Iran J Econ Stud, 2025, 14(2), 323-373

Iranian Journal of Economic Studies

Journal homepage: ijes.shirazu.ac.ir

Assessing the Competitiveness of Renewable Power Plants in Iran's Electricity Market under Renewable Energy Certificates (REC) and Power Plant Fuel Price Reform (PFR): A Stackelberg Game Theory Approach

Majid Raoofmehr[a], Zeinolabedin Sadeghi[a*], Seyyed Abdolmajid Jalaee[a]

a. *Department of Economics, Shahid Bahonar University of Kerman, Kerman, Iran.*

Highlights

- **Develops a Stackelberg game–based framework to analyze strategic interactions between thermal and renewable power plants under two complementary policies: Power Plant Fuel Price Reform (PFR) and Renewable Energy Certificates (REC).**
- **Estimates REC price using the LCOE–Gap approach and shows that PFR increases the marginal cost of thermal generation while REC enhances the output and profitability of renewable units.**
- **Demonstrates that the combined PFR–REC policy package shifts market share toward renewables and improves social welfare, with results confirmed through sensitivity analysis and Monte Carlo simulation.**

Article History

Received: 23 October 2025
Revised: 16 November 2025
Accepted: 21 November 2025
Published:11 December 2025

JEL Classification

C72
Q41
L13
L94
Q48

Keyword

Stackelberg game theory
Competitiveness
Energy policy
Renewable Energy Certificates (REC)
Power Plant Fuel Price Reform (PFR)

Abstract

In an electricity market where hidden fuel subsidies have strengthened the position of thermal power plants and the lack of stable support mechanisms has constrained renewable growth, this study evaluates the impact of implementing two complementary policies, Power Plant Fuel Price Reform (PFR) and Renewable Energy Certificates (REC), on the competitiveness of renewable generation units in Iran. A theoretical framework based on Stackelberg game theory is developed, with the thermal plant as leader and the renewable plant as follower.

To validate the model, sensitivity analysis and Monte Carlo simulation are employed. Two scenarios are analyzed: competition between a conventional thermal unit and a solar plant, and between a thermal unit and a wind plant. Since a formal REC market has not been established in Iran, REC price is estimated using the Levelized Cost of Electricity Gap (LCOE–Gap) approach, reflecting the difference between renewable costs and expected market price. The results show that PFR raises the marginal cost of thermal generation, reducing its output and profit. REC enhances both output and profitability of renewable units. Combined, these policies shift market share toward renewables, increase consumer surplus, and improve social welfare. These outcomes remain robust across assumptions. The proposed model, with its behavioral clarity and calibrability, provides a tool for designing policy packages that support the transition toward a competitive, low-carbon, and equitable electricity market in Iran and other developing economies.

* z_sadeghi@uk.ac.ir
DOI: 10.22099/ijes.2025.54626.2073

1. Introduction

In recent decades, climate change has intensified and become a central global concern (Mohamed et al., 2024). Growing environmental challenges have pushed countries to prioritize greenhouse gas reduction and sustainable development in their national energy strategies (Ahmed et al., 2022). Renewable energy sources serve as clean and sustainable alternatives that can address rising energy demand while reducing dependence on fossil fuels (Xu et al., 2024a). Iran's strong reliance on fossil fuels has created serious economic and environmental challenges, including recurring imbalances in power generation and supply (Gholami & Sadeghi et al., 2024). Therefore, restructuring the national energy mix and accelerating the energy transition have become essential.

However, renewable energy development is hindered by high investment costs, insufficient institutional and financial support, and weaknesses in domestic capital markets (Fang et al., 2024). Existing literature highlights that achieving a sustainable energy system requires large-scale investment in renewable infrastructure, supported by well-designed subsidies and financial incentives (Jalaee & Sadeghi et al., 2025).

Another challenge arises from the competitive disadvantage faced by renewable energy producers relative to thermal power plants. Fossil-fuel units benefit from cost structures and subsidy regimes that allow them to maintain a dominant market position. To examine how policy instruments may alter these dynamics, the present study evaluates competitiveness primarily from the viewpoint of renewable producers.

A combined policy approach involving Power Fuel Rate (PFR) reform and Renewable Energy Certificates (REC) can strengthen the competitive position of renewable generators. PFR makes the cost of thermal production more transparent and improves the relative advantage of renewables (Du et al., 2023). REC provide additional revenue streams and deliver clear price signals, which encourage investment in clean technologies (Bo & Tao-zhen, 2021). Empirical evidence further shows that these certificates can influence investor and producer behavior (Song et al., 2022).

Despite Iran's significant potential for renewable power, its share in the electricity mix remains below one percent, while the global average exceeds 13 percent. Heavy fossil-fuel subsidies, low end-user electricity prices, and the lack of a formal REC market have increased investment risks (Mousavi Dorcheh & Karimian Khuzani, 2022).

In Iran's electricity market, fossil-fuel thermal plants historically dominate installed capacity, dispatch scheduling, and price-setting, operating within a partially regulated pricing framework defined by government energy policy. This institutional structure mirrors the permit-based design of carbon markets, where regulation determines both the tradable asset and price dynamics. Large-scale thermal producers, benefiting from economies of scale and operational rigidity, act as commitment-setters in the market, making production and offer decisions first. Renewable producers, with smaller capacity and stronger reliance on policy incentives such as Renewable Energy Certificates (REC), behave as reactive followers, optimizing their generation after the leader's decision. This asymmetry naturally supports a Stackelberg framework where the thermal unit is the leader and the renewable unit is the follower (Xiang et al., 2024). The institutional and analytical justification is provided in Section 3.1.

International experience indicates that combining price reforms with market-based instruments can enhance renewable energy competitiveness (Ji et al., 2024) and increase social welfare (Ma et al., 2024). For developing countries facing financial constraints and environmental responsibilities, integrated policy mechanisms can help narrow the investment gap (Hashemizadeh et al., 2024) and support sustainable development goals (Xiong-jinatao et al., 2022).

Stackelberg game theory offers an effective analytical foundation for studying strategic interactions in electricity markets, especially where conventional producers have dominant positions while renewable units respond to their decisions (Helgesen & Tomasgard, 2018).

Accordingly, this study uses a Stackelberg game model to examine the combined effects of PFR and REC on the competitiveness of renewable power plants in Iran. It analyzes how these policy tools influence strategic decisions by leaders and followers and evaluates their welfare implications. To ensure robustness, the model is supported by sensitivity analyses and Monte Carlo simulations, calibrated with operational data from the Damavand combined-cycle plant, the Ghadir Mehriz solar facility, and the Binaloud wind power plant.

The main innovation of this study lies in integrating two key policy instruments, Power Fuel Rate (PFR) reform and Renewable Energy Certificate (REC), within a unified Stackelberg competition framework in which the thermal power plant acts as the leader and renewable units behave as followers. Unlike previous studies that typically examine these policies separately and within symmetric market structures, this paper models their strategic interaction under an institutional setting that closely reflects the characteristics of the Iranian electricity market. Furthermore, in the absence of an operational REC market in Iran, the certificate value is endogenously estimated using an LCOE-based cost-gap approach. The robustness of the model is also assessed through both sensitivity analysis and Monte-Carlo simulation, and the framework is validated using real data from three representative power plants. These features distinguish the present work in the existing literature and enhance the relevance of the derived policy implications for energy transition in developing markets.

In the Iranian electricity sector, the dominance of fossil-fuel power plants, reinforced by substantial fuel subsidies, has significantly hindered the competitiveness of renewable technologies. While fuel price rationalization (PFR) can partly correct this distortion, it alone is insufficient to bridge the cost gap between thermal and renewable generation. Complementary incentives such as renewable energy certificates (REC) are necessary yet absent in Iran, requiring their proxy valuation through LCOE, market price differentials. Existing literature largely evaluates PFR and REC independently, overlooking their combined effects and the strategic leader–follower dynamics between fossil-fuel and renewable generators. Moreover, previous studies seldom assess the robustness of policy outcomes under parameter uncertainty. This study addresses these gaps by developing a Stackelberg modeling framework supported by sensitivity analysis and Monte Carlo simulation, and by calibrating the model using data from three representative Iranian power plants. The findings offer policy insights for designing synergistic PFR–REC schemes capable of enhancing renewable deployment and social welfare in Iran's partially deregulated electricity market.

The primary contribution of this research is the introduction of an integrated analytical framework for assessing the joint effects of these complementary policy instruments. Due to similar institutional conditions across developing countries with comparable subsidy regimes, this framework can be applied beyond the Iranian context to support more effective clean energy transition policies.

Moreover, the analytical setting of this study is grounded in well-established theoretical strands in environmental and institutional economics, as well as endogenous growth theory. These theoretical underpinnings justify both the use of a Stackelberg structure to represent strategic asymmetry between fossil-fuel and renewable producers and the deployment of PFR and REC as market-based instruments that internalize externalities and stimulate innovation. Further conceptual details are presented in Section 1.1.

1.1 Theoretical Background and Conceptual Framework

The conceptual structure of this study builds upon established theoretical foundations in environmental economics, institutional economics, and endogenous growth theory. From the perspective of environmental economics, Power Fuel Rate (PFR) reform acts as a Pigouvian mechanism, bringing the marginal private cost of fossil-fuel generation closer to its social cost and mitigating the negative externalities of greenhouse gas emissions. Likewise, Renewable Energy Certificates (REC) function as a market-based mechanism that assigns an economic value to the environmental benefits of renewable electricity, comparable to credit trading systems widely used in green certificate and carbon markets.

Institutional economics provides a second theoretical pillar. Due to historical advantages, subsidized fuel prices, and regulatory priority, fossil-fuel generators predominantly control dispatch and price-setting processes in Iran's power sector (Bichuch et al., 2024). This asymmetry in institutional and operational conditions creates a natural leader–follower hierarchy, in which fossil-fuel producers commit to production decisions first, and renewable producers respond optimally based on remaining demand and policy incentives. This interaction justifies the Stackelberg formulation adopted in this study.

A third theoretical underpinning comes from endogenous growth theory. By increasing revenue streams for renewable producers, REC enhances investment incentives in clean technologies, encouraging innovation, learning, and technological spillovers. Over time, these dynamics contribute to reductions in cost, expansion of renewable penetration, and improvements in economy-wide productivity.

Integrating these theoretical strands leads to a conceptual model in which PFR and REC jointly alter relative cost structures and revenue mechanisms, thereby influencing strategic output decisions, market equilibrium, welfare outcomes, emissions reduction, and renewable penetration. Figure 1 summarizes these relationships by illustrating (i) how each policy affects the strategic behavior of fossil and renewable generators, and (ii) how these decisions propagate to market equilibrium and macro outcomes. This conceptual foundation reinforces the analytical rigor of the study and clarifies the causal pathways linking policy instruments, agent behavior, and outcome variables.

