Energy Economics 150 (2025) 108871

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Design of multi-attribute procurement auction for the Korean clean hydrogen power generation auction market

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ARTICLE INFO

JEL classification:
D44
D82
Q42
Q48

Keywords:
Hydrogen power generation
Multi-attribute auction
Procurement auction
Mechanism design
Low-carbon energy

ABSTRACT

This paper presents a procurement auction mechanism for the Korean clean hydrogen power generation auction market, addressing the limitations of the existing auction design. We design a multi-attribute auction framework with a Vickrey-score sealed-bid auction rule consisting of scoring, allocation, and payment rules, allowing sellers to bid on both price and non-price attributes. We adopt the hydrogen co-firing rate and capacity factor as non-price attributes to comprehensively evaluate the contributions to greenhouse gas reduction and fuel supply reliability. Through equilibrium analysis, we demonstrate that the proposed mechanism induces a weakly dominant bidding strategy for sellers. This strategy leads to optimal price bids based on their levelized cost of energy (LCOE) and independently determined non-price attributes. Numerical analysis using real-world parameters from the Korean hydrogen industry highlights the importance of carefully structuring the score function. Moreover, the results confirm that the proposed auction mechanism achieves higher market efficiency and a greater share of clean hydrogen in fuel usage compared to single-attribute price-only auctions.

1. Introduction

The global energy market is undergoing a rapid shift toward sustainable energy sources to achieve decarbonization and improve energy security. Among these emerging energy resources, clean hydrogen[1] has gained great attention as an efficient alternative in the energy generation sector because it can use existing fossil fuel-based power plants while achieving long-term decarbonization goals (Council of Economic Advisers, 2023; U.S. Department of Energy, 2022). For instance, according to International Energy Agency (2023), the United Kingdom is currently retrofitting a 1200 MW natural gas power plant to co-fire with hydrogen 30% by 2027. Furthermore, the Korean company Hanwha Impact successfully achieved a 60% hydrogen co-firing rate in an 80 MW gas turbine in 2023. Despite such advancements, several challenges remain. Hydrogen-fueled power generation still struggles to secure economic viability and competitiveness in the electricity market due to unstable hydrogen fuel prices and a lack of technological maturity.

To address these challenges, many countries are implementing support policies to enhance the economic competitiveness of hydrogen power generation. Countries in the early stages of clean hydrogen-based power generation, such as Korea and Japan, are focusing primarily on supporting hydrogen power generation (LG Business Research, 2022). In this context, various methods for hydrogen-driven generation exist, as no single technology has yet emerged as dominant. Representative examples include pure hydrogen combustion facilities, coal-ammonia co-firing plants, and LNG-hydrogen co-firing facilities. Consequently, implementing distinct support policies for each generation method entails significant policy costs. One potential solution to this issue is an auction system, where generation companies (Gencos) determine the scale of support themselves and bid competitively. In particular, South Korea has established the world's first hydrogen power generation auction market under government supervision (Korea Power Exchange, 2024).

In this auction, the government provides an investment incentive to Gencos by purchasing hydrogen-generated electricity through competitive bidding. The primary goal of this auction is to secure clean hydrogen-based power generation in the long term and promote competition among various hydrogen power generation technologies. The bidders are hydrogen-based Gencos utilizing different generation methods, which lead to varying characteristics regarding the Levelized Cost

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[1] Clean hydrogen refers to hydrogen produced with a carbon intensity equal to or less than 2 kg of carbon dioxide-equivalent produced at the site of production per kilogram of hydrogen produced (U.S. Department of Energy, 2023).

https://doi.org/10.1016/j.eneco.2025.108871
Received 28 May 2025; Received in revised form 21 August 2025; Accepted 29 August 2025
Available online 8 September 2025

of Electricity (LCOE), greenhouse gas emissions, and project reliability. Therefore, it is crucial to comprehensively evaluate these attributes to procure electricity from Gencos with low emissions and competitive generation costs.

To this end, the Korean government requires Gencos to submit bids that include not only the contract price but also a set of non-price attributes, which refer to quantifiable or qualitative characteristics of electricity supply that influence its social, environmental, or technical contributions beyond the offered price. In the Korean hydrogen power generation market, these non-price attributes include, for example, the hydrogen co-firing rate, the emission factor of existing generation facilities, and the progress of fuel procurement contracts (Korea Power Exchange, 2024). These indicators help assess how effectively a bidder can contribute to reducing greenhouse gas emissions, enhancing the reliability of fuel supply, and promoting the use of clean hydrogen.

By incorporating these non-price attributes into the evaluation, the auction mechanism is able to prioritize not only cost efficiency but also policy goals such as supply stability and environmental performance. Bids are evaluated on the basis of a pre-announced scoring rule that comprehensively considers price competitiveness, contribution to greenhouse gas reduction, and fuel procurement stability. Winning bidders are granted the right to sell their electricity at a fixed price over a long-term period (15–20 years). In this evaluation process, the price attribute is assessed relative to the minimum bid price, while some non-price attributes are quantitatively evaluated and others are assessed qualitatively. The auction determines the contract prices for the winners using a receive-as-bid pricing rule, in which the bid price directly becomes the contract price.

However, under the current scoring rule, Gencos face challenges in accurately predicting their price score due to incomplete information, as they cannot access other bidders' LCOE. Moreover, since the scoring rule includes qualitative evaluation for some non-price attributes, it introduces ambiguity into the non-price score. These factors make it difficult for Gencos to anticipate their auction outcomes, leading to complex game-theoretical behaviors. Therefore, there is a need to develop a suitable scoring rule that accounts for strategic behaviors among bidders arising from information asymmetry and quantitatively evaluates non-price attributes, eliminating the current ambiguity caused by qualitative assessments.

Furthermore, although the debate over which pricing rule is superior remains unresolved in the literature, the receive-as-bid approach has been widely noted for its higher risk of strategic bidding, which can lead to inefficiencies (Kahn et al., 2001; Klemperer, 2002). The current auction system that uses the receive-as-bid rule can exacerbate this issue by inducing strategic behavior among participants and complicating the derivation of equilibrium bidding strategies. Therefore, a new pricing rule that mitigates strategic behavior and better reflects the actual value of hydrogen power generation is necessary. In this respect, the receive-as-clear method, which applies a uniform price standard to all winning bidders, encourages bidders to submit bids based on their true costs. This approach improves price discovery and leads to more efficient outcomes (Cramton and Ockenfels, 2024).

Building on these limitations of the existing auction system, this study proposes a multi-attribute auction mechanism for a hydrogen power generation market where a single buyer procures electricity generated from clean hydrogen from multiple sellers through long-term supply contracts. In this market, the buyer prioritizes social efficiency over profitability. To achieve this, we propose a novel Vickrey-score sealed-bid auction rule, comprising scoring, allocation, and receive-as-clear payment rules. Then, we analyze the equilibrium bidding strategies under the proposed auction framework and investigate the characteristics of these strategies. Our findings reveal that the proposed auction mechanism minimizes efficiency loss by selecting winning sellers who contribute to greater social surplus. Furthermore, we provide a range of insightful numerical experiment results based on cost and price data from the Korean hydrogen power market.

The main contributions of this study are as follows:

1. This study is the first theoretical study to design a multi-attribute procurement auction mechanism for the clean hydrogen power generation sector. Unlike prior literature that primarily focuses on single-unit or discrete capacities (Huang et al., 2019; Xu and Huang, 2017), our model captures the realistic complexities of this emerging market by incorporating continuous bid quantities, thereby addressing a previously unexamined gap in auction design for clean energy procurement. Our work fills the gap in the literature on how to design more practically implementable and tractable hydrogen power generation auctions and how to determine the optimal bidding strategies.
2. We propose a novel multi-attribute auction mechanism that overcomes key limitations of existing multi-unit multi-attribute auction designs (Zhang et al., 2019; Xiao et al., 2021). In contrast to earlier works that either apply lump-sum pricing rules or treat non-price attributes as fixed or exogenous, our mechanism integrates a per-unit pricing rule aligned with electricity markets and allows sellers to make trade-offs between price and non-price attributes, including those that affect the actual bid quantity. This formulation ensures compatibility with real-world hydrogen procurement challenges while enabling more flexible bidding behavior.
3. We show that sellers have weakly dominant bidding strategies under the proposed mechanism, extending prior results from single-unit additive-score auctions (Che, 1993) to a multi-unit setting with a realistic and complex scoring function. In particular, we demonstrate that even when bid quantities are endogenously affected by non-price factors and evaluated attribute values are weighted and scaled by bid quantities, truthful bidding remains optimal. This result provides practical strategic guidance for Gencos participating in a hydrogen power generation market.

The remainder of this paper is organized as follows. Section 2 gives a detailed review of the literature on multi-attribute auctions, their application, and the application of mechanism design to low-carbon markets. Section 3 presents our problem description. Section 4 introduces the multi-attribute procurement auction for the clean hydrogen generation market. Section 5 presents the results of the numerical analysis. Finally, Section 6 concludes the paper. All proofs are given in the Appendix.

2. Literature review

The main focus of this research, designing an auction for the clean hydrogen generation market, can be considered as a multi-attribute auction that involves many dimensions of quality or performance factors as well as the bid price. The seminal work of a multi-attribute auction is Che (1993), which studied multi-attribute auctions by considering price and quality dimensions, proposing three scoring rules: first score, second score, and second preferred offer. Furthermore, Che (1993) identified the scoring rule that implements the optimal mechanism and discussed utility equivalence in these auction formats. Building on this, Branco (1997) extended the model by incorporating correlated costs among firms, while Asker and Cantillon (2008) proposed scoring auctions where bidders' private information is multidimensional. Huang et al. (2016) modeled the winner determination problem in multi-attribute auction accounting for a risk-averse buyer. In a procurement auction, there is an uncertainty in buyer's (dis)satisfaction because of the supplier's unobservable effort and actual delivery performance. To address this challenge, Huang et al. (2019) introduced a multi-attribute auction that combines performance-based contracts when the delivered quality is highly uncertain. However, the above studies focus on the single-unit case, where only one indivisible object is auctioned, and each bidder has a single capacity.

