2023) focused on optimizing the scheduling of different storage technologies within an integrated natural gas and electricity market framework. Moreover, deriving optimal offering strategies in the electricity sector have been thoroughly investigated. This problem was studied by Tsimopoulos and Georgiadis (2020) for a producer with a mixed-generation portfolio and later by Dimitriadis et al. (2022) for an energy storage agent. Strategic investment in an imperfect integrated electricity and gas market has been modelled by Chen et al. (2020). The incorporation of emission reduction policies in generation expansion problems has been assessed by several studies within the context of carbon neutrality. Boffino et al. (2019) studied the generation investment problem, implementing a cap-and-trade policy and a carbon tax policy. However, there is a lack of comprehensive research on how CETS can affect the investment and production strategies in integrated electricity and gas market. This work aims to bridge the above gap by proposing an integrated framework for deriving optimal investment decisions for a producer owing GFPPs and participating in a decoupled gas and emission-embedded electricity market.

* 1. Problem statement

The formulation of the proposed bi-level model is presented below. Uncertainty is introduced in the model through a set of possible scenarios *ω*. Furthermore, a cap-and-trade system is adopted in the carbon market. As indicated in Eq. (1), the total carbon emission allowance, $Q\_{t}$, is contingent upon the emission allowance factor *𝜂* (tCO2/MW) and the difference between electricity demand $L\_{t,d}^{E}$ and wind power generation$ w\_{j}$. Each conventional unit $h$ is granted emission allowances $Q\_{h}^{H}$, as outlined in Eq. (2). The allocated factor regarding carbon emission permits $α\_{h}$, required to determine $Q\_{h}^{H}$, is calculated in Eq. (3) using the emission factor of each conventional unit $ζ\_{h}$.

|  |  |
| --- | --- |
| $$Q\_{t}=η∙\left(\sum\_{d^{E}}^{}L\_{t,d}^{E}-\sum\_{j}^{}w\_{j}\right)$$ | (1) |
| $$Q\_{h}^{H}=α\_{h}∙Q\_{t}$$ | (2) |
| $$α\_{h}=\frac{ζ\_{h}}{\sum\_{h}^{}ζ\_{h}}$$ | (3) |

* + 1. Upper-level problem

This section presents the upper-level problem.

|  |  |
| --- | --- |
| $$maximize \sum\_{ω}^{}π\_{ω}∙\sum\_{t}^{}σ\_{t}∙\left[\sum\_{g\in GaN,g\in GE}^{}v\_{t,g,ω}^{e}∙λ\_{t,n,ω}^{E}-\sum\_{g\in GaR,g\in GE}^{}φ\_{g}^{e}∙λ\_{t,r,ω}^{NG}∙v\_{t,g,ω}^{e}-cp∙\left(ζ\_{g}∙v\_{t,g,ω}^{e}-Q\_{t,g,ω}^{H}\right)+\sum\_{g\in GaN,g\in GC}^{}v\_{t,g,ω}^{c}∙λ\_{t,n,ω}^{E}-\sum\_{g\in GaR,g\in GC}^{}φ\_{g}^{c}∙λ\_{t,r,ω}^{NG}∙v\_{t,g,ω}^{c}-cp∙\left(ζ\_{g}∙v\_{t,g,ω}^{c}-Q\_{t,g,ω}^{H}\right)\right]-\sum\_{g\in GC}^{}K\_{g}^{c}∙X\_{g}^{c}$$ | (4) |
| $s.t. X\_{g}^{c}=\sum\_{l}^{}X\_{l,g}∙u\_{l,g} : ∀g\in GC$ | (5) |
| $$\sum\_{l}^{}u\_{l,g}=1 : ∀g\in GC$$ | (6) |
| $$u\_{l,g}\in \left\{0,1\right\} : ∀g\in GC$$ | (7) |
| $$ζ\_{g}=\sum\_{l}^{}ζ\_{l,g}∙u\_{l,g} : ∀g\in GC$$ | (8) |
| $$α\_{h}=\sum\_{l}^{}α\_{l,h}∙u\_{l,g} : ∀g\in GC, h$$ | (9) |

The upper-level problem aims at the profit maximization of the strategic producer. In the objective function (4) the term $v\_{t,g}^{e}∙λ\_{t,n}^{E}$ corresponds to the revenue from the existing GFPP from producing $v\_{t,g}^{e}$ of power at a price of $λ\_{t,n}^{E}$. The term $φ\_{g}^{e}∙λ\_{t,r}^{NG}∙v\_{t,g}^{e}$ represent the gas purchase cost at a gas price $λ\_{t,r}^{NG}$, while considering a $φ\_{g}^{e}$ electricity-gas conversion factor. The actual emission $(ζ\_{g}∙v\_{t,g}^{e})$ and the permitted allowances $Q\_{t,g}^{H}$, allocated to the existing GFPP, are used to determine the final cost of carbon trading for a carbon price of $cp$. $cp$ is treated as a parameter.The related terms are also applied for the candidate GFPP, as shown in the fourth and fifth line in (4). The hourly operations profit for the strategic producer is multiplied by the probability $π\_{ω}$ of the scenario *ω* and by the weight $σ\_{t}$ of the corresponding operating condition *t*. Hence, the operations profit matches the annualized investment cost for a new unit with $X\_{g}^{c}$ maximum capacity. $K\_{g}^{c}$ denotes the annualized investment cost. Constraints (5)-(7) allow the selection of a single MW-investment option. Constraints (8)-(9) ensure that if no investment is realised, the candidate GFPP cannot contribute to the emission trading.