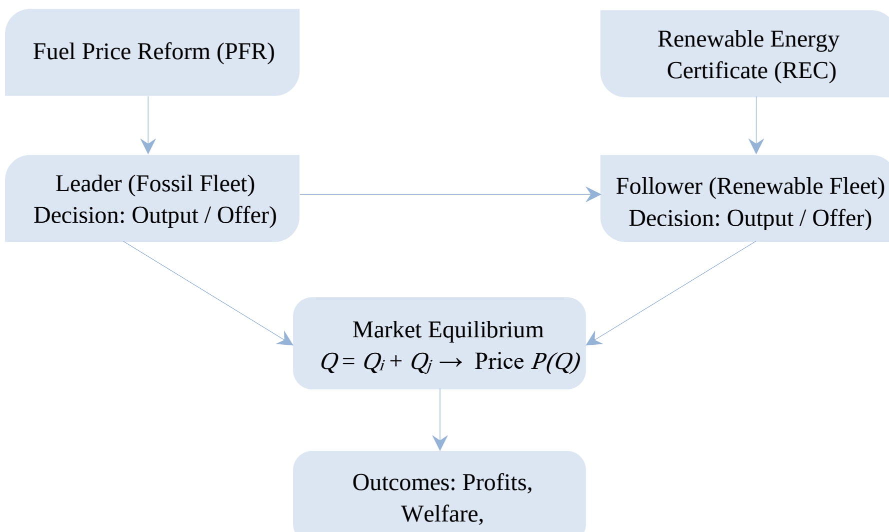

Figure 1. Conceptual Model of the Study
Source: *Developed by the authors*

2. Theoretical Foundations and Literature Review

2.1 Energy Policies and the Competitiveness of Renewable vs. Conventional Power Plants

Conventional and renewable power plants differ fundamentally in their cost dynamics. While thermal plants typically incur high fixed and variable costs driven largely by volatile fossil fuel prices, renewable technologies require substantial upfront capital investment (CAPEX) but much lower operation and maintenance (O&M) costs (Monavariyan et al., 2020). Although recent estimates from IRENA place the levelized cost of solar electricity at approximately 0.043–0.048 $/kWh for 2023–2024, the persistence of fuel-linked costs in thermal plants continues to erode their relative competitiveness amid rising fossil fuel prices (Xu et al., 2024; Brusiło & Tomski, 2025). These observations align with empirical studies that confirm a significant decarbonization effect from renewable deployment, which is further moderated by institutional factors such as market structure, renewable development stage, and regional power exchange (Liu & Han, 2024).

However, existing literature tends to underestimate how structural distortions such as fossil fuel subsidies weaken genuine competition. In settings like Iran, subsidization maintains artificially low production costs for conventional generators, creating competitive asymmetry (Mousavi Dorcheh & Karimian Khuzani, 2022). This suggests that simple cost comparison between renewable and thermal power is insufficient without considering policy distortions (Tsao et al., 2024). PFR reform, by correcting relative pricing, is therefore highlighted as a targeted restructuring instrument capable of realigning incentives toward renewables (Pajooyan et al., 2023). Yet, the magnitude of this realignment remains debated; empirical studies often assume full pass-through of fuel prices to market costs, ignoring institutional rigidities. Thus, while consensus affirms the theoretical benefit of PFR, its practical impact depends on broader governance structures, an issue underexplored in prior work.

Taken together, the literature suggests that renewable energy competitiveness is not merely technologically driven but institutionally conditional (Andres, 2024). The absence of coherent and subsidy-correcting policy frameworks remains a major barrier, underscoring the need for integrated models that capture such distortions (Nepal et al., 2024).

2.2 Market-Based Policies and Renewable Energy Certificates (REC)

REC instruments represent an increasingly adopted mechanism for internalizing environmental benefits of renewable power (Bo & Tao-zhen, 2021). Early studies generally highlight their ability to provide additional revenue and to transmit environmental price signals. Nonetheless, later empirical evidence questions their systemic efficiency: integrating green certificate trading with carbon markets can indeed lower renewable costs (Xiong-jinatao et al., 2022), but this effect depends strongly on institutional design. Studies such as Helgesen & Tomasgard (2018) and Song et al. (2022) emphasize the role of well-structured market mechanisms and active consumer participation to enhance REC market efficiency, yet both contributions use idealized markets, offering limited insight into conditions of weak institutional capacity.

More recent research has revealed critical weaknesses. For instance, empirical analysis of the European Guarantees of Origin (GO) market finds that price signals are unstable and only weakly correlated with the spatio-temporal value of green electricity, demonstrating that current designs fail to reflect actual system decarbonization value (Bösch, 2025). Similarly, Langer et al. (2024) conclude that voluntary REC purchases may have minimal emissions impact unless accompanied by strict spatial and hourly matching. These studies demonstrate that REC markets alone do not guarantee environmental effectiveness and may induce greenwashing behavior if poorly regulated.

At the same time, empirical work in Türkiye confirms high consumer willingness to pay for green electricity and highlights the potential financial benefits of well-designed certificate markets (Calikoglu & Koksal, 2022). This implies that demand-side appetite is not a binding constraint; rather, institutional capacity and robust market rules determine REC efficacy. Augmenting this view, recent modeling evidence suggests that multi-market frameworks, allowing mutual recognition of carbon and green certificates, can strengthen participation incentives for thermal plants and maximize renewable consumption (Wang et al., 2025).

In Iran, REC markets remain unrealized despite policy proposals and interest expressed in national energy planning (Mousavi Dorcheh & Karimian Khuzani, 2022). Taken as a whole, the literature suggests that while REC can theoretically stimulate renewable development, empirical effectiveness strongly hinges on market architecture and supporting policy instruments such as PFR.

2.3 Power Fuel Rate (PFR) Reform and Its Implications for Renewable Competitiveness

Fuel price rationalization through PFR reform reduces subsidy distortions and aligns the marginal cost of thermal power generation with its economic value. Empirical studies demonstrate that increases in fossil fuel prices tend to decrease investment attractiveness of thermal plants while improving renewable competitiveness (Fang et al., 2024). Research framed in the context of high energy-intensity economies further identifies PFR reform as a necessary turning point for restructuring electricity markets (Hashemizadeh et al., 2024). Nonetheless, these studies often assume frictionless policy implementation. In Iran, where extensive subsidies and institutional inefficiencies prevail, PFR reforms face enforcement challenges.

Existing analyses therefore affirm PFR as a necessary, but insufficient, condition for leveling competition (Molaei & Rezaee, 2016). The literature has not rigorously quantified its effectiveness in environments where energy subsidies persist and market participants behave strategically. Moreover, interactions between PFR and complementary market-based policies have received limited attention. These gaps justify a modeling framework that embeds strategic behavior under combined REC–PFR regimes.

2.4 Game Theory and Modeling Competition Between Renewable and Conventional Power Plants

Game theory offers a powerful framework to analyze strategic interactions among heterogeneous electricity producers. The Stackelberg leader–follower structure is widely used to model asymmetric competition where fossil-fuel power plants act as price leaders and renewable producers follow (Ma et al., 2024). While prior studies show that policy tools including ETS, RPS, and combinations of REC and PFR can alter firms' production decisions and improve social welfare (Chen et al., 2022), their treatments are often partial, emphasizing single-market dynamics.

Recent contributions suggest that multi-market equilibrium models, capturing generator bidding behavior and simultaneous interactions in electricity, carbon, and green certificate markets, yield a more realistic representation of market dynamics (Wang et al., 2025). Yet despite these advances, empirical calibration remains limited, particularly for subsidy-heavy environments where market behavior deviates from rational-competitive benchmarks. In addition, most prior studies treat thermal leadership as exogenous rather than a function of policy and market reforms.

This underscores the need for models that integrate multi-instrument designs and strategic behavior to better understand the interplay between policy coordination, market efficiency, and welfare outcomes (Wu et al., 2024).

2.5 Economic Modeling and the Joint Impact of REC and PFR Policies

Earlier research focused mainly on single policy instruments, such as REC or capital subsidies; however, more recent work demonstrates that combining price-based and market-based instruments produces more durable renewable deployment (Ji et al., 2024; Lin & Huang, 2022). Nonetheless, these studies largely abstract from institutional complexity and assume efficient market clearing. Evidence from China indicates that green certificates can substitute for government subsidies only partially and that their efficiency depends heavily on price formation mechanisms and market architecture (Liu et al., 2024). This finding highlights potential limitations of REC-only designs.

A key observation is that optimal policy performance emerges when signals are aligned and policy instruments are coordinated (Morris et al., 2010). Without such alignment, policy interactions may become counterproductive, resulting in market distortions or suppressed investment. Despite these insights, the literature lacks a unified analytical framework capable of examining how PFR and REC interact strategically under asymmetric market structures.

2.6 Research Gaps and the Rationale for This Study

Existing studies collectively demonstrate that the competitiveness of renewable energy technologies is not solely determined by technological cost reductions but is fundamentally shaped by institutional and pricing reforms. Although recent empirical works acknowledge the role of renewable energy price competitiveness, they show that subsidy regimes and market structure significantly condition the real economic advantage of renewables (Wang et al., 2023). Market-based instruments such as Renewable Energy Certificates (REC) have shown promise in transmitting environmental price signals, yet their effectiveness remains highly sensitive to market architecture (Panny & del Río, 2025); empirical findings from Europe and voluntary REC systems show that weak temporal or locational matching can lead to negligible emission reductions, revealing limited additionality. Meanwhile, Power Fuel Rate (PFR) reforms are widely recognized as an essential mechanism to correct price distortions, but their practical effectiveness under subsidy-dominated electricity markets remains insufficiently studied. Although recent advances in game-theoretic and multi-market equilibrium modeling reveal important insights regarding strategic behavior under combined electricity-carbon-certificate schemes, they rarely incorporate coordinated REC-PFR frameworks under asymmetric leader-follower structures typical of developing country energy systems. Moreover, emerging empirical evidence from Europe and China indicates that even in institutionally well-developed markets, certificate systems face limitations in terms of price efficiency, cooperation mechanisms, and investment additionality, highlighting the need for models that can evaluate policy interactions under real-world constraints. Despite these developments, the joint impact of PFR and REC policies has not been assessed within a unified analytical framework, particularly in markets characterized by heavy subsidies, high investment risks, and institutional weaknesses such as Iran. Consequently, applying a Stackelberg game-based approach to examine the interaction of PFR and REC provides a novel and policy-relevant analytical contribution, offering insights that can support more effective energy transition strategies not only for Iran but also for other developing electricity markets with similar characteristics (Cheng et al., 2025).

In contrast to earlier studies that typically examine PFR and REC in isolation, this research provides the first integrated analytical framework that evaluates their joint effects within a Stackelberg leader–follower structure tailored to asymmetric electricity markets such as Iran. Furthermore, due to the absence of an operational REC trading market in Iran, an endogenous estimation approach based on the LCOE cost-gap is developed, enabling policy evaluation in settings without explicit certificate pricing. The combined use of sensitivity analysis and Monte-Carlo simulation to assess the structural robustness of the equilibrium outcomes also represents a methodological contribution that extends beyond conventional approaches in the existing literature.

3. Energy Policies and the Competitiveness of Renewable vs. Conventional Power Plants

This study is applied in purpose and quantitative and analytical in method. Its main objective is to examine the impact of the simultaneous implementation of two complementary energy policies, Power Fuel Rate (PFR) reform and Renewable Energy Certificates (REC), on the competitiveness of renewable power plants relative to conventional thermal power plants.

To achieve this objective, the Stackelberg game theory framework is employed, as it aligns closely with the structural characteristics of Iran's electricity market. Furthermore, to assess the broader implications of these policies, a social welfare function is formulated and optimized. This allows for evaluating both the strategic behavior of market participants and the aggregate welfare outcomes arising from policy interactions.

3.1 Conceptual Framework of the Model

In the Stackelberg game framework, conventional thermal and renewable power plants are modeled as the two main players in the electricity market. Their strategic interactions are examined under the simultaneous implementation of the following two key government policies:

PFR (Power Fuel Rate Reform): Expected to increase the costs of thermal power generation, thereby reducing their competitiveness.