In contrast, the auctioneer of the hydrogen power generation market must consider the procurement of continuous multi-unit electricity and producers' varying capacities. While prior studies, such as Xu and Huang (2017), proposed an allocative efficient multi-attribute auction for multi-unit procurement on a B2B platform, they assumed suppliers had only single-unit capacities. Moving beyond this, Zhang et al. (2019) and Xiao et al. (2021) designed multi-unit multi-attribute auctions for bidders with multiple capacities. Zhang et al. (2019) focused on transportation procurement, incorporating bidders' private information on costs, transportation time, capacity, and service quality, but assumed non-price attributes were neither controllable nor cost-related. Xiao et al. (2021) proposed a truthful and efficient auction design for crowd-sourced delivery, accommodating single-unit and multi-unit cases, but treated suppliers' capacities and non-price attributes as discrete and finite. Moreover, both studies applied lump-sum pricing rules. In contrast, our study assumes sellers can control non-price attributes by evaluating trade-offs between price and non-price attributes while treating both capacities and non-price attributes as continuous variables. Additionally, we propose a new auction rule that determines payments based on a unit price per kWh, aligning with standard pricing practices in the electricity market.

Meanwhile, multi-attribute auction models have been applied across various industries, especially in transportation procurement in the e-commerce logistics sector. Xu and Huang (2017) applied a multi-unit multi-attribute auction to a B2B e-commerce logistics problem, demonstrating that such auctions can be modeled as single-attribute multi-unit Vickrey auctions. Similarly, Yu et al. (2022) investigated a truthful multi-unit multi-attribute double auction for e-commerce logistics services, where each carrier bids on cost, delivery time, and transportation quality. Also, Zhang and Kong (2022) designed a multi-attribute double auction to address participant matching in emergency material procurement, incorporating a bargaining model to determine the transaction price and quantity. More recently, Sun et al. (2024) employed a multi-attribute reverse auction to select clients for federated learning in data markets. However, research on the application of multi-attribute auctions in low-carbon markets remains limited. To the best of our knowledge, this study is the first approach to propose an effective multi-attribute auction design for the hydrogen power generation market.

In terms of the field of energy economics, our study aligns with and contributes to the growing body of research applying mechanism design to low-carbon energy markets. Bichler et al. (2020) designed a combinatorial auction for renewable energy, aiming to induce efficient locational choices for power plants. Jung et al. (2024) proposed an optimal procurement auction model for long-term photovoltaic energy contracts, using a two-dimensional auction model where generators have private information on their costs and capacities. Furthermore, Sim et al. (2025) designed a trustful double auction mechanism for peer-to-peer energy trading by incorporating power losses and transaction costs, proposing efficient matching and allocation rules. In the context of hydrogen markets, Zhu et al. (2023) developed a trading mechanism for an integrated electricity-hydrogen market to address renewable energy fluctuations and introduced a profit allocation method based on the Shapley value. Although mechanism design theory is increasingly applied in renewable energy markets, few efforts have focused on efficient mechanisms for the clean hydrogen market, a key part of the low-carbon energy transition. Therefore, our research aims to fill this gap by proposing a multi-attribute procurement auction for the clean hydrogen power generation market, where the buyer engages in long-term contracts with multiple power generators and they compete based on both price and non-price attributes.

3. Problem description

3.1. Auction environment

In this study, we design a procurement auction scheme for the clean hydrogen generation market. In this auction, winning Gencos can enter into long-term contracts to supply energy generated by full hydrogen combustion or hydrogen co-firing over T years. The auction consists of an auctioneer (the buyer) and n hydrogen-fueled Gencos (the sellers) indexed by $i \in I = \{1, 2, \dots, n\}$. The buyer seeks to procure up to Q kWh of clean hydrogen co-fired electricity annually for T years from the sellers.

The unit cost of each seller i to generate 1 kWh of electricity using clean hydrogen can be defined in terms of LCOE. LCOE of each Gencos is determined by three critical attributes: co-firing rate ω_i, capacity factor ρ_i, and cost inefficiency parameter θ_i. The hydrogen co-firing rate refers to the proportion of hydrogen used in the fuel mix for power generation. A higher co-firing rate contributes more significantly to reducing greenhouse gas emissions. The capacity factor, on the other hand, represents the ratio of actual energy produced to the maximum possible energy that could be made over a given period. While a higher capacity factor can enhance efficiency by spreading fixed costs over greater output, it may negatively impact the stability of hydrogen fuel supply and technical reliability. Then, the LCOE function can be defined as follows.

$$c(\omega_i, \rho_i; \theta_i) = \theta_i \left(\omega_i VC_c + (1 - \omega_i) VC_{nc} + \frac{FC}{H\rho_i} \right), \quad (1)$$

where VC_c and VC_{nc} represent the annual variable costs of generating 1 kWh using clean hydrogen and non-clean hydrogen fuel, respectively, and FC represents the annual fixed costs for 1 kW of generation capacity. Also, note that $VC_c > VC_{nc}$ and H represents the total number of hours in a year, i.e., $H = 8760$.

In align with the model of Che (1993), we assume that each seller i has private information about its cost inefficiency parameter θ_i. In other words, a higher θ_i indicates a more cost-inefficient seller. We assume that θ_i is independently and identically distributed over $[\underline{\theta}, \overline{\theta}] \subset \mathbb{R}$ $(0 < \underline{\theta} < \overline{\theta})$ according to some cumulative distribution function $F(\theta)$ for which a positive, continuously differentiable density function $f(\theta)$ exists. These probability distributions are common knowledge. Since all Gencos must obtain a generation business license from the government for their generation facilities to participate in this market, the generation capacity of the Gencos, denoted as k_i, is assumed to be public information.

Though various non-price attributes can be considered in this auction, this study uses the co-firing rate ω_i and capacity factor ρ_i as non-price attributes to quantitatively evaluate contributions to greenhouse gas reduction and fuel supply reliability. Thus, sellers participate in the auction by submitting multi-attribute bids $b_i = (p_i, \omega_i, \rho_i)$ to compete for the contracts. The price attribute $p_i \in [\underline{p}, \overline{p}]$ represents the desired contract price per 1 kWh, while the non-price attributes $\omega_i \in [0.2, 1]$ and $\rho_i \in [0.2, 1]$ represent the promised hydrogen co-firing rate and capacity factor, respectively. To ensure minimum use of clean hydrogen fuel and consistent operation of generation facilities, both the co-firing rate and the capacity factor in bids have lower bounds of 0.2. For a given bid b_i, the bid quantity q_i (promised total electricity generation in a year) can be automatically computed as $q_i = k_i H \rho_i$. We denote the bid profile as $b = (b_i)_{i\in I}$ and the bid space as $\mathbb{B} = ([\underline{p}, \overline{p}] \times [0.2, 1] \times [0.2, 1])^n$.

3.2. Procurement mechanism

Following the information structure presented in the previous section, we define the procurement mechanism and the associated profit function for the Gencos and the buyer. Let $\Gamma = (S, a, p)$ be a procurement mechanism, where $S(b) = (s(b_i))_{i\in I} : \mathbb{B} \to \mathbb{R}^n_+$ is a scoring rule, $a(b) = (a_i(b))_{i\in I} : \mathbb{B} \to \mathbb{R}^n_+$ is an allocation rule, and $p(b) = ((\tilde{p}_i(b), \tilde{\omega}_i(b), \tilde{\rho}_i(b)))_{i\in I} : \mathbb{B} \to \mathbb{B}$ is a payment rule. After receiving the multi-attribute bids from the sellers, the auctioneer determines the winners based on the scoring rule and finalizes contracts based on the pre-announced auction rule. Each contract specifies an allocated quantity a_i, a contract price $\tilde{p}_i$, a co-firing rate $\tilde{\omega}_i$, and a capacity factor $\tilde{\rho}_i$. Under a contract $(a_i, \tilde{p}_i, \tilde{\omega}_i, \tilde{\rho}_i)$, seller i is required to supply hydrogen co-fired power with a co-firing rate of $\tilde{\omega}_i$ and a capacity factor of $\tilde{\rho}_i$ for T years in exchange for the payment $\tilde{p}_i$. The total annual power generation $\tilde{q}_i = k_i H \tilde{\rho}_i$ consists of clean hydrogen generation $\tilde{\omega}_i \tilde{q}_i$ and non-hydrogen generation $(1 - \tilde{\omega}_i)\tilde{q}_i$. The buyer intends to purchase power generated by the contracted sellers at a level of $a_i \leq \tilde{q}_i$. Therefore, each seller i with type θ_i earns the following profit from the contract $(a_i, \tilde{p}_i, \tilde{\omega}_i, \tilde{\rho}_i)$ is defined as follows.

$$\pi_i(a_i, \tilde{p}_i, \tilde{\omega}_i, \tilde{\rho}_i; \theta_i) = \sum_{t=1}^{T} [\tilde{p}_i - c(\tilde{\omega}_i, \tilde{\rho}_i; \theta_i)] a_i, \quad (2)$$

where a discount rate is assumed to be 1 for simplicity.

The auction awards contracts to the winners according to a specific scoring rule pre-announced to all participants. Each seller's bid $b_i = (p_i, \omega_i, \rho_i)$ is evaluated using a score function that integrates the price and non-price attributes with a weighting factor $\gamma \in [0, 1]$ as follows:

$$s(b_i) = [\gamma \cdot \frac{\overline{p} - p_i}{\overline{p} - \underline{p}} + (1 - \gamma) \cdot g(\omega_i, \rho_i)] q_i. \quad (3)$$

In this function, the first term normalizes the bid price p_i to a value between 0 and 1, allowing for a consistent and comparable evaluation of the price attribute. The second term evaluates the non-price attributes ω_i and ρ_i through a function g, which maps their contribution to greenhouse gas reduction and fuel supply reliability onto the same [0,1] scale. All attribute scores, whether price or non-price, are thus normalized to the range from 0 to 1, ensuring that differences in measurement units do not hinder comparability. The overall score is then computed by multiplying each normalized score by the offered supply quantity, with the weighting factor γ applied to reflect the relative importance between price and non-price attributes. This approach enables the auction to aggregate heterogeneous attributes into a unified score in a transparent and systematic manner. Furthermore, since the scoring rule is pre-announced and publicly disclosed before bidding begins, bidders can anticipate how their offers will be evaluated, thereby ensuring fairness and credibility in the auction process.