* + 1. Lower-level problem: Electricity market clearing

This section represents the electricity market clearing problem.

|  |  |
| --- | --- |
| $$minimize \sum\_{g\in GE}^{}o\_{t,g,ω}^{e}∙v\_{t,g,ω}^{e}+\sum\_{g\in GC}^{}o\_{t,g,ω}^{c}∙v\_{t,g,ω}^{c}+\sum\_{g,r:g\in GaR,g\in GNS }^{}λ\_{t,r,ω}^{NG}∙φ\_{g}^{ns}∙v\_{t,g,ω}^{ns}+\sum\_{i}^{}C\_{t,i}∙p\_{t,i,ω}+\sum\_{g\in GE}^{}cp∙(ζ\_{g}∙v\_{t,g,ω}^{e}-Q\_{t,g,ω}^{H})+\sum\_{g\in GC}^{}cp∙(ζ\_{g}∙v\_{t,g,ω}^{c}-Q\_{t,g,ω}^{H})+\sum\_{g\in GNS}^{}cp∙(ζ\_{g}∙v\_{t,g,ω}^{ns}-Q\_{t,g,ω}^{H})+\sum\_{i}^{}cp∙(ζ\_{i}∙p\_{t,i,ω}-Q\_{t,i,ω}^{H}) ∀t,∀ω$$ | (10) |
| $$s.t. -\sum\_{g\in GaN,g\in GE}^{}v\_{t,g,ω}^{e}-\sum\_{g\in GaN,g\in GC}^{}v\_{t,g,ω}^{c}-\sum\_{g\in GaN,g\in GNS}^{}v\_{t,g,ω}^{ns}-\sum\_{i\in IaN}^{}p\_{t,i,ω}-\sum\_{j\in JaN}^{}w\_{j}+\sum\_{d^{E}\in DaN}^{}L\_{t,d,ω}^{E}+\sum\_{m\in NaM}^{}B\_{nm}∙\left(δ\_{t,n,ω}-δ\_{t,m,ω}\right)=0 :\left[λ\_{t,n,ω}^{E}\right] ∀n,∀t,∀ω$$ | (11) |
| $$-Q\_{t,h,ω}^{H}+α\_{h}∙η∙\left(\sum\_{d^{E}}^{}L\_{t,d,ω}^{E}-\sum\_{j}^{}w\_{j}\right)=0 :\left[ρ\_{t,h,ω}\right] ∀h,∀t,∀ω$$ | (12) |
| $$0\leq v\_{t,g,ω}^{c}\leq X\_{g}^{c} :\left[\overline{β\_{t,g,ω}^{c}} , \overline{β\_{t,g,ω}^{c}}\right] ∀g\in GC,∀t,∀ω$$ | (13) |

The negative social welfare is derived from the objective function (10). $o\_{t,g,ω}^{e}$, $o\_{t,g,ω}^{c}$ and $C\_{t,i}$ correspond to the strategic offers for existing/candidate GFPPs g and the cost offers of non-GFPPs *i*. The offers of the non-strategic GFPP depend on the natural gas price. $v\_{t,g,ω}^{ns}$, $v\_{t,g,ω}^{c}$ and $p\_{t,i,ω}$ denotes the hourly power production for non-strategic/candidate GFPPs and non-GFPP units. Constraints (11) ensure that the generation-demand balance is satisfied at each electric bus n, considering power demand $L\_{t,d,ω}^{E}$ and the susceptance $B\_{n,m}$ for the transmission line connecting buses *n, m*. Constraints (12) allocate the emission allowances for each conventional power unit *h*. Constraints (13) enforce capacity limits for the candidate GFPP. Constraints imposing transmission capacity limits and capacity limits on the other generating units are also implemented in the model. Moreover, voltage angle $δ\_{t,n,ω}$, used to formulate power flow in (11) is bound in each bus *n* and bus 1 is imposed as the slack bus, setting its voltage angle to zero.