REC (Renewable Energy Certificate): Issued for each unit of renewable electricity generated. These certificates are tradable in the market and provide renewable producers with additional revenue, thus enhancing the attractiveness of investments in clean energy. In this model, REC revenues are incorporated as part of the profit function of renewable producers.

Within this structure, conventional power plants act as leaders, while renewable power plants act as followers responding strategically to the leader's decisions. In this study, both the leader and the follower compete in quantities rather than prices. This assumption aligns with how electricity is dispatched in Iran, where generating units commit production levels subject to operational and fuel constraints, and the resulting market-clearing price is determined endogenously via the inverse demand function. Hence, a Stackelberg-quantity formulation provides a more realistic representation of strategic behavior than a Bertrand-price game. In this study, each "player" represents a representative coalition (aggregated fleet) rather than a single physical unit: the thermal fleet (leader) versus the renewable fleet (follower). This aggregation reflects how the policy instruments studied, PFR and REC, act at the technology class level. As long as each coalition maximizes aggregate profit, internal transfers among member plants are irrelevant to external equilibrium (quantities, prices, and welfare). Therefore, we model each fleet as a single decision-making entity, which is consistent with reduced-form oligopoly representations of electricity markets. The government acts as a regulator, aiming to maximize social welfare through the joint application of PFR and REC, taking into account how market participants react to these policies.[1]

The players in the model are defined as follows:

Conventional Power Plant (Leader): Fossil-fuel-based power generators with greater market power due to established infrastructure and subsidies.

Renewable Power Plant (Follower): Renewable generators whose behavior is influenced by both supportive policies and the strategic decisions of conventional plants.

Government (Regulator): Aims to maximize social welfare by internalizing externalities, realigning costs through PFR, and creating investment incentives through REC.

The model is formulated within a Stackelberg competition structure, where the leader (thermal plant) moves first and the follower (renewable plant) reacts. The sequence of decisions is as follows:

---

[1] Since each coalition maximizes its aggregate profit, the internal profit-sharing rule among its members does not affect external equilibrium outcomes (quantities, prices, welfare). Therefore, specifying such a rule is unnecessary for the validity of the present model.

Leader's decision-making process: The conventional power plant determines its optimal output level to maximize profit, taking into account the increased marginal cost resulting from PFR implementation.

Follower's response: The renewable power plant decides its output level in response to the leader's strategy, maximizing its profit by considering both electricity sales revenue and REC revenues.

Equilibrium analysis: The Stackelberg equilibrium is obtained by solving the profit maximization problems of both leader and follower, yielding equilibrium output levels and market-clearing prices for both types of generation.

The model is solved using numerical techniques and optimization algorithms, which determine optimal production levels and market prices for conventional and renewable power plants.

The simulation results reveal how changes in fuel prices and REC issuance and trading affect market equilibrium, production levels, and producer profitability. Finally, the government, acting as the policymaker, determines the optimal PFR level and equilibrium REC price in order to maximize the social welfare function, which incorporates both consumer and producer surplus.

It should be clarified that the methodological framework of this study is analytical and game-theoretic rather than econometric. The purpose is not to statistically estimate relationships from historical datasets but to derive equilibrium strategies of competing agents under alternative policy scenarios, grounded in Stackelberg competition theory. Consequently, typical econometric diagnostic procedures (e.g., unit-root, multicollinearity, serial correlation, or heteroskedasticity tests) are not applicable in the present context.

Instead, the credibility of the proposed model is ensured through (i) theoretical consistency with microeconomic and environmental-policy frameworks, (ii) parameter calibration based on real-world electricity-sector data, and (iii) comprehensive numerical validation procedures. These include sensitivity analysis, Monte-Carlo simulations, and a realistic case-study evaluation. Collectively, these mechanisms guarantee that equilibrium behavior remains stable, theoretically coherent, and policy-relevant.

Accordingly, the objectives of the model's players are:

Leader (Conventional Plant): Maximization of profit, subject to PFR-induced cost structures and market conditions.

Follower (Renewable Plant): Maximization of profit, taking into account revenue from REC trading and market dynamics.

Government (Regulator): Policy optimization to maximize aggregate social welfare through the coordinated use of PFR and REC.

3.1.1 Justification of Leader–Follower Roles in Iran's Electricity Market

We adopt a Stackelberg (quantity) competition framework in which the thermal producer acts as the leader and the renewable producer as the follower. This choice is grounded in the institutional, regulatory, and operational realities of Iran's electricity sector:

(i) Dominant capacity and regulated pricing: Fossil-fuel plants account for the overwhelming share of generation and operate under a partially regulated pricing mechanism that effectively anchors both the cost and price environment. This arrangement parallels permit-based systems such as carbon markets, where regulation determines both the tradable asset and the market price.

(ii) Commitment timing and scale advantages: Thermal units, due to economies of scale, dispatch priority, and fuel-based commitment constraints, determine and commit their output earlier than other producers, making them the natural first movers in production planning.

(iii) Renewables' reactive payoff structure: Renewable producers maximize profits given the market price and certificate (REC) value, both of which depend on the leader's quantity choice, thus making their best-response behavior explicit in the model's profit and reaction functions.

(iv) Policy-driven asymmetry: The two policy instruments, PFR and REC, reinforce this leader–follower dynamic: PFR primarily alters the leader's marginal cost, while REC directly enhances the follower's unit revenue.

Collectively, these characteristics justify the Stackelberg timing in which the thermal plant initiates the game by committing output first and the renewable plant optimally responds. The regulator's (government's) role is to define the overarching policy environment, through PFR and REC, within which this operational game unfolds.

Methodological Note. While one could also model price competition, electricity markets with unit-commitment and capacity constraints are commonly approximated by quantity (Cournot/Stackelberg-quantity) games. Our choice is therefore standard for supply-function environments where the leader's committed quantity shapes the residual demand faced by the follower.

3.2 Model Specification

This section presents the mathematical framework for modeling the strategic interactions between conventional and renewable power plants under the simultaneous implementation of Power Fuel Rate (PFR) reform and Renewable Energy Certificate (REC) mechanisms. The objective is to determine the equilibrium conditions for production, pricing, and social welfare maximization.

The parameters and input data applied in this study were calibrated using official statistics and technical reports from the Iranian electricity market. Since the model is constructed under a Stackelberg game-theoretic framework, the selection of variables relies primarily on their theoretical and institutional relevance rather than on statistical convenience.

The policy variables, namely, Power-Fuel-Rate (PFR) and Renewable Energy Certificate (REC), were selected due to their strategic importance in Iran's energy policy agenda. Cost and demand parameters were set according to empirical averages reported by the Ministry of Energy and benchmark estimates used in prior literature. Because a formal REC market has not yet been established in Iran, REC values were calculated using a levelized-cost-gap method, representing the difference between the levelized cost of renewable electricity (LCOE) and the benchmark electricity market price.

This calibration-based strategy ensures that the model realistically incorporates institutional and technological characteristics of the Iranian power sector while remaining analytically tractable.

3.2.1 Definition of Variables and Notation

This study utilizes a combination of primary and secondary data sources to assess the competitiveness of renewable and conventional power plants under the joint application of REC and PFR policy instruments.

The required data encompass:

Electricity generation variables: including installed capacity, actual production levels, and operational efficiency of both renewable and conventional power plants.

Market and policy variables: including the initial and maximum market price of electricity, demand slope coefficient, REC trading rate and unit value, the adjusted PFR level, and relevant regulatory parameters.

Cost structure variables: for estimating and calculating the generation cost components of different units, based on official national energy statistics and reports.

The primary sources of these data include publications and statistical bulletins from Ministry of Energy of Iran, Iran Grid Management Company, Iran Power Market, and Renewable Energy and Energy Efficiency Organization (SATBA[1]). These data are validated through statistical analyses and comparative studies to ensure their accuracy and consistency with market conditions.

In addition to the official sources, the policy-related parameter PFR was obtained based on the adjustment ranges reported by Iran's Ministry of Energy for the year 2024. Since a formal REC trading market has not yet been established in Iran, the REC parameter was estimated using a levelized cost-gap method consistent with Section 3.2.2, whereby the certificate value was approximated as the gap between the LCOE of renewable technologies and the reference market price. Thus, REC values used in the model strictly originate from cost-based estimations rather than from market quotations.

The symbols and variables used in the model's equations and formulations are summarized in Table 1.

[1] Levelized Cost of Electricity Gap; LCOE–Gap.

Table 1. Variables Used in the Model Equations and Formulations

Symbol	Title	Unit
P_0	Initial electricity price before supply and demand adjustments	IRR/MWh
Q	Total electricity generated by conventional and renewable power plants	MWh
Q_i	Electricity generated by conventional power plants (leader)	MWh
Q_j	Electricity generated by renewable power plants (follower)	MWh
α	Price sensitivity coefficient with respect to supply changes	—
REC	Renewable Energy Certificate	IRR/MWh
PFR	Power Fuel Rate Reform	IRR/m³ (gas) or IRR/litre (oil product`
C_{fi}	Fixed cost of the conventional power plant	Million IRR
C_{vi}	Variable cost of the conventional power plant	IRR/MWh
C_i	Total cost of the conventional power plant	Million IRR
C_{fj}	Fixed cost of the renewable power plant	Million IRR
C_{vj}	Variable cost of the renewable power plant	IRR/MWh
C_j	Total cost of the renewable power plant	Million IRR
π_i	Profit of the conventional power plant	Million IRR
π_j	Profit of the renewable power plant	Million IRR
Q_i^*	Optimal electricity output of the conventional power plant (leader)	MWh
Q_j^*	Optimal electricity output of the renewable power plant (follower)	MWh
P^*	Equilibrium electricity price after leader–follower decisions	IRR/MWh
W^*	Optimal value of the social welfare function after equilibrium calculations	Million IRR

Note: *Index i denotes the aggregated thermal fleet (leader coalition), and index j denotes the aggregated renewable fleet (follower coalition). Accordingly, all variables carrying subscripts i and j are interpreted at the coalition level.*
Source*: Research Findings*

3.2.2 Estimation of Hypothetical REC Prices Using the LCOE–Gap Approach

In Iran, over the past several years, the legal and regulatory foundations for establishing a Renewable Energy Certificate (REC) market have been laid within the framework of upstream energy and environmental legislation. Nevertheless, as of the time of this study, a formal market for REC trading has not yet been established, and no empirical price data are available. Consequently, this research estimates hypothetical REC prices to analyze the impact of implementing REC and Power Fuel Rate (PFR) reform policies simultaneously, using scientifically accepted valuation methods.

To this end, the LCOE–Gap[1] approach was adopted. The logic behind this method is that for renewable power plants to become competitive with conventional plants, the gap between their levelized cost of electricity and the average market price of electricity must be compensated through the REC mechanism. The computational relationship is expressed as follows:

$$REC_t = \max\{0, LCOE_{R,t} - \mathbb{E}[P_{market,t}]\}$$

Where:

REC_t: Hypothetical REC price in year t

$LCOE_{R,t}$: Levelized cost of renewable electricity generation in year t

$\mathbb{E}[P_{market,t}]$: Expected annual average market price of electricity after the implementation of PFR.