To characterize the properties of the non-price attribute scoring function g, we impose the following assumptions.

Assumption 1 (*The Shape of the Non-Price Attribute Scoring Function*).

(a) $g_\omega > 0$ and $g_\rho < 0$,[2]
(b) $g_{\omega\omega} < 0$, $g_{\rho\rho} < 0$, and $g_{\omega\rho} = 0$.

Assumption 1(a) reflects the environmental impact of power generation facilities. As the proportion of clean hydrogen power generation increases, it becomes more environmentally friendly; however, the more these facilities operate, the more cumulative emissions are generated. Additionally, to ensure that our mechanism is well-behaved, we impose Assumption 1(b).

By the definition of our scoring rule, $s_p \leq 0$ and $s_\omega \geq 0$ are satisfied, meaning that the buyer assigns higher scores to sellers who offer lower prices or use cleaner hydrogen in power generation. However, s_ρ may be either positive or negative depending on the parameter values and the functional form of g. This is because our scoring rule evaluates the total bid quantity, rather than on a per-unit basis, unlike prior studies such as Che (1993) and Asker and Cantillon (2008). A higher capacity factor could lead to a higher price score. Still, it may simultaneously reduce the non-price score due to increased instability in the hydrogen fuel supply. Additionally, since $s_{\omega\rho} > 0$, it indicates that the co-firing rate and capacity factor exhibit complementary interactions in their contribution to the overall score. In other words, bidding both a high co-firing rate and a high capacity factor improves a seller's chances of winning the auction.

[2] The functions with the subscripted variables in this paper imply the partial derivative of the functions with respect to the corresponding variables.

Meanwhile, the buyer's utility function from contracts is defined as follows:

$$u_b = \sum_{t=1}^{T} \sum_{i \in I^*} [V(\tilde{\omega}_i, \tilde{\rho}_i) - \tilde{p}_i a_i], \quad (4)$$

where I^* is the set of winning sellers and $V(\tilde{\omega}_i, \tilde{\rho}_i)$ represents the buyer's value derived from the contract with each seller i. In practice, the buyer evaluates sellers using a scoring rule that aggregates price and non-price attributes. This suggests that the buyer's utility from a contract should be proportional to the seller's score. Thus, we assume that the buyer's utility $u_b = \sum_{t=1}^{T} \sum_{i \in I^*} \frac{(\overline{p}-\underline{p})(1-\gamma)}{\gamma} s(b_i)$, which implies that $V(\tilde{\omega}_i, \tilde{\rho}_i)$ takes the following form:

$$V(\tilde{\omega}_i, \tilde{\rho}_i) = [\overline{p} + \frac{1-\gamma}{\gamma}(\overline{p} - \underline{p}) g(\tilde{\omega}_i, \tilde{\rho}_i)] a_i. \quad (5)$$

So, the buyer's value increases as the evaluation of non-price attributes improves. That is, the buyer's utility captures the aspect of the government securing hydrogen energy at a low cost, while also making it more stable and environmentally friendly.

Given the previously defined profit functions of Gencos and the buyer, social surplus is defined as the sum of their utilities, denoted as $W(\Gamma)$. This can be expressed as:

$$W(\Gamma) = \sum_{t=1}^{T} \sum_{i \in I} [V(\tilde{\omega}_i, \tilde{\rho}_i) - c(\tilde{\omega}_i, \tilde{\rho}_i; \theta_i) a_i]. \quad (6)$$

This formulation captures the overall efficiency of the auction mechanism by aggregating the economic benefits of all market participants.

Finally, to ensure that the optimal solutions do not result in corner solutions, we impose the following assumption.

Assumption 2 (*Uniqueness of the Optimal Solution*). $V(\omega_i, \rho_i) - c(\omega_i, \rho_i, \theta_i) q_i$ has a unique maximum in (ω_i, ρ_i) for all $\theta_i \in [\underline{\theta}, \overline{\theta}]$, $\omega_i \in [0.2, 1]$, $\rho_i \in [0.2, 1]$, and $\forall i \in I$.

4. Multi-attribute procurement auction

In this section, we design a Vickrey-score sealed-bid auction rule for the multi-attribute procurement auction framework, where the buyer procures up to Q kWh of clean hydrogen co-fired power from multiple sellers. The entire procedure of the proposed procurement auction for the clean hydrogen generation market is as follows:

(1) The buyer publicly announces the Vickrey-score sealed-bid auction rule in advance, including the scoring rule $S(b)$, the allocation rule $a(b)$, and the payment rule $p(b)$ to all market participants.
(2) Each seller i privately learns its type θ_i and submits a multi-attribute bid b_i which consists of both price and non-price attributes.
(3) The buyer calculates the score $s(b_i)$ of each seller according to the pre-announced scoring rule.
(4) The buyer allocates contracts to the sellers with the highest scores according to the allocation rule $a(b)$ and determines the contract prices, co-firing rates, and capacity factors based on the payment rule $p(b)$.

We will describe the detailed structure of our Vickrey-score sealed-bid auction rule, which deals with scoring, allocation, and payment rules based on the multi-attribute bids of participating sellers. Furthermore, we also specify how sellers determine their equilibrium bidding strategies under our auction rule and analyze the theoretical and practical implications of these strategies.

4.1. Vickrey-score sealed-bid auction rule

Whereas a price-only single-attribute auction determines winners and allocations solely by ranking bid prices, a multi-attribute auction accounts for both bid prices and non-price attributes. To resolve this, each seller's multi-attribute bid is converted into a score using a predefined scoring rule. This allows the buyer to rank the sellers' bids by score values. Therefore, it is important to apply an appropriate scoring rule to evaluate the bids properly and facilitate the calculation of the equilibrium bidding strategy. Our auction employs the score function in Eqs. (4) and we discuss the specific functional form in Section 5.

Once the bids of sellers are reported, the buyer can evaluate the score of each bidder i, denoted as $s(p_i, \omega_i, \rho_i)$, using the scoring rule. Then, the buyer can rank the bidders in descending order based on their scores. Let the index of each bidder according to their rank be denoted as $[i]$, i.e.,

$$s(p_{[1]}, \omega_{[1]}, \rho_{[1]}) \geq s(p_{[2]}, \omega_{[2]}, \rho_{[2]}) \geq \cdots \geq s(p_{[n]}, \omega_{[n]}, \rho_{[n]}). \tag{7}$$

The buyer allocates the supplies to multiple sellers according to the following allocation rule. Assuming a sufficiently large number of sellers participate in the auction, it is possible to find a seller with index k that satisfies

$$\sum_{i=1}^{k-1} q_{[i]} < Q \leq \sum_{i=1}^{k} q_{[i]}. \tag{8}$$

Because the buyer aims to procure at most Q kWh of hydrogen co-fired power from the highest-scoring sellers, we allocate an annual supply quantity q_i as follows.

$$a_i(b) = \begin{cases} q_i, & \text{if } [i] < [k] \\ 0, & \text{if } [i] \geq [k] \end{cases} \tag{9}$$

If we were to allocate only $Q - \sum_{i=1}^{k-1} q_{[i]}$ to the kth seller, the buyer would procure exactly Q kWh. However, this could lead to sellers' complex gaming behavior, where they attempt to secure their entire bid quantity. Therefore, in our allocation rule, we assign the full bid quantity q_i to each winning seller i to reduce the incentive for strategic bidding.

After the allocation is finalized, the buyer must determine the contract's remaining parts: contract price, hydrogen co-firing rate, and capacity factor. To do this, we adopt the key idea of the Vickrey auction, which determines the winning price as the highest losing bid. Similar to the Vickrey auction, we consider the highest score among the rejected sellers, i.e, $s(b_{[k]}) = s(p_{[k]}, \omega_{[k]}, \rho_{[k]})$. The suggested payment rule can be described as follows. Each winning seller i is required to enter into a contract at a price $\tilde{p}_i$ that matches the highest rejected score under the submitted (ω_i, ρ_i). That is, the contract price of winning bidder i is determined as $\tilde{p}_i$ that satisfies the following equation:

$$s(\tilde{p}_i, \omega_i, \rho_i) = s(p_{[k]}, \omega_{[k]}, \rho_{[k]}). \tag{10}$$

Thus, the winning seller i must supply hydrogen-generated power annually with a co-firing rate of ω_i and a capacity factor of ρ_i for T years in exchange for the payment $\tilde{p}_i$ per 1 kWh of electricity.

4.2. Equilibrium analysis

Under the suggested Vickrey-score sealed-bid auction rule, we can characterize the equilibrium bidding strategies. The auction rule induces a Bayesian game in which sellers determine their price and non-price attributes to bid as a function of their cost inefficiency parameters. The following proposition establishes how the equilibrium non-price bids are determined for each seller based on their cost parameter, utility function, and the scoring rule. Che (1993) proved a similar lemma for the case where a single indivisible unit is auctioned and one non-price dimension is considered. We extend this result to show that it also holds for the case of multiple units and multiple non-price dimensions.