* + 1. Lower-level problem: Natural gas market clearing

This section represents the gas market clearing problem.

|  |  |
| --- | --- |
| $$minimize \sum\_{k}^{}C\_{t,k}∙f\_{t,k,ω} ∀t,∀ω$$ | (14) |
| $$s.t. -\sum\_{k\in KaR}^{}f\_{t,k,ω}+\sum\_{d^{NG}\in DaR}^{}L\_{t,d,ω}^{NG}+\sum\_{g\in GaR,g\in GE}^{}φ\_{g}^{e}∙v\_{t,g,ω}^{e}+\sum\_{g\in GaR,g\in GNS}^{}φ\_{g}^{ns}∙v\_{t,g,ω}^{ns}+\sum\_{g\in GaR,g\in GC}^{}φ\_{g}^{c}∙v\_{t,g,ω}^{c}=0 :\left[λ\_{t,r,ω}^{NG}\right] ∀r,∀t,∀ω$$ | (15) |
| $$0\leq f\_{t,k,ω}\leq \overbar{F}\_{k} :\left[\overline{ε\_{t,k,ω}} ,\overline{ε\_{t,k,ω}} \right] ∀k,∀t,∀ω$$ | (16) |

Objective function (14) aims at minimizing the operating cost of the natural gas market. The cost offers of each gas suppliers *k* are indicated as $C\_{t,k}$. Constraints (15) guarantee the energy balance at each gas node *r* considering gas demand $L\_{t,d,ω}^{NG}$. Constraint (16) enforce capacity limits on the natural gas production $f\_{t,k,ω}$ of each gas supplier.

* + 1. Solution strategy

The lower-level problems are convex and therefore they can be replaced by their KKT optimality conditions, reducing the bi-level model to an MPEC. Using disjunctive constraints, the strong duality theory, and a binary expansion method the model is further recast into a MILP.

* 1. Illustrative example

The proposed model for strategic investment decisions is applied on a modified PJM 5-bus power and a single-node natural gas system, as illustrated in Fig. 1(a). The coupling between these two systems includes an existing and non-strategic GFPP, a strategic existing GFPP and a strategic candidate GFPP. Three non-GFPPs and a wind farm are also located at the power network. Additionally, two gas suppliers and three gas loads exist at the gas network. GFPPs are considered as additional gas loads with capacities equal to the power that GFPPs provide to the electricity market. The capital cost of the candidate unit is 22,900 €/MW (Cong et al., 2019) and carbon price is set to be 35.5 €/tCO2 (Bank, 2023). It should be mentioned that the wind power plant is considered cost-free and emission-free, hence the wind farm cannot participate in emission trading.



Figure 1: Topology of the PJM 5-bus, single-node system (a). Investment results for Case 2a and Case 2b (b).

1. (b)

Table 1: Data and results for Case 1a, Case 1b and Case 1c.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Case 1a | Case 1b | Case 1c |
| Gas price increase | 0% | 10% | 20% |
| Capacity investment (M W) | 150 | 100 | 50 |
| Emission cost (M €) | 4.4 | 0.4 | -1.8 |
| Profit (€) | 30.1 | 26.2 | 22.9 |

* 1. Results and discussion
		1. Case 1

The proposed model is solved using GAMS/CPLEX. Regarding the investment decisions, a static approach is adopted, and decisions are made at a single time point considering a single future target year. This case contemplates the impact of gas prices on the expansion planning decisions. Different gas prices are considered in Case 1a, Case 1b and Case 1c. Table 1 summarizes the results indicating that the strategic producer opts for a less capacitated GFPP as the fuel cost increases. Furthermore, carbon emission trading acts as a coping mechanism in Case 1c to navigate profit loss. Negative values in emission costs indicate that the strategic producer profits from trading the unused allowances.

* + 1. Case 2

In this case an increased carbon price and uncertainty regarding gas and electric demands are implemented. Two cases (Case 2a and Case 2b) are used to demonstrate the results. In Case 2b the probability for the scenarios with high gas demand increases compared to Case 2a. CETS and gas demand-load act in an opposite manner. Increasing carbon prices promote investments in GFPPs. The producers increase their bids according to their emission factor to account for the additional carbon cost. Consequently, the system relies on GFPPs to replace high-emission non-GFPPs to moderate electricity prices and emissions. Higher gas demand enables expensive gas producers to enter the market, increasing the fuel cost of GFPPs and discouraging new investments. However, for higher carbon prices the economic benefits derived from carbon trading outweigh the economic drawbacks of increased gas prices. Consequently, as shown in Fig. 1(b) the strategic producer does not alter his investment decisions, even though his marginal costs differ.

* 1. Conclusions

This work presents an integrated market framework for strategic investment in decoupled emission-embedded electricity and natural gas markets. The results demonstrate that an increase in gas prices signifies profit loss and lower investment for the strategic producer, while higher carbon prices lead the GFPPs to increase their market share. Implementing high uncertainty on gas demand discourages new investments for low carbon prices. Nevertheless, there is not such impact for higher carbon prices.

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