The LCOE in the above relationship is calculated using the following standard formula:

$$LCOE = \frac{CAPEX \times CRF + O\&M_{fix}}{E_{annual}} + \frac{O\&M_{var}}{MWh}$$

Where:

CAPEX: Initial capital investment cost

CRF: Capital recovery factor based on the discount rate and project lifetime

$O\&M_{fix}$: fixed operation and maintenance costs

$O\&M_{var}$: variable operation and maintenance costs

E_{annual}: annual electricity generation.

The variables related to solar and wind power plants in Iran were estimated using national data and internationally recognized reports, adjusted for domestic economic conditions and capital cost structures.

The adoption of the LCOE–Gap method in this study is justified by the availability of reliable cost and price data and the method's strong generalizability. Although the actual REC price has not yet been discovered in Iran, LCOE values and market electricity prices are observable and reliable. The calculated hypothetical REC prices serve as annual average benchmarks for policy analysis and can later be compared with actual prices discovered through trading in the Iran Energy Exchange.

In the absence of an operational REC market, these calculated values, while hypothetical in nature, are derived from a well-established theoretical framework and empirically robust data. They can therefore be considered scientifically sound proxies for REC prices under Iranian market conditions. Naturally, in real-world settings, price discovery would occur through supply and demand interactions within the REC trading platform.

3.2.3 Model Assumptions

The proposed model is designed based on the Stackelberg game theoretical framework combined with social welfare optimization. The electricity market is assumed to operate under semi-competitive conditions, where conventional power

---

[1] Levelized Cost of Electricity Gap; LCOE–Gap.

plants act as market leaders due to the presence of subsidies and stronger infrastructure, while renewable power plants act as followers, adjusting their decisions according to the leader's strategies.

Both conventional and renewable producers seek to maximize their individual profits, while the government, as the market regulator, aims to maximize social welfare, which includes both producer profits and consumer surplus. This objective is achieved by defining and optimizing a social welfare function with respect to the two key policy variables: REC (Renewable Energy Certificate) and PFR (Power Fuel Rate), in order to identify their optimal values that maximize total welfare.

3.3 Mathematical Functions and Relationships

Within the Stackelberg game structure, the leader (conventional power plant) first optimizes its profit function, after which the follower's reaction function is derived. The follower's decision is therefore expressed as a function of the leader's production strategy. Once the follower's reaction function is determined, equilibrium values for output and prices are computed simultaneously. The sequence of decisions and game process can be summarized as follows:

Stage (1): The leader (conventional power plant) determines its optimal electricity production quantity Q_i.

Stage (2): After the leader's decision, the follower (renewable power plant) optimizes its reaction function and determines its output Q_j.

Stage (3): Once Q_i and Q_j are determined, the market price of electricity (P) and the social welfare function (W) are calculated.

3.3.1 Profit Function of the Leader (Conventional Power Plant)

Conventional power plants, acting as market leaders, make their decisions first. The general form of the leader's profit function is defined as:

$$\pi_i = R_i - C_i \tag{1}$$

where:

π_i: Profit of the conventional power plant.

R_i: Revenue function of the conventional power plant.

C_i: Cost function of the conventional power plant.

The revenue function is defined as:

$$R_i(Q_i) = P(Q)Q_i = (P_0 - \alpha Q)Q_i \tag{2}$$

Where:

$P(Q) = P_0 - \alpha Q$: market price function of electricity

$Q = \sum_{i=1}^{n} Q_i + \sum_{j=1}^{m} Q_j$: total electricity output produced by both conventional (Q_i) and renewable (Q_j) power plants

The cost function of the conventional power plant is expressed as a function of output and the PFR:

$$C_i(Q_i, PFR) = C_{fi} + C_{vi}(PFR)Q_i \tag{3}$$

Where:

C_{fi}: fixed cost of electricity generation (infrastructure and capital investment)

$C_{vi}(PFR)$: variable cost of generation as a function of PFR, defined as:

$$C_{vi}(PFR) = C_{fs} + C_{om} + C_{fuel}(PFR) \tag{4}$$

Where:

C_{fs}: base fuel cost prior to PFR reform (linked to domestic or global fuel prices such as gas, coal, or oil)

C_{om}: operation and maintenance costs (repairs, personnel, equipment, and other variable costs)

$C_{fuel}(PFR)$: variable fuel cost after PFR reform, defined as:

$$C_{fuel}(PFR) = PFR \times C_{fs} \times Q_i \tag{5}$$

Since the primary objective is to capture the direct effect of PFR on variable costs, the model simplifies the cost function by focusing on the variable fuel cost C_{fuel} and neglecting C_{om}. Substituting the revenue and cost expressions into the general profit function yields:

$$\pi_i = \left(P_0 - \alpha(Q_i + Q_j)\right)Q_i - C_{fi} - (PFR \times C_{fs} \times Q_i) \tag{6}$$

This equation represents the leader's profit as a function of its own output level (Q_i), the follower's output (Q_j), the market price function, and the fuel price reform parameter (PFR). In this formulation, the market price is determined endogenously through the inverse demand function rather than chosen strategically, reflecting the quantity-setting nature of the Stackelberg competition. The resulting profit function forms the basis for the leader's optimization problem in the Stackelberg game structure.

3.3.2 Deriving the Follower's Reaction Function (Renewable Power Plant)

Consistent with the institutional timing and Stackelberg-quantity framework described in Section 3.1, Q_j and Q_j denote the coalition-level outputs of the thermal (leader) and renewable (follower) fleets, respectively. The thermal coalition moves first by committing to Q_j ; given this commitment, the renewable coalition maximizes its profit and selects Q_j, yielding the follower's best-response function Q_j^*. The market-clearing price is then determined endogenously through the inverse demand function. Renewable power plants make their decisions after conventional plants. The general form of the renewable producer's profit function is:

$$\pi_j = R_j - C_j \tag{7}$$

where:

π_j: profit of the renewable power plant.

R_j: revenue of the renewable plant, which is affected by the REC policy and is a function of Q_j and REC:

$$R_j(Q_j, REC) = P(Q)Q_j + REC.Q_j = (P_0 - \alpha Q)Q_j + REC.Q_j \tag{8}$$

Here, $\mathrm{P(Q) = P_0 - \alpha Q}$ is the inverse demand (price) function for electricity, and $\mathrm{Q} = \sum_{i=1}^{n} \mathrm{Q_i} + \sum_{j=1}^{m} \mathrm{Q_j}$ denotes total market output as the sum of conventional outputs ($\mathrm{Q_i}$) and renewable outputs ($\mathrm{Q_j}$).

The cost function of the renewable plant is specified as:

$$C_j\left(Q_j\right) = C_{fj} + C_{vj}.Q_j \tag{9}$$

where C_{fj} is fixed cost (infrastructure and upfront investment) and C_{vj} is the variable generation cost per unit.

Because C_{fj} is constant and independent of output, and since the REC and PFR policies directly affect variable generation costs rather than fixed costs, including C_{fj} in the optimization does not alter the output equilibrium, it only shifts the profit level by a constant. Given that the primary objective here is to assess operational/production competitiveness rather than investment appraisal or capital recovery, we omit C_{fj} from the renewable cost function in the final specification to test, in a direct manner, whether renewable plants can compete with conventional plants on the basis of production cost and market price.

By contrast, fixed costs for conventional plants cannot be ignored. Unlike renewables, whose cost structure is dominated by variable components, conventional plants typically bear large fixed costs (infrastructure, construction, equipment, periodic maintenance) that must be paid even at zero output. Omitting such fixed costs would unrealistically overstate their competitiveness.

Substituting the revenue and cost expressions into the renewable plant's profit function yields:

$$\pi_j = \left(P_0 - \alpha(Q_i + Q_j)\right)Q_j + REC.Q_j - C_{vj}.Q_j \tag{10}$$

To obtain the follower's reaction function, maximize πjπj with respect to Q_j:

$$\frac{\partial \pi_j}{\partial Q_j} = P_0 - \alpha\left(Q_i + Q_j\right) + REC - C_{vj} = 0 \Rightarrow$$

$$Q_j^* = \frac{P_0 + REC - C_{vj} - \alpha Q_i}{\alpha} \tag{11}$$

Equation (11) is the follower's reaction function, expressing the renewable plant's optimal output Q_j^* as a decreasing linear function of the leader's output Q_i and an increasing function of the net margin term $(P_0 + REC - C_{vj})$.

3.3.3 Optimizing the Leader's Profit Using the Follower's Reaction Function

Given the follower's reaction function, substitute it into the leader's profit function. The conventional (leader) plant's profit becomes:

$$\pi_i = \left(P_0 - \alpha\left(Q_i + Q_j\right)\right)Q_i - C_{fi} - \left(PFR \times C_{fs} \times Q_i\right)$$

To optimize the above and determine the leader's equilibrium output Q_i^*, take the first-order condition with respect to Q_i:

$$\frac{\partial \pi_i}{\partial Q_i} = \left(P_0 - \alpha(Q_i + Q_j)\right)Q_i - \overline{C_{fi}} - (PFR \times C_{fs} \times Q_i) = 0 \Rightarrow$$

$$Q_i^* = \frac{P_0 - C_{fs}.PFR - \alpha Q_j}{2\alpha} \tag{12}$$

3.3.4 Stackelberg Equilibrium Conditions

Given Q_i^*, use the follower's reaction function:

$$Q_j^* = \frac{P_0 + REC - C_{vj} - \alpha Q_i^*}{\alpha} \quad (13)$$

The equilibrium electricity price is then:

$$P^* = P_0 - \alpha\left(Q_i^* + Q_j^*\right) = \frac{P_0}{4} + \frac{REC}{4} - \frac{C_{fs}.PFR}{4} + \frac{C_{fs}.PFR}{2} \quad (14)$$

3.3.5 Social Welfare Function under Stackelberg Equilibrium

The social welfare function ww is formulated to evaluate the effects of the simultaneous implementation of the Power Fuel Rate (PFR) reform and the Renewable Energy Certificate (REC) policy on overall welfare, which includes both consumer surplus and producer surplus (i.e., profits of both conventional and renewable power plants).

The welfare function is defined as:

$$w = CS + \pi_i + \pi_j \quad (15)$$

where:

CS: consumer surplus,

π_i: profit of the conventional (leader) power plant,

π_j: profit of the renewable (follower) power plant.

To compute w, since π_i and π_j are already derived, the remaining component is the consumer surplus.

Consumer surplus is obtained from the area under the demand curve minus the total revenue of producers:

$$CS = \int_0^{Q_i^* + Q_j^*} P(Q)dQ - P(Q_i^* + Q_j^*) \quad (16)$$

Substituting the linear demand function $P = P_0 - \alpha Q$ into the above integral and solving gives:

$$CS = \int_0^{Q_i^* + Q_j^*} (P_0 - \alpha Q)dQ - P(Q_i^* + Q_j^*) \Rightarrow$$

$$CS = P_0\left(Q_i^* + Q_j^*\right) - \frac{\alpha}{2}\left(Q_i^* + Q_j^*\right)^2 - P\left(Q_i^* + Q_j^*\right)$$

Given $P = P_0 - \alpha\left(Q_i^* + Q_j^*\right)$, we have:

$$CS = P_0\left(Q_i^* + Q_j^*\right) - \frac{\alpha}{2}\left(Q_i^* + Q_j^*\right)^2 - P^*\left(Q_i^* + Q_j^*\right) \quad (17)$$

Finally, substituting CS, π_i^*, and π_j^* into Equation (15) yields the equilibrium social welfare level under the simultaneous implementation of REC and PFR policies.

This welfare measure captures the combined effects of policy instruments on both market participants (producers) and end-users (consumers).