Proposition 1. *Given the scoring rule and the seller's utility function, the optimal co-firing rate ω_i and capacity factor ρ_i that maximize the seller's utility are chosen independently of the bid price and the seller's beliefs about the other participants, at $\omega_i^*(\theta_i)$ and $\rho_i^*(\theta_i)$ for all $\theta_i \in [\underline{\theta}, \overline{\theta}]$, where*

$$(\omega_i^*(\theta_i),\ \rho_i^*(\theta_i)) = \underset{\omega_i, \rho_i}{\operatorname{argmax}}\ \{V(\omega_i, \rho_i) - c(\omega_i, \rho_i, \theta_i) q_i\},\ \forall i \in I. \tag{11}$$

Proposition 1 shows that sellers should jointly optimize their co-firing rate and capacity factor before computing a bid price. The most noticeable point is that the other bidders' strategies do not influence the equilibrium strategies for both non-price attributes. The only factors influencing the equilibrium strategies are the seller's type, the form of the utility, and the announced score function. From this fact, we can restrict our attention to finding the equilibrium bid price, while fixing the non-price attributes as the optimal values satisfying Eq. (11). Furthermore, by the proposed auction rule, the winning seller i will contract with the buyer based on the submitted non-price attributes $(\omega_i^*(\theta_i),\ \rho_i^*(\theta_i))$.

Then, one of the questions that can be asked here is how the cost inefficiency parameter θ_i affects the optimal non-price attributes. To answer this, we define the pseudotype of seller i who bids $(\omega_i^*(\theta_i),\ \rho_i^*(\theta_i))$, denoted as $S^o(\theta_i, k_i)$. The mathematical expression of $S^o(\theta_i, k_i)$ is as follows.

$$S^o(\theta_i, k_i) = \max_{\omega_i, \rho_i} \left\{V(\omega_i, \rho_i) - c(\omega_i, \rho_i, \theta_i) q_i\right\} \tag{12}$$

$$= V\left(w_i^*(\theta_i), \rho_i^*(\theta_i)\right) - c\left(w_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i\right) q_i \tag{13}$$

This represents the maximum level of social surplus that seller i with type θ_i and capacity k_i can generate. According to the envelope theorem, $S^o(\theta_i, k_i)$ is strictly decreasing in θ_i for a given fixed capacity. Using this definition, we can derive the next proposition that shows the impact of cost parameters on the optimal co-firing rate and capacity factor.

Proposition 2. *Under the Vickrey-score sealed-bid auction rule, $\omega_i^*(\theta_i)$ and $\rho_i^*(\theta_i)$ always decreases in θ_i for every seller $i \in I$.*

Proposition 2 demonstrates that as sellers become more cost-inefficient, represented by an increase in θ_i, their optimal strategies shift toward choosing lower co-firing rates and capacity factors. This result contrasts with the behavior observed in price-only auctions, where cost-inefficient sellers may try to increase capacity factors to spread fixed costs and enhance price competitiveness. However, such a strategy could harm the seller's overall score in a multi-attribute auction, where both price and non-price attributes are jointly evaluated. Therefore, sellers are incentivized to lower the co-firing rate and capacity factor simultaneously when faced with higher cost inefficiency to maintain an optimal score. This adjustment reflects the need to balance the trade-offs between price and non-price attributes under the proposed auction's scoring rule.

So far, we have demonstrated that there exists an optimal pair of non-price attributes. The remaining task is to determine the optimal bidding price strategy of sellers under the proposed auction rules. The following proposition establishes the existence of a weakly dominant strategy for each seller in the Bayesian game induced by the proposed auction rule.

Proposition 3. *The proposed multi-attribute procurement auction has a weakly dominant strategy equilibrium, where each seller with type θ_i offers the non-price attributes as (11) and the price attribute as*

$$p_i^*(\theta_i) = c(\omega_i^*(\theta_i),\ \rho_i^*(\theta_i), \theta_i), \tag{14}$$

and under this bidding strategy, the seller will receive the following score

$$s(p_i^*(\theta_i),\ \omega_i^*(\theta_i),\ \rho_i^*(\theta_i)) = \frac{\gamma}{\overline{p} - \underline{p}} S^o(\theta_i, k_i). \tag{15}$$

The dominant strategy stands for the strategy that always provides the best outcome for a player, regardless of what strategies other players choose. Thus, regardless of other participants' reports, each seller's optimal strategy for the price attribute is to bid according to (14), based on their type and the corresponding equilibrium non-price bids. Furthermore, the equilibrium bid price of each seller is exactly its LCOE when the non-price attributes are set to the level that satisfies (11). Since the score calculated under the equilibrium bidding strategy is proportional to the pseudotype, awarding contracts based on the designed scoring rule yields the same outcome as selecting winners based on pseudotype rankings. Given that the pseudotype represents the maximum level of social surplus that a seller i can generate, the contracts are awarded in a way that prioritizes sellers contributing the highest social surplus.

Through the above proposition, we have mathematically derived how sellers determine the levels of both non-price and price attributes when submitting bids. Notably, the price attribute is determined at the LCOE level, which varies depending on changes in the non-price attribute. Since our scoring rule divides these two attributes based on a weight parameter γ, bidding strategies may change based on variations in this weight. The following proposition aims to establish a general relationship that explains this phenomenon.

Proposition 4. *Let $\Lambda(\omega_i^*(\theta_i), \rho_i^*(\theta_i))$ be defined as*

$$\Lambda(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) = g(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) + \rho_i^*(\theta_i) g_\rho(\omega_i^*(\theta_i), \rho_i^*(\theta_i)). \tag{16}$$

Under the proposed Vickrey-score sealed-bid auction rule,

(a) $\omega_i^*(\theta_i)$ always decreases in γ.
(b) If $\Lambda(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) \geq 0$, $\rho_i^*(\theta_i)$ decreases in γ.
(c) If $\Lambda(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) < 0$, $\rho_i^*(\theta_i)$ increases in γ.

Proposition 4 provides key insights into how the weight γ, which reflects the buyer's relative preference for price versus non-price attributes, influences sellers' bidding strategies. Specifically, as the weight γ increases, sellers place more emphasis on the price attribute, which leads to a reduction in the promised co-firing rate. This reflects a fundamental trade-off in multi-attribute auctions: when more weight is given to price, sellers are incentivized to lower their commitments to non-price attributes such as clean energy contributions. The proposition also highlights the effect of the weight γ on the optimal capacity factor, which depends on the sign of the term $\Lambda(\omega_i^*(\theta_i), \rho_i^*(\theta_i))$. Notably, $\Lambda(\omega_i^*(\theta_i), \rho_i^*(\theta_i))$ represents the partial derivative of the total non-price score, i.e., $\Lambda(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) = \frac{1}{k_i H} \frac{\partial g(\omega_i, \rho_i) q_i}{\partial \rho_i} |_{\omega_i = \omega_i^*(\theta_i), \rho_i^*(\theta_i)}$. Thus, the sign of $\Lambda(\cdot)$ determines the relationship between the non-price score and the capacity factor.

When $\Lambda(\cdot) \geq 0$, increasing the capacity factor decreases the price score while raising the non-price score. In this case, under the equilibrium strategy, the capacity factor influences each score in a counter-intuitive manner. As the weight γ increases, sellers must lower their optimal capacity factor to effectively balance the price and non-price scores. Conversely, when $\Lambda(\cdot) < 0$, an increase in capacity factor has the opposite effect—it raises the price score while reducing the non-price score. Under these conditions, a higher γ incentivizes sellers to increase their capacity factor and decrease their co-firing rate to maximize their price score advantage. Thus, Proposition 3 reveals the strategic interplay between the price and non-price attributes, illustrating how sellers adjust their capacity factor and co-firing rate in response to the scoring rule and the resulting trade-offs.

5. Numerical experiment

This section studies the outcomes of the proposed multi-attribute procurement auction in the clean hydrogen power generation market. To this end, we first define cost parameters based on actual data from South Korea's hydrogen co-firing power generation sector. Using these parameters, we analyze the impact of different scoring weights on sellers' equilibrium strategies and auction outcomes such as social welfare and winners' LCOE. We further compare the performance of the multi-attribute auction under the Vickrey-score sealed-bid auction rule with that of a price-only single-attribute auction.

5.1. Experiment parameters

First, we aim to define the function g used in the score function as follows:

$$g(\omega_i, \rho_i) = \alpha(1 - (1 - \sqrt{\omega_i}) EF_i) + (1 - \alpha)(1 - \rho_i^2), \tag{17}$$

where α represents the score weight assigned to the two non-price attributes, and $EF_i \in [0, 1]$ denotes the emission factor of seller i's generation facility before its conversion to hydrogen generation. Typically, hydrogen producers retrofit existing natural gas or coal-fired power plants to enable hydrogen co-firing. Hence, the first term in g evaluates the hydrogen co-firing rate based on the reduction in greenhouse gas emissions due to hydrogen co-firing. A higher co-firing rate leads to a greater reduction in emissions. Moreover, just as we assume capacity to be public information, we similarly assume that the emission factors of all sellers are also public information. The second term reflects the increasing instability in the hydrogen fuel supply as the capacity factor rises. We can easily verify that this function g satisfies our assumptions: $g_\omega > 0$, $g_\rho < 0$, $g_{\omega\omega}, g_{\rho\rho} < 0$, and $g_{\omega\rho} = 0$.

To set up the parameters for the numerical experiment, we assume that sellers participate in the market using either coal-ammonia co-firing or natural gas-hydrogen co-firing technologies. Both technologies involve retrofitting existing coal or gas power plants to use hydrogen co-firing fuel. Sellers utilizing these technologies can rely on different types of hydrogen fuel and their acquisition methods as shown in Table 1. We use values based on historical data and research reports from South Korea to closely reflect real market conditions in our numerical experiments. Table 1 presents the CAPEX and fixed operation and maintenance (O&M) costs for different power generation technologies, along with the non-hydrogen and clean hydrogen fuel costs. The CAPEX and fixed O&M costs are presented as annual values, applying a discount rate of 4.5% and a lifespan of 20 years. Finally, we use the averages of these costs as the values for the parameters FC, VC_c, and VC_{nc} as shown in Table 2.

The scoring weights γ and α can take various values between 0 and 1, depending on the buyer's preferences. In this experiment, we consider the weights presented in Table 2. These specific weights ensure that the equilibrium bidding strategies for non-price attributes, as determined by Proposition 1, result in interior solutions. This approach allows the buyer to select sellers more effectively.

To generate the sellers' information, we assume a total of 30 Gencos participating in the auction as sellers, with their type distribution following a uniform distribution with a mean of 1. The standard deviation of the type is set at 20% of the mean. Thus, a seller i with a type $\theta_i = 1$ has average levels of fixed and fuel costs considering various power generation technologies and fuel types. The capacity follows a uniform distribution within the range of $[100, 215]$ (MW), representing the capacity scale of medium-sized gas turbine power plants. Finally, the sellers' emission factors follow a normal distribution with a mean of 0.42 and a standard deviation of 10% of the mean.

5.2. Results and implications

5.2.1. Impact of weights on the bidding strategies and auction outcomes

We first present the impact of scoring weights on auction outcomes. All results are averaged over 100 randomly generated scenarios for sellers' information. The results presented in Fig. 1 provide critical insights into the dynamics of scoring weights and their impact on auction outcomes. As the price score weight γ increases, social welfare consistently declines, indicating a trade-off between prioritizing price and overall efficiency. While adjustments in the non-price attribute weight α also influence social welfare, the effect is less significant compared to changes in γ, suggesting that price sensitivity plays a dominant role in determining auction efficiency.

Table 1
Generation technologies and cost data.

Generation technology	Fuel type	CAPEX (KRW/kW)	Fixed O&M (KRW/kW)	Non-hydrogen fuel cost (KRW/kWh)	Hydrogen fuel cost (KRW/kWh)
Coal-ammonia co-firing	A	106,857[a]	66,000[a]	79.1[b]	132.2[c]
Natural gas -Hydrogen co-firing	B	99,938[a]	9636[a]	71.5[d]	108.3[e]
	C				573.2[f]
	D				287.9[f]
	E				210.4[g]
	F				186.2[g]

KRW is a monetary unit of South Korea, and 1 USD is about 1400 KRW as of 2025.
A: Imported green ammonia, B: Natural gas reformed hydrogen with CCS, C: Green hydrogen using renewable energy, D: Green hydrogen using PPA, E: Imported liquefied clean hydrogen, F: Clean hydrogen reconversion from imported ammonia.
[a] Korea Institute of Energy Research (2021).
[b] Korea Power Exchange (2020-2024).
[c] Korea Energy Economics Institute (2023).
[d] Korean Gas Corporation (2020-2024).
[e] BNEF (2020).
[f] Korea Energy Economics Institute (2022).
[g] Hwang et al. (2022).

Table 2
Parameters for numerical example.

Parameters	Values
FC (KRW/kW)	141,216
VC_c (KRW/kWh)	249.7
VC_{nc} (KRW/kWh)	75.3
Q (GWh)	6500
$[\underline{p}, \overline{p}]$ (KRW/kWh)	$[82.6, 444.7]$
γ	$\{0.2, 0.25, 0.3, 0.35, 0.4\}$
α	$\{0.35, 0.4, 0.45, 0.5, 0.55\}$

These results highlight the importance of carefully calibrating the balance between price and non-price attributes. As γ increases, a lower α is more suitable for enhancing social welfare, implying that the relative weight assigned to non-price attributes, such as environmental performance or capacity reliability, should be adjusted based on the buyer's objectives. The auctioneer must, therefore, optimize scoring rules in accordance with specific policy goals. By doing so, it is possible to achieve a socially beneficial outcome without overly sacrificing cost efficiency.

In addition, Fig. 1 indicates that increasing the weight on the co-firing rate incentivizes sellers to improve their environmental performance. The observed rise in equilibrium capacity factor as both γ and α increase further suggests that sellers are willing to adjust their LCOE to optimize their bids based on the auction's scoring system.

Table 3 provides a detailed summary of the key metrics under varying scoring weights. In particular, the first row illustrates the overall results for different values of α when $\gamma = 0.2$. Firstly, as the weight on price increases or the weight on the co-firing rate decreases, the average LCOE of the winners decreases. Since bidders submit their LCOE as bid prices according to Proposition 3, this implies a corresponding effect on equilibrium bid prices. However, as γ increases, this also narrows the gap between the contract price and LCOE, meaning that while sellers are bidding lower, their profit margins shrink. This reduction in seller utility suggests that higher price weightings could reduce the incentive for bidders to compete aggressively in future auctions, as the potential rewards diminish. In addition, it is evident that a smaller γ and a larger α result in a higher proportion of clean hydrogen generation within the total procurement. Therefore, the results in Table 3 suggest that to support the transition to clean hydrogen energy, auction mechanisms should be designed with a balanced weighting scheme, where both price and non-price attributes are adequately considered.

5.2.2. Sensitivity analysis of capacity

Fig. 2 illustrates the impact of bidder capacity and variations in price score weight on the winning bidders' LCOE and contract prices. The figure reveals that sellers with smaller capacities tend to have higher generation costs and consequently supply electricity at higher prices to the buyer, even under the same auction scheme. In comparison to the results presented in Table 3, when the capacity range for auction participants is divided into narrower intervals, sellers with larger capacities face increased competition from other sellers with similarly low LCOE. It results in worse contract terms than when the capacity range is broader. From the buyer's perspective, narrowing the capacity range may lead to reduced payments. Therefore, setting appropriate capacity intervals for auction participants is crucial to ensuring a balanced adjustment of contract prices and fostering fair competition among bidders.

Fig. 3 shows the effects of the lower bound of the capacity range and changes in the price score weight on social welfare. Since the score function is heavily influenced by capacity, changes in the lower bound affect the auction outcome. Also, limiting the capacity range of auction participants alters the pool of competitors, which subsequently impacts the auction outcome. The figure shows that the optimal capacity range depends on the level of price score weight. When γ is relatively low, larger capacity intervals and a much lower bound tend to generate greater social welfare through the auction. However, as γ exceeds 0.3, the results are reversed, showing that tighter capacity intervals generally yield higher social welfare. This outcome suggests that greater emphasis on price benefits larger capacity bidders, as their ability to offer lower prices leads to more favorable auction outcomes. Therefore, the buyer must carefully determine the permissible capacity range according to their preferences for price versus non-price attributes to achieve socially efficient outcomes.

5.2.3. Sensitivity analysis of costs

Now, we investigate how the change of hydrogen cost and technologies can impact the market outcome. First of all, we assume that technological change would affect the fixed cost (FC) and conduct a sensitivity analysis accordingly. Table 4 presents how the key auction performance metrics change as the baseline value of FC assumed in Table 2 varies from 60% to 130%. As fixed costs decrease, the average LCOE drops, while the average contract price declines accordingly. Notably, social welfare increases steadily when fixed costs are reduced. These results indicate that as fixed costs decline, potentially due to technological advancement or economies of scale, the economic efficiency of the auction improves, leading to lower procurement costs for the buyer and higher overall social welfare.

Meanwhile, Table 5 summarizes the impact of varying hydrogen fuel costs (VC_c), from 60% to 130% compared to the baseline variable cost component (VC_c) assumed in Table 2, on key auction outcomes.

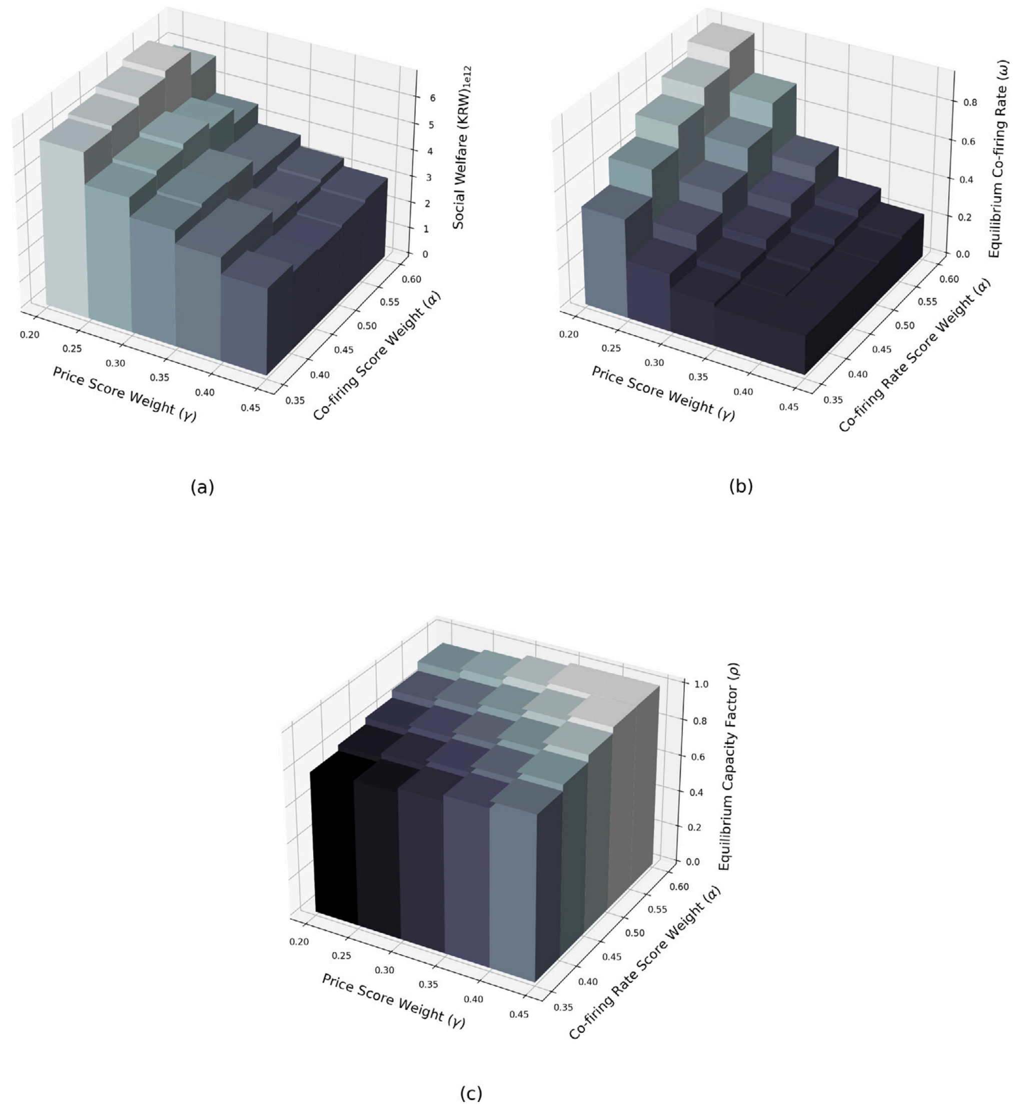

Fig. 1. Impact of scoring weights on (a) social welfare, (b) equilibrium co-firing rate, and (c) equilibrium capacity factor.