Subsequently, sensitivity analysis can be performed to examine how different values of REC and PFR influence the overall level of social welfare.

3.4 Computational Methods, Model Validation, and Software Tools

3.4.1 Numerical and Computational Methods

To solve the Stackelberg equilibrium (the mathematical core of this study) and to optimize both the profit functions and the social welfare function, this research employs nonlinear optimization techniques. Specifically:

- Gradient descent algorithms are applied to iteratively optimize profit functions, identify local optima, and assess the sensitivity of outcomes to variations in model parameters.
- The Newton–Raphson method is used to find the roots of nonlinear equations derived from the first-order optimality conditions of the model.
- Sensitivity analysis is conducted by varying key policy parameters, in particular, REC and PFR, to examine their impact on equilibrium outcomes and social welfare levels.

This combination of computational methods ensures both numerical accuracy and flexibility in exploring different policy scenarios.

3.4.2 Software Tools

All mathematical calculations and simulations were carried out using MATLAB, owing to its powerful numerical computation capabilities. In addition, GAMS was employed to perform precise optimization and sensitivity analyses. The selection of these tools enhances the reliability and precision of equilibrium point calculations and the robustness of policy sensitivity evaluations.

3.4.3 Model Validation and Data Sources

Monte Carlo simulations were conducted to evaluate the robustness of the model under various hypothetical scenarios, ensuring its generalizability.

In contrast to empirical econometric studies relying on regression-based inference, the analytical Stackelberg framework developed here employs structural validation techniques to ensure reliability of the model. Specifically, three complementary procedures were implemented:

(i) Sensitivity analysis, in which key policy parameters (REC and PFR) were perturbed within realistic policy ranges to verify stability of equilibrium outcomes;

(ii) Monte-Carlo simulation, where parameter uncertainties were incorporated by drawing random samples from truncated distributions and recalculating equilibrium responses across thousands of replications;

(iii) A case-study evaluation, in which the model was calibrated using empirical cost and operational data from representative thermal, solar, and wind units to examine real-world applicability.

These validation procedures serve an equivalent function to econometric diagnostic tests in empirical research, namely, demonstrating internal consistency, robustness to uncertainty, and practical relevance of model behavior.

Predictive accuracy was assessed through scenario testing for different REC and PFR implementations using sensitivity analysis.

Moreover, the proposed model was validated through a case study of selected power generation units in Iran, utilizing official statistical data published by Ministry of Energy of Iran, Iran Grid Management Company, and Renewable

Energy and Energy Efficiency Organization (SATBA). Model outputs were compared with existing studies and statistical reports related to the Iranian electricity market.

Since the official green certificate market in Iran has not yet been launched, the REC values in this study are estimated using the LCOE-gap approach, serving as scientifically valid proxy values for scenario analysis and robustness testing. Actual price discovery of REC will depend on the establishment of a formal trading platform. To strengthen reliability, both sensitivity analysis and Monte Carlo simulation are applied to the key parameters of the model.

To further enhance transparency, two complementary approaches were employed to examine model robustness: sensitivity analysis and Monte-Carlo simulation. In the sensitivity analysis, key policy parameters (REC and PFR) were varied over realistic ranges consistent with the Iranian power market, and for each parameter combination, the Stackelberg equilibrium was recalculated to obtain equilibrium production, profits, and welfare. The Monte-Carlo approach further accounted for uncertainty by sampling ex-ante random parameter values. The initial electricity market price was sampled from a truncated normal distribution centered around the reference value, while PFR and REC were sampled from uniform distributions over 50–300 and 0–30,000 IRR/MWh, respectively, consistent with LCOE-based estimation. For each renewable technology, approximately 3,000 Monte-Carlo replications were executed. The equilibrium outcomes were computed via GAMS, while MATLAB was used for random sampling, simulation control, and visualization.

3.4.4 Comparison with Previous Studies

The model developed in this study offers an innovative analytical framework for evaluating the simultaneous implementation of PFR and REC policies, an area that has not been comprehensively examined, particularly in the Iranian context.

Unlike prior research, which typically focused on a single policy or employed simpler competition models such as Cournot or Bertrand, this study adopts a Stackelberg competition structure. This allows for a more realistic representation of the dynamics of the Iranian electricity market, where conventional power plants act as leaders due to infrastructural strength and subsidies, and renewable producers respond strategically as followers influenced by REC incentives.

This framework also enables the integration of social welfare optimization, combining consumer surplus with producer profits, and provides a comprehensive assessment of policy impacts on overall welfare.

In sum, this methodological advancement enhances the policy relevance of the findings, offering practical insights for designing balanced energy policies that promote energy security, economic efficiency, and environmental sustainability.

4. Findings, Computations, and Results Analysis

To strengthen theoretical contextualization, the following discussion connects the model outcomes to concepts from microeconomic theory and previously established empirical findings. The strategic behavior observed under different PFR–REC policy regimes is consistent with the theoretical logic of price-based and market-based instruments, whereby higher marginal costs for thermal units through PFR improve renewable competitiveness, while REC enhances relative profitability by internalizing environmental externalities. This dual mechanism is aligned with the prediction from welfare economics that combining corrective fiscal tools with market coordination reduces allocative inefficiencies caused by fuel subsidies and underpricing of externalities.

4.1 Sensitivity Analysis and Model Robustness

Sensitivity analysis is a fundamental step in evaluating the robustness of economic models, particularly in those based on game theory and Stackelberg competition frameworks, where strategic interactions between agents play a critical role.

In conducting the sensitivity analysis, REC and PFR were varied within empirically reasonable ranges based on the structure of the Iranian electricity market. REC values were obtained from the LCOE-gap estimation described in Section 3.2.2, whereas PFR was set within the admissible 50–300 IRR policy range. For each value pair, the Stackelberg equilibrium was recomputed to derive equilibrium production, profit, and welfare changes. Consistent with theoretical expectations, increasing REC stimulates renewable output and profitability, while increasing PFR reduces thermal output and shifts profitability toward the renewable unit, thereby validating the internal stability of model behavior under deterministic perturbations.

In this study, sensitivity analysis is employed to examine how variations in the Power Fuel Rate (PFR) for conventional power plants and the Renewable Energy Certificate (REC) value for renewable generators (solar and wind) affect:

- Equilibrium production levels of both conventional and renewable units,
- Equilibrium profit functions of the two types of power plants, and
- The overall social welfare function.

To assess the resilience and responsiveness of the proposed model to changes in key variables, different values of PFR rates and REC price levels are introduced into the model. For each scenario, the resulting optimal equilibrium outputs, profits, and social welfare levels are computed.

The outcomes of the sensitivity analysis are then interpreted and illustrated through graphical representations, providing a clear view of how policy instruments shape market dynamics and welfare outcomes. This step plays a crucial role in evaluating the policy effectiveness and strategic responses of different producers under various regulatory conditions.

4.1.1 Sensitivity Analysis of the Model to Assess the Competitiveness of Renewable Power Plants

In the proposed Stackelberg competition framework, the strategic players are conventional and renewable power plants. To align the model outcomes with the realities of Iran’s electricity market, the analysis was conducted under two sensitivity scenarios corresponding to different REC price levels for solar and wind generation units.

In Scenario 1, the conventional fossil-fuel power plant is modeled as the leader, while the solar power plant acts as the follower. In Scenario 2, the solar follower is replaced by a wind power plant, and the results are analyzed accordingly.

The profit functions and optimal output levels were calculated based on the Stackelberg model under the simultaneous implementation of the Power Fuel Rate (PFR) reform and the Renewable Energy Certificate (REC) policy. The resulting equilibrium outcomes were then visualized using MATLAB.

According to official data published by Ministry of Energy of Iran for the year 2024 (1403 in the Iranian calendar):

- Conventional power plants (fossil-fuel-based) pay 100 IRR per liter of oil product or cubic meter of natural gas,
- The feed-in tariff for large-scale solar power generation is 22,000 IRR per kWh,
- The feed-in tariff for large-scale wind power generation is 17,000 IRR per kWh.

At this stage of the sensitivity analysis, the leader–follower competition was simulated using cost structure parameters aligned with Iran's current market conditions and consistent with global trends in LCOE (Levelized Cost of Energy).

Since an official domestic REC market does not yet exist, the annual average REC value was estimated using the LCOE-gap method described in Section 2.3.1. This value was then introduced into the model as a policy parameter, allowing the analysis to capture the impact of different REC levels on market equilibrium and renewable competitiveness.

4.1.1.1 Profit Function of the Conventional Power Plant

Figures (2) and (3) illustrate the results of the sensitivity analysis for the optimal profit function of the conventional power plant (π_i^*) within the Stackelberg competition framework, under the simultaneous implementation of the Power Fuel Rate (PFR) reform and the Renewable Energy Certificate (REC) policy.

In both figures:

-The x-axis represents the PFR values,

-The y-axis represents the REC values, and

-The z-axis depicts the optimal profit level of the leader (conventional power plant).

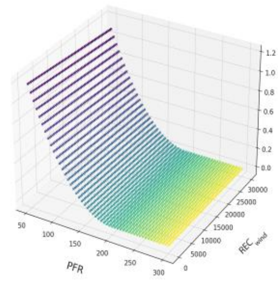

Figure 3. Corresponds to Scenario 2, in which the conventional power plant remains the leader, but the wind power plant replaces the solar unit as the follower
Source: *Authors' research findings*

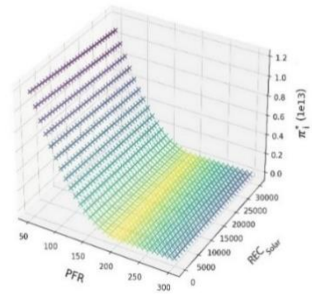

Figure 2. Corresponds to Scenario 1, in which the conventional power plant acts as the leader and the solar power plant as the follower
Source: *Authors' research findings*

These 3D surface plots provide a clear visualization of how variations in PFR and REC influence the profitability of the leader, reflecting its strategic advantage under different policy settings.

As observed, the results are consistent with theoretical expectations. An increase in PFR leads to a monotonic decline in the leader's profit, driven by two key mechanisms: the rising fuel cost burden and the reduction in the leader's equilibrium output (Q_i^*).

Moreover, for any fixed level of PFR, an increase in REC reduces the leader's profit through two channels:

- Strengthening the follower's output response (Q_j^*), and
- Lowering the equilibrium electricity price (P^*).

The magnitude of this effect is slightly stronger in Scenario 2, where a wind power plant acts as the follower, compared to Scenario 1 with a solar follower. This is because the lower variable cost of wind power results in a stronger production response to REC signals.

Overall, the combined implementation of PFR and REC leads to the minimum profit level for the leader, thereby shifting the competitive landscape in favor of renewable power plants and enhancing their relative competitiveness in the electricity market.

4.1.1.2 Profit Function of Renewable Power Plants

Figures (4) and (5) present the results of the sensitivity analysis of the optimal profit function of renewable power generation units within the Stackelberg competition framework, under the simultaneous implementation of Power Fuel Rate (PFR) reform and Renewable Energy Certificate (REC) policy.

In both figures:

- The x-axis represents the PFR,
- The y-axis represents the REC, and

- The z-axis indicates the optimal profit level of the follower (renewable power plant).

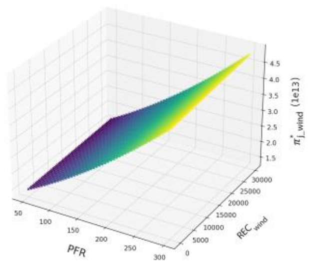

Figure 5. Corresponds to Scenario 2, which simulates the competition between a conventional power plant (leader) and a wind power plant (follower)
***Source:** Authors' research findings*

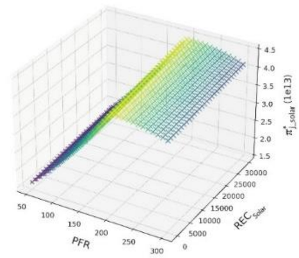

Figure 4. Corresponds to Scenario 1, which simulates the competition between a conventional power plant (leader) and a solar power plant (follower)
***Source:** Authors' research findings*

These 3D surface plots demonstrate how changes in the two key policy parameters (PFR and REC) affect the profitability of renewable producers, reflecting their increasing strategic advantage as REC values rise and PFR reforms reshape the competitive market structure.

As illustrated in the two figures above, an increase in REC leads to a significant rise in the profit of renewable units. This increase occurs through both direct and indirect channels:

- Directly, via the additional revenue stream generated by REC, and
- Indirectly, through an increase in the follower's equilibrium output.

Moreover, as PFR increases, the effective cost pressure on conventional power plants grows due to higher fuel costs. This results in a decline in the leader's production, thereby improving the competitive position of the renewable follower and increasing its profit level.

A technology comparison reveals that wind power plants, owing to their lower variable costs, are more responsive to both policy levers, especially REC. Consequently, to achieve a target profit level, the required REC range for wind units can be lower than that of solar units, reflecting their higher cost-competitiveness under similar policy conditions.

4.1.1.3 Optimal Stackelberg Output of Conventional Power Plants

Figures (6) and (7) present the results of the sensitivity analysis of the optimal output level of the conventional power plant based on the Stackelberg production function, under the simultaneous implementation of the Power Fuel Rate (PFR) reform and Renewable Energy Certificate (REC) policy.

In both figures:

- The x-axis represents the PFR,
- The y-axis represents the REC, and
- The z-axis shows the optimal equilibrium output of the conventional power plant (Q_i^*).

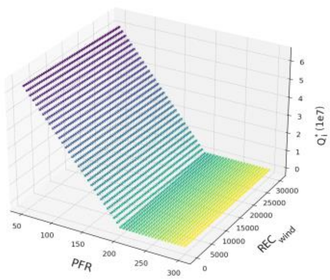

Figure 7. Corresponds to Scenario 2, which analyzes the competition between a conventional power plant (leader) and a wind power plant (follower)
Source: *Authors' research findings*

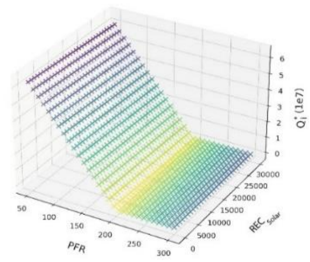

Figure 6. Corresponds to Scenario 1, which examines the hypothetical competition between a conventional power plant (leader) and a solar renewable power plant (follower)
Source: *Authors' research findings*

These 3D surface plots illustrate how variations in the two key policy parameters, PFR and REC, shape the leader's equilibrium production decisions, providing critical insights into the competitive dynamics of the electricity market under different renewable technology scenarios.

The pattern observed in both figures is fully consistent with economic intuition. As PFR increases, the optimal output of the conventional power plant declines steadily due to the more realistic internalization of fuel costs. At the same time, an increase in REC, which strengthens the revenue stream of renewable units, shifts the follower's reaction function toward higher production levels and constrains the leader's production space. As a result, a rise in REC also leads to a systematic reduction in Q_i^*.

A comparison of the two scenarios reveals that, due to the lower variable costs of wind power, the market share shift from the leader to the follower is more pronounced in the wind scenario. Consequently, Q_i^* remains lower across most policy combinations compared to the solar scenario. This finding implies that fuel price rationalization, combined with increased renewable revenues, systematically expands the equilibrium share of clean power plants while narrowing the production domain of fossil-based units.

4.1.1.4 Optimal Stackelberg Output of Renewable Power Plants

Figures (8) and (9) present the results of the sensitivity analysis of the equilibrium electricity generation of renewable units, based on the Stackelberg output function, under the simultaneous implementation of the Power Fuel Rate (PFR) reform and the Renewable Energy Certificate (REC) policy.

In both figures:

- The x-axis represents the PFR,
- The y-axis represents the REC, and
- The z-axis displays the optimal equilibrium output of the renewable power plant.

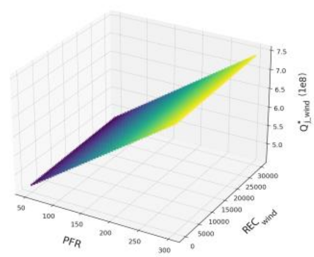

Figure 9. Corresponds to Scenario 2, which examines competition between a conventional power plant (leader) and a wind power plant (follower)
Source: *Authors' research findings*

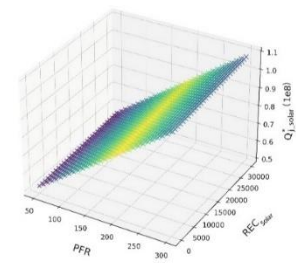

Figure 8. Corresponds to Scenario 1, which examines hypothetical competition between a conventional power plant (leader) and a solar power plant (follower)
Source: *Authors' research findings*

These 3D surface plots demonstrate how variations in PFR and REC affect the equilibrium output behavior of renewable power plants, providing valuable insights into their competitive responses under different policy settings.

The pattern observed in the two figures aligns closely with theoretical expectations. First, an increase in PFR, by internalizing the true cost of fuel for the leader, constrains the production space of conventional power plants. This, through the reduction in Q_i^* and an improvement in the price environment, leads to a steady increase in Q_j^*.

Second, a higher REC, serving as a complementary revenue stream for renewables, directly shifts the follower's reaction function toward greater output, resulting in a systematic upward trend in Q_j^* across the entire policy range. Consequently, the equilibrium production of renewable units exhibits a positive and economically significant sensitivity to both policy instruments.

From a technology perspective, due to their lower variable costs, wind power units achieve a higher level of $Q_{j\_wind}^*$ compared to solar units under similar combinations of PFR and REC. In other words, the production shift from the leader to the follower is stronger in the wind scenario, implying that a less aggressive policy mix can achieve a larger renewable energy share.

4.1.2 Welfare Effects under the Simultaneous Implementation of PFR and REC

Figures (10) and (11) illustrate the level of social welfare at the Stackelberg equilibrium under the simultaneous implementation of PFR and REC. Welfare is computed according to:

$$w^* = CS + \pi_i^* + \pi_j^* \tag{18}$$

where CS denotes consumer surplus, and π_i^* and π_j^* represent the leader's and follower's equilibrium profits, respectively. The x-axis indicates PFR, the y-axis shows REC, and the z-axis displays the resulting level of w^*. The analysis is carried out under two scenarios:

Scenario 1: Competition between a conventional power plant (leader) and a solar power plant (follower).

Scenario 2: Competition between a conventional power plant (leader) and a wind power plant (follower).

(1) *Positive effect of REC on welfare*

The impact of REC on welfare is positive and monotonic. As REC increases, the follower's reaction function shifts upward, leading to higher Q_j^*. With larger total output, the equilibrium price P^* tends to decline, resulting in a rise in consumer surplus (CS) and a reinforcement of π_j^*. Although the leader's profit π_i^* declines due to the shrinking production space, this effect is insufficient to offset the net positive impact of REC. Consequently, w^* increases systematically with higher REC levels.

(2) Mixed and interaction-dependent effect of PFR on welfare

The impact of PFR on welfare depends on its magnitude and interaction with REC. A rise in PFR raises the effective fuel cost of the leader, decreases Q_i^*, and increases P^* in the absence of supply-side reinforcement. This leads to a reduction in CS and a decline in π_i^*, while π_j^* is partially strengthened through market share reallocation. On net, the standalone effect of PFR is generally negative.However, when higher REC levels accompany PFR, the positive channel through π_j^* and the price-mitigating effect of higher Q_j^* significantly offset the negative welfare impact of PFR. At intermediate levels of PFR, this interaction can improve w^*. At very high PFR levels, however, the price pressure and leader output contraction dominate, causing welfare to erode again.

(3) Technological differences between solar and wind

Due to the lower variable costs of wind power plants, increases in REC raise $Q_{j\_wind}^*$ more sharply, amplifying the downward pressure on P^*. As a result, the welfare curve is steeper with respect to REC in the wind scenario than in the solar scenario. In other words, a smaller REC range is sufficient to reach a target welfare level in the wind case. While the negative welfare sensitivity to PFR is present in both technologies, the ability of REC to neutralize this effect is stronger in the wind scenario.

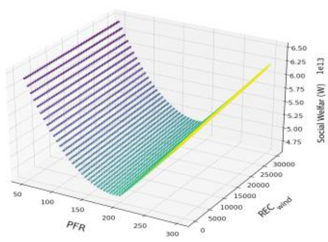

Figure 11. Sensitivity Analysis of the Social Welfare Function with Respect to PFR and REC in the Wind Power Plant Scenario
Source: *Authors' research findings*

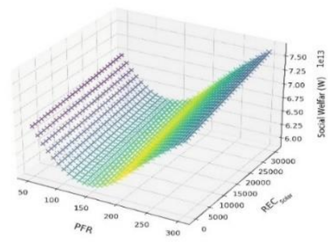

Figure 10. Sensitivity Analysis of the Social Welfare Function with Respect to PFR and REC in the Solar Power Plant Scenario
Source: *Authors' research findings*

4.1.3 Combined and Individual Policy Effects

The sensitivity analysis in this study reveals that raising the power fuel rate (PFR), by increasing the effective fuel cost for the conventional leader, consistently reduces leader output Q_i^*, lowers profit π_i^*, and diminishes consumer surplus due to upward price pressure. Accordingly, in the absence of complementary policy instruments, the stand-alone effect of PFR on social welfare w^* is largely negative.

By contrast, strengthening the revenue of the renewable follower through the Renewable Energy Certificate (REC) shifts the follower's reaction function upward, raises Q_j^*, boosts π_j^*, and moderates the equilibrium price by increasing the renewable share in total generation. The net effect of this policy is a rise in consumer surplus and improved social welfare.

However, the joint implementation of PFR and REC produces a synergistic effect. PFR realigns the leader's cost structure, constraining conventional output, while REC simultaneously strengthens the follower's revenue incentives. The combined result is a significant increase in the equilibrium renewable generation share Q_j^*, a systematic decline in conventional output Q_i^*, and a notable improvement in social welfare w^*.

Moreover, the reinforcing relationship between PFR and REC confirms earlier observations that mixed-policy architectures (e.g., RPS + ETS) outperform single-instrument designs (Ji et al., 2024; Song et al., 2022). This synergy arises because the PFR eliminates fuel-subsidy distortions at the supply side, while REC provides additional incentives through demand-side valuation of green attributes. As a result, renewable units obtain both cost advantage (via PFR) and revenue advantage (via REC), which jointly increase equilibrium renewable penetration and societal welfare.

Based on this evidence, it is recommended that technology-specific REC ranges (accounting for cost differentials between solar and wind units) be designed and that PFR be calibrated gradually and prudently. Overall, the robustness of results across parameter variations underscores the stability of the model and the policy relevance of its implications.