Table 3
Impact of each scoring weight on primary metrics.

γ	α	Average LCOE of winners (KRW/kWh)	Average contract price (KRW/kWh)	Average utility of winners (10^6 KRW-year)	Hydrogen procurement (GW)	Total procurement (GW)
0.2		193.3	250.9	87,923	4268	5775
0.25		155.5	200.2	69,968	2829	5765
0.3	–	130.0	166.8	59,473	1819	5733
0.35		116.8	148.7	53,361	1340	5661
0.4		110.4	138.8	49,150	1128	5440
	0.35	127.9	168.4	60,037	1647	5836
	0.4	133.9	174.4	62,122	1967	5842
–	0.45	140.8	181.2	64,542	2326	5776
	0.5	147.9	187.5	66,060	2647	5597
	0.55	155.5	194.0	67,114	2798	5322

As hydrogen fuel costs decrease, both the equilibrium hydrogen co-firing rate and capacity factor increase significantly. Concurrently, the average LCOE declines from 153 to 146 KRW/kWh, and the average contract price decreases from 203 to 192 KRW/kWh. These cost improvements translate into a substantial increase in social welfare. This analysis suggests that reductions in hydrogen fuel cost potentially achieved through improvements in hydrogen production, supply chain efficiency, or government subsidies can lead to more hydrogen-intensive generation, lower procurement prices, and greater overall efficiency in the hydrogen power market.

The above experiments demonstrate how changes in fixed cost and hydrogen fuel cost affect auction outcomes such as equilibrium bids, contract prices, and social welfare. These findings suggest that the auction performance can be sensitive to evolving cost structures driven by technological progress or market developments. Accordingly, the buyer may adapt the scoring rule over time to reflect changing market conditions. In particular, as hydrogen technologies mature and the variation in non-price attributes among sellers diminishes, it becomes important to fine-tune the scoring weights to maintain efficient and

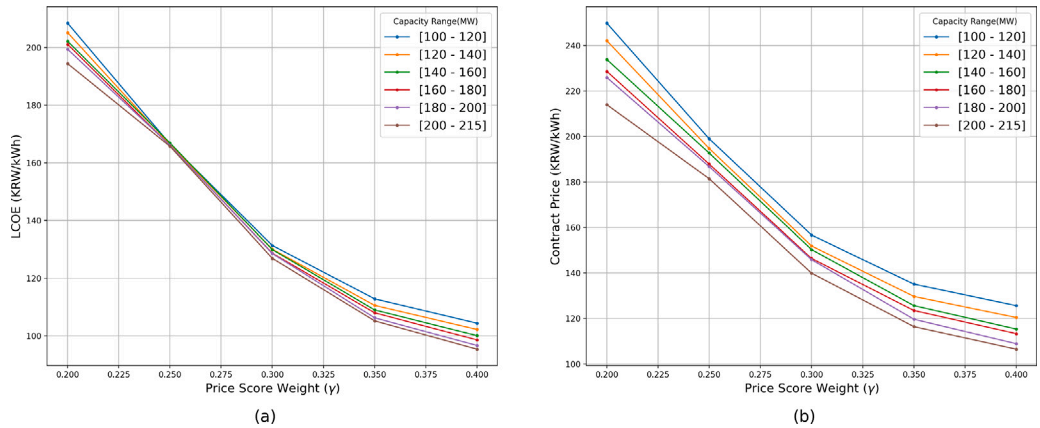

Fig. 2. Impact of capacity ranges and price score weights on (a) LCOE and (b) contract price.

Table 4
Impact of fixed cost on primary metrics.

Rate of change in fixed cost	Average LCOE (KRW/kWh)	Max LCOE (KRW/kWh)	Min LCOE (KRW/kWh)	Average contract price (KRW/kWh)	Average social welfare (10^9 KRW/year)
130%	181	200	165	223	4450
120%	179	199	164	222	4457
110%	178	198	162	220	4464
90%	175	195	159	217	4478
80%	174	193	158	216	4485
70%	173	192	156	215	4492
60%	171	191	155	213	4499

Table 5
Impact of hydrogen fuel cost on primary metrics.

Rate of change in fuel cost	Equilibrium hydrogen co-firing rate	Equilibrium capacity factor	Average LCOE (KRW/kWh)	Average contract price (KRW/kWh)	Average social welfare (10^9 KRW/year)
130%	0.35	0.94	153	203	4351
120%	0.42	0.94	158	208	4391
110%	0.55	0.95	170	220	4441
90%	0.80	0.96	180	234	4585
80%	0.89	0.96	175	226	4677
70%	0.99	0.98	166	215	4783
60%	1.00	0.99	146	192	4899

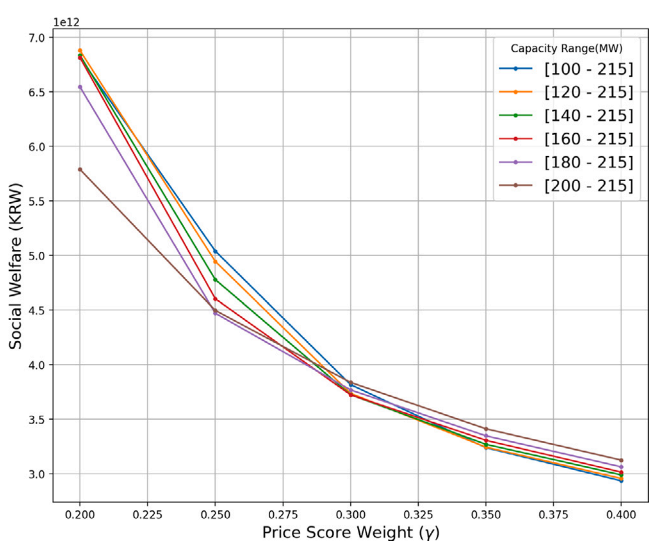

Fig. 3. Sensitivity of social welfare to capacity range and price score weight.

socially desirable outcomes. This adaptability ensures that the mechanism remains aligned with policy goals even as the hydrogen power generation evolves.

5.2.4. Comparison of auction formats

The price-only single-attribute auction determines winners and allocations based solely on bid prices. It can be considered a special case of the multi-attribute auction where $\gamma = 1$ and the uniform pricing rule is applied. Fig. 4 compares the outcomes of social welfare, hydrogen-generated power within the total procurement, and average LCOE of winners between the two auction formats: the proposed auction and a price-only single-attribute auction. For this comparison, we fixed α at 0.5 for convenience.

The figure shows that regardless of the value of the scoring weight γ, the proposed multi-attribute auction is more socially beneficial. However, regarding clean hydrogen generation, there is no significant difference between the two auction formats when γ is between 0.35 and 0.4 or higher. We should note that the primary goal of this market is to promote hydrogen generation and activate the hydrogen economy. Therefore, while specific values may vary depending on the parameter settings, setting an appropriate price score weight is crucial for achieving the market's objectives. Finally, since price competitiveness is the most critical factor in a single-attribute auction, winners always have a lower LCOE compared to the multi-attribute auction, regardless of γ.

Beyond its performance advantages, the multi-attribute auction enables more informed decision-making by allowing buyers to evaluate non-price attributes. This supports procurement decisions aligned with broader policy goals like emission reduction and energy security, which price-only auctions cannot capture. Furthermore, since the score of

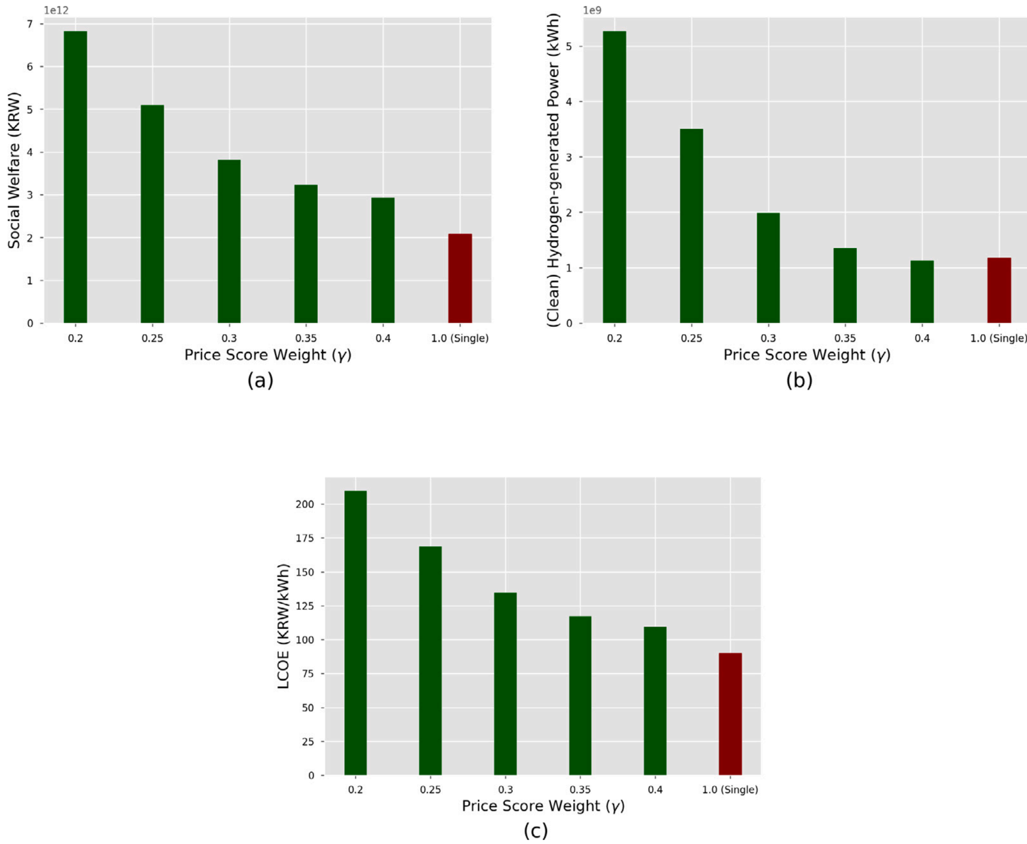

Fig. 4. Comparison for (a) social welfare, (b) hydrogen generation, and (c) average LCOE of each auction format.

each attribute is quantitatively calculated, buyers can monitor how these non-price factors influence outcomes and revise scoring weights in future auctions to further refine the procurement strategy.