These results are consistent with theoretical literature indicating that fossil-fuel subsidy removal increases the marginal production cost of thermal units, thereby shifting equilibrium toward renewable generation (Fang et al., 2024; Monavariyan et al., 2020). The observed welfare improvements with increased PFR and REC levels are aligned with the findings of Morris et al. (2010), who show that coordinated policy instruments minimize distortions and enhance social welfare relative to stand-alone measures..

4.2 Monte Carlo Simulation and Model Validation

To assess the stability of results and the equilibrium behavior of the Stackelberg model under uncertainty, a Monte Carlo simulation was employed.

To assess the resilience of equilibrium behavior under uncertainty, Monte-Carlo simulation was implemented. The initial market price was sampled from a truncated normal distribution with a mean of 1,000,000 IRR/MWh and standard deviation of 100,000 IRR, bounded within 500,000–1,500,000 IRR. The PFR and REC parameters were drawn uniformly from 50–300 and 0–30,000 IRR/MWh, respectively, the latter obtained from the LCOE-gap calculation. Structural cost parameters were held constant. For each renewable technology, 3,000 simulation runs were executed, and for every draw, the Stackelberg equilibrium, production, profits, market price, and welfare, was computed. This stochastic evaluation confirmed that model outcomes remain qualitatively stable across a wide range of parameter realizations.

In the present problem, variables such as the initial market price, price elasticity of supply, baseline fuel cost, the range of power fuel rate (PFR) adjustments, and the price of renewable energy certificates (REC) are all influenced by market conditions and policy choices. Consequently, testing the robustness of the model requires a stochastic framework rather than a purely deterministic one.The simulation design was calibrated to align with both baseline assumptions and domestic/international evidence:

- The initial price fluctuated around its reference value within a controlled variance.
- PFR was sampled uniformly within the policy-relevant range of 50 to 300.
- REC varied from 0 to 30,000 IRR/MWh, corresponding to the gap between renewable levelized cost of energy (LCOE) and the market price.

Structural demand and cost parameters for both the leader and follower were kept fixed throughout the simulations, and a non-negativity constraint on output was imposed.

For each renewable technology, solar and wind, 3,000 scenarios were executed. In each scenario, random draws of policy and market variables were generated, after which the Stackelberg equilibrium system was solved to obtain the leader’s and follower’s equilibrium output and profit, the equilibrium price, and social welfare. Central tendency measures and percentiles were then computed, and three-dimensional surface plots and multivariate mappings were constructed to jointly visualize PFR, REC, and the output variables.

The validation results confirmed that the direction and magnitude of the observed effects were consistent with theoretical intuition: increasing PFR contracts leader output, whereas increasing REC strengthens renewable generation and profit. The results proved robust to reasonable parameter variations and aligned with empirical evidence from similar energy markets, where fuel cost internalization and complementary revenue mechanisms for renewables have been implemented.

Finally, selecting solar and wind technologies reflected their dominant role and distinct cost and generation profiles, ensuring that technology-specific policy recommendations could be derived clearly and effectively.

4.2.1 Implementation of the Monte Carlo Method

To evaluate the simultaneous effects of power fuel rate (PFR) reform and renewable energy certificate (REC) policies and to assess the robustness of the results, a Monte Carlo simulation was implemented. In this approach, key parameters were randomly sampled from predefined probability distributions, and in each iteration, the equilibrium values of leader and follower outputs Q_i^* and Q_j^*, the equilibrium price P^*, profits π_i^* and π_j^*, and social welfare w^* were computed and recorded based on the Stackelberg model relations. A large number of repetitions allowed the extraction of mean, median, quartiles, and 5th–95th percentile ranges, thereby enabling a comprehensive analysis of stability and variability in the model outcomes.

Parameter calibration was based on domestic and international evidence. The initial market price followed a truncated normal distribution with a mean of 1,000,000 IRR/MWh, a standard deviation of 100,000 IRR/MWh, and bounds between 500,000 and 1,500,000 IRR/MWh. PFR followed a uniform distribution within the 50–300 IRR/MWh range (as a policy adjustment index), and REC followed a uniform distribution in the 0–30,000 IRR/MWh interval. The demand slope in the baseline scenario was fixed at 0.006, the baseline thermal fuel rate coefficient at 2,500 IRR/MWh, the variable cost of renewable generation for solar at 1,500 IRR/MWh, and for wind at 1,200 IRR/MWh. The fixed cost of the thermal unit remained constant according to the baseline calibration, and a non-negativity constraint on output was imposed for both units.

The simulation was conducted under two technology scenarios, corresponding to the dominant renewable options in the country, solar and wind. For each technology, the Monte Carlo process included 3,000 independent iterations, generating a robust distribution of equilibrium outcomes for policy analysis.

4.2.2 Monte Carlo Simulation Results and Graphical Analysis

Figure (12) illustrates the Stackelberg equilibrium outputs of the conventional unit Q_i^* and the renewable unit Q_j^* under the joint implementation of PFR and REC policies. In this figure, the x-axis represents the power fuel rate (PFR), the y-axis indicates the renewable energy certificate (REC) price, and the z-axis shows the level of output.

As expected, increasing PFR, through higher fuel cost pressure, leads to a decline in Q_i^*. This contraction in conventional output indirectly creates more market space for renewable units by affecting the equilibrium price mechanism. On the other hand, increasing REC directly stimulates renewable generation by providing complementary revenue, resulting in a systematic increase in Q_j^*. The effect is particularly pronounced at moderate-to-high REC levels, where renewable generation expands significantly, and conventional generation retreats more sharply.

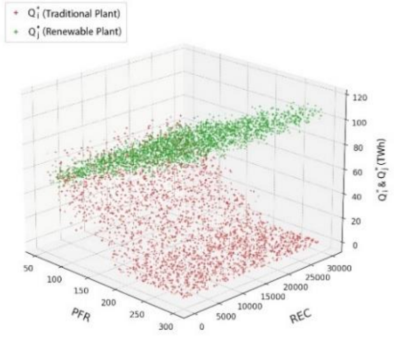

Figure 12. Monte Carlo simulation results for the Stackelberg equilibrium production of conventional and renewable power plants
Source: *Authors' research findings*

Figure (13) depicts the Stackelberg equilibrium profits of the conventional unit π_i^* and the renewable generation unit π_j^* as functions of PFR and REC. The results of the Monte Carlo simulation confirm that an increase in PFR, through higher effective marginal costs, leads to a significant reduction in the profit of the conventional power plant. In contrast, increasing REC, by providing complementary certificate-based revenue, strengthens π_j^*.

The sensitivity of renewable profit to REC is found to be stronger than its sensitivity to PFR. Nonetheless, in intermediate levels of PFR, the indirect effect of higher equilibrium prices also supports renewable profit, partly offsetting the downward pressure that might arise from other market forces.

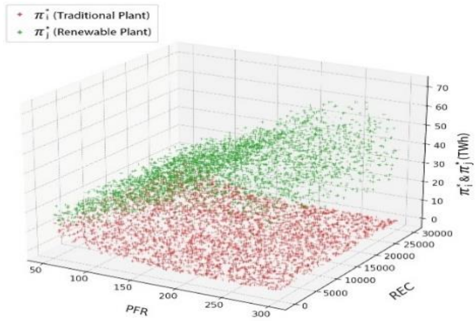

Figure 13. Monte Carlo simulation results for the optimal Stackelberg profit of conventional and renewable power plants
Source: *Authors' research findings*

Figure (14) illustrates the social welfare level w^* resulting from the joint implementation of PFR and REC policies. The overall outcome of the simulation indicates that the combination of the two instruments generally leads to welfare improvement. Among the two, REC plays the dominant role, and increasing its level generates a monotonic upward trend in w^*.

In contrast, PFR alone can exert downward pressure on welfare, particularly at very high levels, where the decline in conventional generation and the resulting price increase reduce consumer surplus and aggregate efficiency. However, when PFR is combined with appropriate REC levels, this negative effect is effectively offset, leading to a clear welfare enhancement in the intermediate PFR and moderate-to-high REC regions.

Thus, the Monte Carlo simulation results, consistent with theoretical mechanisms, highlight the policy complementarity between PFR and REC in improving allocative efficiency and social welfare.

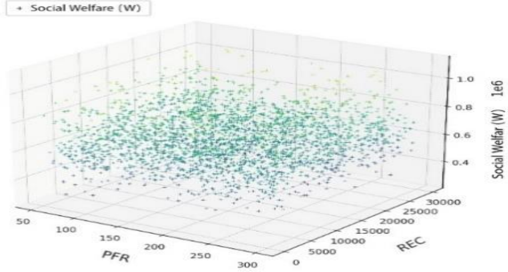

Figure 14. Monte Carlo simulation results for social welfare (w) under the simultaneous implementation of REC and FIT
Source: *Authors' research findings*

4.2.3 Economic Interpretation and Analysis of Monte Carlo Simulation Results

The results of the Monte Carlo simulations, conducted to empirically validate the Stackelberg equilibrium framework and assess the combined effects of PFR and REC policies, support the robustness of the model and confirm that the sign and slope of effects are consistent with theoretical predictions.

According to the findings, an increase in PFR raises the effective marginal cost of the thermal unit, leading, as expected, to a decrease in Q_i^* and a reduction in π_i^*. This cost pressure creates a price space for renewables through market rebalancing, and in the presence of green electricity supply, increases the equilibrium share of renewable energy. At very high levels of PFR, however, the price effect can erode part of the welfare gains.

Conversely, REC strengthens the revenue component of renewable units directly by providing complementary income, resulting in an increase in Q_j^* and a rise in π_j^*. Its indirect effect, through enhanced competitiveness at the margin, also leads to a retreat in thermal generation. The sensitivity of renewable profit to REC is significantly stronger than its sensitivity to PFR.

The combination of the two policy instruments leads to an overall improvement in social welfare (w^*). The observed pattern shows that REC plays the dominant role in enhancing welfare, while PFR at intermediate levels, especially when paired with moderate-to-high REC, contributes to maximizing welfare. In contrast, very high PFR levels, if not sufficiently compensated by REC, can have negative welfare impacts.

Due to the lower variable cost (cv_j) of wind power, the response slopes of Q_j^* and π_j^* are steeper for wind technology compared to solar. This implies that to achieve equivalent output and welfare targets, the required REC level for wind can be set lower than for solar units.

Overall, these results underscore that gradual fuel price reform (PFR), when paired with a credible REC market, can significantly strengthen renewable competitiveness while simultaneously enhancing social welfare. Successful joint implementation of these policy instruments requires institutional reliability in certificate issuance and trading, predictable regulatory rules, alignment with complementary mechanisms (such as quota setting or capacity targets), and avoiding extreme PFR levels without adequate REC compensation.

In summary, the Monte Carlo results, consistent with the logic of the Stackelberg model, indicate that a hybrid policy with PFR at intermediate levels and REC in the moderate-to-high range represents the most effective configuration for enhancing renewable competitiveness, improving profitability, and increasing social welfare in Iran and similar economies.

The Monte-Carlo simulation confirms that these qualitative patterns are robust under broad parameter uncertainty. This finding is consistent with analytical expectations from game-theoretic models under stochastic perturbations, where equilibrium allocation remains directionally stable in response to moderate policy shocks (Ma et al., 2024). The fact that results remain monotonic under random PFR-

REC draws provides strong support for the structural resilience of the model, thus reducing concerns regarding sensitivity to narrow parameter assumptions, as emphasized in Chen et al. (2022).