It is worthwhile that a direct comparison with actual Korean hydrogen auctions is challenging due to the theoretical intractability of equilibrium in the current receive-as-bid scheme, as Ausubel et al. (2014) mentioned that equilibrium does not exist in a multi-unit receive-as-bid auction in general. However, our proposed mechanism demonstrates strong potential for improving allocative efficiency, price discovery, and policy alignment in practice by addressing its critical weaknesses, such as ambiguity in qualitative scoring and incentives for strategic misreporting. The results of our numerical simulations offer valuable insights into how institutional design improvements can be translated into more socially desirable outcomes, even in settings with complex multi-attribute evaluation.

In sum, our experiment results emphasize the importance of carefully balancing scoring weights to optimize auction outcomes. Specifically, lower price score weights tend to yield more socially beneficial results, and selecting an appropriate α value based on the γ value is essential. Furthermore, how the capacity of bidders is restricted in the auction significantly affects outcomes such as average contract prices and can influence fair competition among bidders. Lastly, the results indicate that our multi-attribute auction, using the Vickrey-score sealed-bid auction, outperforms the price-only single-attribute auction in terms of social welfare in the hydrogen power generation market.

These findings underscore the potential of our multi-attribute auction design to enhance market efficiency and promote clean energy generation, aligning with the long-term goals of the hydrogen economy. Moreover, the proposed mechanism can be applicable to other countries like Japan and Germany, pursuing similar policy objectives. However, in countries where hydrogen power generation technologies are relatively mature, the performance gap between multi-attribute and price-only auctions may be less pronounced, as there is less significant variation in bidders' non-price attributes. In such contexts, additional auction design features may be necessary to further improve efficiency, for example, by introducing more granular scoring criteria.

6. Conclusion

In a remarkable shift toward cleaner and more sustainable energy sources, low-emission hydrogen has emerged as an important alternative in the power generation sector. In 2024, South Korea established the world's first hydrogen power generation auction market to improve the economic viability of hydrogen-fueled power projects. The official policy goals of this market are twofold: to reduce greenhouse gas emissions through the use of clean hydrogen and to establish stable electricity prices through competition. To support these goals, this study proposed a new procurement auction mechanism for the Korean hydrogen power generation market, addressing key limitations of the current scheme, such as ambiguous scoring rules and the potential for strategic bidding behavior.

We introduced a multi-attribute auction where bidders submit both a price offer and non-price attributes, including the hydrogen co-firing rate and capacity factor. These non-price attributes are quantitatively evaluated to reflect each project's contribution to emissions reduction and fuel supply reliability. The proposed Vickrey-score sealed-bid auction rule, consisting of scoring, allocation, and payment rules, is designed to reduce strategic behavior and enhance allocative efficiency. Importantly, we designed the scoring rule so that a seller's score reflects the social surplus their contract would generate for the government. As a result, the auction mechanism selects winning Gencos in a manner that aligned with the government's dual policy objectives. By awarding contracts to sellers that maximize social surplus, the mechanism ultimately fosters an efficient allocation of hydrogen generation resources while supporting South Korea's long-term transition to a low-carbon economy.

Through equilibrium analysis, we demonstrated that the proposed auction rule leads to a weakly dominant equilibrium bidding strategy for sellers. The analysis revealed that non-price attributes in equilibrium are determined independently of other sellers' information, while the price attribute is optimally set based on the seller's own LCOE. However, it is important to note that in real-world applications, sellers may not always follow this dominant strategy. The actual utility structure of sellers may differ from the assumptions used in this study due to risk aversion or alternative objective functions. As a result, sellers might have incentives to misreport their bid prices that deviate from their actual LCOE. In some cases, there could even be incentives for collusive behavior among bidders. To address these concerns, practical implementations of the auction mechanism may incorporate verification processes for submitted bids, particularly for winning sellers.

Numerical analysis based on realistic parameters from the Korean hydrogen market highlighted the importance of carefully balancing scoring weights and considering the range of sellers' potential capacities. Our results showed that lower price score weights tend to yield more socially beneficial outcomes. While the proposed auction mechanism resulted in higher LCOEs compared to a single-attribute, price-only auction, it achieved greater market efficiency and a higher proportion of clean hydrogen generation among the total procured power, aligning with the broader objectives of the hydrogen economy.

Future research can build on this study by exploring the dynamic aspects of multi-attribute auctions in long-term contracting, such as the impact of evolving technologies and fluctuating market conditions on auction outcomes. Moreover, examining alternative scoring and payment rules that incorporate more complex interdependencies between attributes could further improve procurement efficiency. Additionally, empirical validation of our model through case studies in different markets would provide valuable insights for refining the auction mechanism and extending its applicability to other emerging clean energy sectors.

CRediT authorship contribution statement

Jisu Sim: Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Jihyeok Jung:** Writing – review & editing, Methodology, Investigation. **Deok-Joo Lee:** Writing – review & editing, Supervision. **Kiho Yoon:** Writing – review & editing, Supervision.

Acknowledgments

This work was supported by the Basic Science Research Program through National Research Foundation of Korea (NRF) funded by the Ministry of Education, Republic of Korea (RS-2021-NR066377), and by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (RS-2022-KP002828).

Appendix A

Proof of Proposition 1. Suppose that a seller whose cost inefficiency parameter is θ_i bids (p_i, ω_i, ρ_i) in which $\omega_i \neq \omega_i^*(\theta_i)$ or $\rho_i \neq \rho_i^*(\theta_i)$. What we have to show is that this strategy is dominated by an alternative bid $(p_i', \omega_i^*(\theta_i), \rho_i^*(\theta_i))$. To do this, we set p_i' to make the scores of these two bids be equal, i.e., $s(p_i, \omega_i, \rho_i) = s(p_i', \omega_i^*(\theta_i), \rho_i^*(\theta_i))$. Since the scoring rule is given as (3), we can compute p_i' as follows.

$$p_i' = \bar{p} - \frac{\rho_i}{\rho_i^*(\theta_i)}(\bar{p} - p_i) + \frac{(\bar{p} - \underline{p})(1-\gamma)}{\gamma \rho_i^*(\theta_i)} \left\{ \rho_i^*(\theta_i) g(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) - \rho_i g(\omega_i, \rho_i) \right\} \tag{A.1}$$

Since both bids (p_i, ω_i, ρ_i) and $(p_i', \omega_i^*(\theta_i), \rho_i^*(\theta_i))$ receive the same scores, the seller will win the auction with the same probability, and the corresponding contract quantities are denoted as q_i and q_i'.

Then, the expected profit before entering into the contract if the seller i wins the auction can be computed as follows.

$$\pi_i(p_i', \omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i) = \sum_{t=1}^{T} [p_i' q_i' - c(\omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i) q_i'] \tag{A.2}$$

$$\begin{aligned} &= \sum_{t=1}^{T} \Big[p_i q_i - c(\omega_i, \rho_i, \theta_i) q_i \\ &\quad + \{\bar{p} + \frac{\bar{p} - \underline{p}}{\gamma}(1-\gamma) g(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) \\ &\quad - c(\omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i)\} q_i' \\ &\quad - \{\bar{p} + \frac{\bar{p} - \underline{p}}{\gamma}(1-\gamma) g(\omega_i, \rho_i) - c(\omega_i, \rho_i, \theta_i)\} q_i \Big] \end{aligned} \tag{A.3}$$

$$\begin{aligned} &= \pi_i(p_i, \omega_i, \rho_i, \theta_i) + \left\{ V(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) \right. \\ &\quad \left. - c(\omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i) q_i' \right\} \\ &\quad - \left\{ V(\omega_i, \rho_i) - c(\omega_i, \rho_i, \theta_i) q_i \right\} \end{aligned} \tag{A.4}$$

$$\geq \pi_i(p_i, \omega_i, \rho_i, \theta_i), \tag{A.5}$$

which completes the proof. Note that (A.3) is derived by substituting p_i' using (A.1) and (A.5) holds due to the assumption that $(\omega_i^*(\theta_i), \rho_i^*(\theta_i))$ achieves the maximum of $V(\cdot) - c(\cdot) q_i$. □

Proof of Proposition 2. To show that $\omega_i^*(\theta_i)$ and $\rho_i^*(\theta_i)$ decrease in θ_i, we can use the partial derivatives, which are also known as the first order condition. The first order condition of the seller's pseudotype $S_i^o(\theta_i, k_i)$[3] are given as follows:

$$\begin{aligned} S_\omega^o(\theta_i, k_i) = \Big\{ &\frac{1-\gamma}{\gamma}(\bar{p} - \underline{p}) g_\omega(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) \\ &- c_\omega(\omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i) \Big\} \rho_i^*(\theta_i) = 0 \end{aligned} \tag{A.6}$$

$$\begin{aligned} S_\rho^o(\theta_i, k_i) = &\left\{ \frac{1-\gamma}{\gamma}(\bar{p} - \underline{p}) g_\rho(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) - c_\rho(\omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i) \right\} \rho_i^*(\theta_i) \\ &+ \left\{ \bar{p} + \frac{1-\gamma}{\gamma}(\bar{p} - \underline{p}) g(w_i^*(\theta_i), \rho_i^*(\theta_i)) - c(\omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i) \right\} = 0 \end{aligned} \tag{A.7}$$

To ensure the optimality of the solution that satisfies the first order condition, we assume that $V(\omega_i, \rho_i) - c(\omega_i, \rho_i) q_i$ has a unique maximum. So, the following second-order condition should be satisfied:

$$S_{\omega\omega}^o(\theta_i, k_i) = \frac{1-\gamma}{\gamma}(\bar{p} - \underline{p}) g_{\omega\omega}(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) \rho_i^*(\theta_i) < 0 \tag{A.8}$$

$$\begin{aligned} S_{\rho\rho}^o(\theta_i, k_i) = 2 &\left\{ \frac{1-\gamma}{\gamma}(\bar{p} - \underline{p}) g_\rho(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) - c_\rho(\omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i) \right\} \\ &+ \Big\{ \frac{1-\gamma}{\gamma}(\bar{p} - \underline{p}) g_{\rho\rho}(\omega_i^*(\theta_i), \rho_i^*(\theta_i)) \\ &- c_{\rho\rho}(\omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i) \Big\} \rho_i^*(\theta_i) < 0 \end{aligned} \tag{A.9}$$

$$S_{\omega\omega}^o(\theta_i, k_i) \cdot S_{\rho\rho}^o(\theta_i, k_i) - S_{\omega\rho}^o(\theta_i, k_i)^2 > 0 \tag{A.10}$$

Since participation in the auction requires the bid capacity factor to be greater than zero, (A.6) implies that the seller participating in the auction will bid non-price attributes that satisfy

$$\frac{1-\gamma}{\gamma}(\bar{p} - \underline{p}) g_\omega(\omega^*(\theta_i), \rho_i^*(\theta_i)) - c_\omega(\omega_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i) = 0 \tag{A.11}$$

[3] For convenience in the derivation, we redefine $S_i^o(\theta_i, k_i)$ as $S_i^o(\theta_i, k_i) = [\bar{p} + \frac{1-\gamma}{\gamma}(\bar{p} - \underline{p}) g(w_i^*(\theta_i), \rho_i^*(\theta_i)) - c\left(w_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i\right)] \rho_i$ instead of the original expression $S_i^o(\theta_i, k_i) = [\bar{p} + \frac{1-\gamma}{\gamma}(\bar{p} - \underline{p}) g(w_i^*(\theta_i), \rho_i^*(\theta_i)) - c\left(w_i^*(\theta_i), \rho_i^*(\theta_i), \theta_i\right)] \rho_i k H$. This transformation does not affect the final result.

Taking the partial derivatives with respect to θ_i to (A.11), we obtain the following:

$$\frac{1-\gamma}{\gamma}(\bar{p}-\underline{p})\left\{g_{\omega\omega}(\cdot)\frac{\partial\omega_i^*(\theta_i)}{\partial\theta_i}+g_{\omega\rho}(\cdot)\frac{\partial\rho_i^*(\theta_i)}{\partial\theta_i}\right\}$$

$$-\left\{c_{\omega\omega}(\cdot)\frac{\partial\omega_i^*(\theta_i)}{\partial\theta_i}+c_{\omega\rho}(\cdot)\frac{\partial\rho_i^*(\theta_i)}{\partial\theta_i}+c_{\omega\theta_i}(\cdot)\right\}=0 \tag{A.12}$$

$$\iff \frac{\partial\omega_i^*(\theta_i)}{\partial\theta_i}=\frac{\gamma(VC_c-VC_{nc})}{(1-\gamma)(\bar{p}-\underline{p})g_{\omega\omega}(\cdot)}<0 \tag{A.13}$$

Note that (A.13) holds due to Eq. (1) ($c_{\omega\omega}(\cdot)=0$, $c_{\omega\rho}(\cdot)=0$) and Assumption 1-(b) ($g_{\omega\rho}(\cdot)=0$, $g_{\omega\omega}(\cdot)<0$).

Similarly, if we take the partial derivatives with respect to θ_i to (A.7), we obtain the following:

$$\frac{\partial\rho_i^*(\theta_i)}{\partial\theta_i}=\frac{w_i^*(\theta_i)VC_c+(1-w_i^*(\theta_i))VC_{nc}}{S^o_{\rho\rho}(\theta_i,k_i)}<0, \tag{A.14}$$

due to (A.8). □

Proof of Proposition 3. In Proposition 1, we have shown that each seller i will bid its non-price attributes as $(\omega_i^*(\theta_i),\rho_i^*(\theta_i))$ which satisfies (11). So, what we have to prove is that it is a weakly dominant strategy for each seller i to bid $p_i^*(\theta_i)=c(\omega_i^*(\theta_i),\rho_i^*(\theta_i),\theta_i)$.

Denote $b_i^*(\theta_i)=(p_i^*(\theta_i),\omega_i^*(\theta_i),\rho_i^*(\theta_i))$. Under this bid, the seller's score can be computed as follows:

$$s(b_i^*(\theta_i))=\left[\gamma\left(\frac{\bar{p}-c(\omega_i^*(\theta_i),\rho_i^*(\theta_i),\theta_i)}{\bar{p}-\underline{p}}\right)+(1-\gamma)g(\omega_i^*(\theta_i),\rho_i^*(\theta_i))\right]q_i^* \tag{A.15}$$

$$=\frac{\gamma}{\bar{p}-\underline{p}}S^o(\theta_i,k_i). \tag{A.16}$$

Meanwhile, if the seller wins the auction when the highest rejected score is $s_{[k]}$, the seller enters into the contract at the price $\tilde{p}$ that satisfies

$$s(\tilde{p},\omega_i^*(\theta_i),\rho_i^*(\theta_i))=s_{[k]} \tag{A.17}$$

$$\iff \tilde{p}q_i^*=\left[\bar{p}+\frac{(\bar{p}-\underline{p})(1-\gamma)}{\gamma}g(\omega_i^*(\theta_i),\rho_i^*(\theta_i))\right]q_i^*-\frac{\bar{p}-\underline{p}}{\gamma}s_{[k]}. \tag{A.18}$$

Using (A.18), the profit of the winning seller can be computed as

$$\pi_i(q_i^*,\tilde{p},\omega_i^*(\theta_i),\rho_i^*(\theta_i);\theta_i)=\sum_{t=1}^{T}[\tilde{p}-c(\omega_i^*(\theta_i),\rho_i^*(\theta_i),\theta_i)]q_i^* \tag{A.19}$$

$$=T\left(S^o(\theta_i,k_i)-\frac{\bar{p}-\underline{p}}{\gamma}s_{[k]}\right). \tag{A.20}$$

Consider the case where the seller bids $b_i'=(p_i',\omega_i^*(\theta_i),\rho_i^*(\theta_i))$ where $p_i'<p_i^*(\theta_i)$. Since the bid price is lower, $s(b_i')>s(b_i^*)$ holds. There are three possible cases: (1) $s(b_i')>s(b_i^*)>s_{[k]}$; (2) $s_{[k]}\geq s(b_i')>s(b_i^*)$; (3) $s(b_i')>s_{[k]}\geq s(b_i^*)$.

In the first case, both bids win the auction and receive the same payoff as defined (A.20). In the second case, both bids lose the auction and receive the same payoff as 0. Finally, in the last case, $s_{[k]}\geq s(b_i^*)$ implies $s_{[k]}\geq\frac{\gamma}{\bar{p}-\underline{p}}S^o(\theta_i,k_i)$ from (A.16). Therefore, winning the auction by bidding b_i' other than b_i^* can obtain a negative profit by (A.20).

Then, consider the other case where the seller bids $b_i'=(p_i',\omega_i^*(\theta_i),\rho_i^*(\theta_i))$ where $p_i'>p_i^*(\theta_i)$. Since the bid price is higher, $s(b_i^*)>s(b_i')$ holds. There are three possible cases: (1) $s(b_i^*)>s(b_i')>s_{[k]}$; (2) $s_{[k]}\geq s(b_i^*)>s(b_i')$; (3) $s(b_i^*)>s_{[k]}\geq s(b_i')$. Both bids obtain the same profit in the first and second case. However, in the last case, bidding b_i' other than b_i^* can lose a chance to obtain a positive profit.

In conclusion, bidding the price attribute as $p_i^*(\theta_i)=c(\omega_i^*(\theta_i),\rho_i^*(\theta_i),\theta_i)$ is a weakly dominant strategy for every bidders. Followed by this fact, each seller will receive the score $\frac{\gamma}{\bar{p}-\underline{p}}S^o(\theta_i,k_i)$. □

Proof of Proposition 4. Taking the partial derivative with respect to γ for the first bracket of (A.6) yields the following:

$$\frac{\partial\omega_i^*(\theta_i)}{\partial\gamma}=\frac{(\bar{p}-\underline{p})g_\omega(\cdot)+c_\omega(\cdot)}{(1-\gamma)(\bar{p}-\underline{p})g_{\omega\omega}(\cdot)}<0, \tag{A.21}$$

which proves the statement of (a).

Similarly, when we take the partial derivative with respect to γ for (A.7), we obtain:

$$\frac{\partial\rho_i^*(\theta_i)}{\partial\gamma}=\frac{(\bar{p}-\underline{p})(g(\cdot)+\rho_i^*(\theta_i)\cdot g_\rho(\cdot))}{\gamma^2S^o_{\rho\rho}(\theta_i,k_i)}. \tag{A.22}$$

Hence, the effect of γ on the equilibrium capacity factor depends on the sign of $\Lambda(\omega_i^*(\theta_i),\rho_i^*(\theta_i))$, which is defined in (16). □

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2025.108871.

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