5. Case Study of Selected Power Plants

5.1 Introduction to the Selected Plants

In this study, three representative power plants were selected to analyze the impact of the simultaneous implementation of Renewable Energy Certificate (REC) and Power Fuel Rate (PFR) policies on the competitiveness of renewable power plants compared to conventional units over a four-year period (2020–2023).

Given the dominant role of photovoltaic and wind power generation in the renewable energy landscape of Iran, the analysis focuses on two competitive scenarios:

I. Conventional vs. Solar PV plant (Stackelberg competition model)

II. Conventional vs. Wind power plant (Stackelberg competition model)

The effects of these combined policies are evaluated with respect to optimal equilibrium output, profitability, and social welfare levels, arising from the strategic interaction between the competing power producers.

The main criterion for selecting these three plants was the availability of their financial statements and operational data, obtained from publicly disclosed documents on the Iranian stock exchange platforms and official national statistical reports.

(a) Damavand Combined Cycle Power Plant (Conventional)

This plant is one of the largest combined-cycle power stations in Iran, generating electricity primarily from fossil fuels (natural gas and gas oil).

It acts as the market leader in the Stackelberg competition model used in this research, reflecting the real structure of Iran's power market in which thermal plants dominate capacity and influence pricing dynamics.

(b) Ghadir Mehriz Solar PV Renewable Plant

This facility is one of Iran's largest photovoltaic solar power plants, generating electricity independently from fossil fuels.

It acts as the follower in the Stackelberg model, adjusting its production levels in response to governmental policies and the strategic decisions of the conventional leader.

Its inclusion enables the examination of how solar energy units respond to policy-driven market incentives.

(c) Binaloud Wind Power Renewable Plant

Located in a region with strong wind potential, this wind farm represents the second renewable technology considered in the model.

Similar to the solar unit, it operates as a follower, responding to both market and policy signals, specifically the REC mechanism.

The conventional Damavand Combined Cycle Power Plant is directly exposed to PFR, as its cost structure depends on fuel price reforms.

The renewable units, Ghadir Mehriz Solar Power Plant and Binaloud Wind Power Plant, are primarily influenced by REC, which supplements their revenue.

This plant combination allows for a comparative policy analysis of renewable vs. conventional generation technologies in Iran's electricity market within the Stackelberg competition framework.

5.2 Calculations and Results Analysis

To enhance empirical relevance and to align the model with realistic operational conditions, a case study was conducted using three representative generating units, including a thermal plant, a solar unit, and a wind unit. Input data for this analysis, including fixed and variable operating costs, annual production, and policy parameters, are reported in Table (2). These parameters were then embedded into the model framework, and the corresponding Stackelberg equilibria were computed for each scenario. Resulting outcomes, including optimal production levels, profits, and welfare impacts, are reported in subsequent tables and interpreted accordingly. This case-based evaluation demonstrates the applicability of the model to real-world conditions in Iran's electricity sector.

5.2.1 Stackelberg Equilibrium in the Competition between the Conventional and Solar Renewable Power Plants

a) ***Data***

In line with the model formulation, input data were collected and cross-validated from multiple sources including the financial statements disclosed on the CODAL[1] system, detailed industry and electricity market reports, and the Iranian Electricity Market Annual Statistical Yearbook.

The policy variables considered in this case study are:

PFR; Power Fuel Rate reform (fuel price adjustment for conventional power plants)

REC; Renewable Energy Certificate (supporting mechanism for renewable generation)

The annual REC values were estimated using the "LCOE-Gap" approach, the difference between renewable levelized cost of electricity and the average market price, and were introduced into the model as exogenous variables.

All other parameters and cost components in the input table were sourced directly from official reports and kept unchanged, ensuring consistency with the actual economic and technical conditions of the selected power plants.

[1] Comprehensive Database of All Listed Companies (CODAL); an official online disclosure platform in Iran for publishing the financial statements, reports, and announcements of publicly listed companies, operated under the Securities and Exchange Organization of Iran.

Table 2. Required Data for Solving the Stackelberg Model in the Competitiveness Study of Selected Conventional and Renewable Power Plants

Variable	Symbol	Year				Unit
		2020	2021	2022	2023	
Electricity Market Price	P	238,593	581,830	913,495	990,104	IRR/MWh
Initial Electricity Market Price	P_0	301,824	646,648	1,002,189	1,021,658	IRR/MWh
Price Sensitivity Coefficient of Electricity Supply	α	0.002	0.002	0.006	0.006	—
Power Plant Fuel Price Reform	PFR	50	50	150	150	IRR/unit fuel
Solar Renewable Energy Certificate	REC_{Solar}	40,761	32,418	29,087	28,010	IRR/MWh
Wind Renewable Energy Certificate	REC_{Wind}	32,711	28,918	27,087	25,510	IRR/MWh
Electricity Output of the Reference Conventional Power Plant	Q_i	31,590,793	32,385,917	14,758,549	5,236,350	MWh
Electricity Output of the Reference Solar Power Plant	Q_{j_Solar}	24,500	23,114	23,795	22,616	MWh
Electricity Output of the Reference Wind Power Plant	Q_{j_Wind}	378	469	58,485	56,864	MWh
Annual Revenue of the Reference Conventional Power Plant (Post-PFR)	$R_i(Q_i, PFR)$	7,537,342	18,843,091	13,481,864	5,184,533	Million IRR
Revenue of the Reference Solar Power Plant (Pre-REC)	R_{j_Solar}	5,845,548	13,448,592	21,736,919	22,392,672	Million IRR
Revenue of the Reference Solar Power Plant (Post-REC)	$R_{j\_Solar}(REC)$	6,001,614	13,654,725	22,129,542	22,777,152	Million IRR
Revenue of the Reference Wind Power Plant (Pre-REC)	R_{j_Wind}	90,188	272,878	53,425,768	56,301,291	Million IRR
Revenue of the Reference Wind Power Plant (Post-REC)	$R_{j\_Wind}(REC)$	92,252	276,463	54,150,982	57,267,979	Million IRR
Fixed Cost of the Reference Conventional Power Plant	C_{fi}	75,547	145,745	326,727	517,405	Million IRR
Variable Fuel Cost of the Conventional Power Plant (Post-PFR)	$C_{fuel}(PFR)$	123,169	352,380	948,690	2,884,224	Million IRR
Incremental Variable Fuel Cost Induced by PFR	C_{fuel_i}	2,463	7,048	6,325	19,228	Million IRR
Baseline Fuel Cost of the Reference Conventional Power Plant	C_{fs_i}	77.978	217.613	428.538	3672.054	Million IRR
Annual Operating Cost of the Reference Solar Power Plant	C_{j_Solar}	79,732	197,552	226,047	252,658	Million IRR
Annual Operating Cost of the Reference Wind Power Plant	C_{j_wind}	13,592	26,055	45,202	87,833	Million IRR

Source: *Research findings and authors' calculations based on CODAL financial statements, industry reports, and market data.*

Note: *IRR = Iranian Rial MWh = Megawatt-hour Monetary values are presented in nominal terms*

(b) ***Substitution of Data into Model Functions and Calculations***

To solve the model, the revenue and cost functions were first formulated for:

Scenario I: Competition between the conventional (thermal) and solar renewable power plants

Scenario II: Competition between the conventional (thermal) and wind renewable power plants.

Based on these functions, the profit functions of each power plant were then derived.

Subsequently, by optimizing the profit functions, the follower's reaction function, as well as the optimal production quantities and Stackelberg equilibrium profits for each plant in both scenarios, were obtained.

In the next step, the level of social welfare was calculated before and after the simultaneous implementation of PFR and REC policies in both scenarios.

Finally, by graphical presentation, interpretation, and comparative analysis of the results, the effects of the combined policies on the competitiveness of solar and wind renewable plants against the conventional unit were evaluated.

In line with the methodological explanation in Section 4.3.1 and based on Equation (6), the profit function and its components for the conventional (leader) power plant, before and after the implementation of the Power Fuel Rate (PFR) policy, were constructed.

By substituting the relevant data from Table (2) and performing the calculations, the profit values for this plant were derived as presented in Table (3):

$$\pi_i = \left(P_0 - \alpha(Q_i + Q_{j\_Solar})\right)Q_i - C_{fi} - (PFR \times C_{fs} \times Q_i) \quad (19)$$

Table 3. Calculated Profit Values for Damavand Combined-Cycle Power Plant Before and After PFR Implementation

Variable ↓ / Year →	2020	2021	2022	2023
Profit of the Leader Power Plant Before PFR Implementation	7,534,879	18,836,043	13,475,539	5,165,304
Profit of the Leader Power Plant after PFR Implementation	7,338,626	18,344,966	12,206,447	1,782,904

Source: *Research calculations based on the Stackelberg competition model. Million Rials*

In accordance with the modeling steps described in Section 4.3.2, the profit function of Ghadir Mehriz Solar Power Plant as the follower in Scenario I and the profit function of Binaloud Wind Power Plant as the follower in Scenario II were formulated based on Equation (10). By substituting the relevant parameters into the model, the profit levels of the renewable followers were obtained for both scenarios and are summarized in Table (4).

For the solar renewable plant:

$$\pi_{j\_Solar} = \left(P_0 - \alpha(Q_i + Q_{j\_Solar})\right)Q_{j\_Solar} + REC.\,Q_{j\_Solar} - C_{vj\_Solar}.\,Q_{j\_Solar} \quad (20)$$

For the wind renewable plant:

$$\pi_{j\_Wind} = \left(P_0 - \alpha(Q_i + Q_{j\_Wind})\right)Q_{j\_Wind} + REC.\,Q_{j\_Wind} - C_{vj\_Wind}.\,Q_{j\_Wind} \quad (21)$$

Table 4. Calculated Profit Values for the Follower Power Plant under Scenarios I and II (before and after REC implementation)

Scenarios	Variable ↓ / Year →	2020	2021	2022	2023
I	Profit of Ghadir Solar Power Plant before REC implementation	5,765,816	13,251,040	21,510,872	22,140,014
	Profit of Ghadir Solar Power Plant after REC implementation	6,764,460	14,000,350	22,202,997	22,773,488
II	Profit of Binaloud Wind Power Plant before REC implementation	76,596	246,823	53,380,566	56,213,458
	Profit of Binaloud Wind Power Plant after REC implementation	88,961	260,386	54,964,749	57,664,059

Source: *Research calculations based on the Stackelberg competition model. Million Rials*

By differentiating the leader's profit function with respect to Q_i and optimizing, and then substituting the relevant parameter values from Table (2), the Stackelberg equilibrium output for the Damavand combined-cycle (conventional) power plant is obtained as shown in Table (5), consistent with Equation (11):

$$Q_i^* = \frac{P_0 - C_{fs}.PFR - \alpha Q_{j\_Solar}}{2\alpha} \quad (22)$$

Table 5. Calculated values of Q_i^* for the Damavand conventional power plant

Variable ↓ / Year →	2020	2021	2022	2023
Optimal Stackelberg equilibrium production of the leader	74,439,854	158,843,484	78,100,374	39,174,618

Source: *Research calculations based on the Stackelberg competition model.MWh*

Next, by substituting the computed values of Q_i^* into the follower's reaction function for both scenarios (in accordance with Equation (13)) and inserting the relevant parameters from Table (2), the Stackelberg equilibrium outputs of the renewable followers are obtained (reported in Table (6)) as follows:

For Scenario I (Solar follower): $Q_{j\_Solar}^* = \frac{P_0 + REC - C_{vj} - \alpha Q_i^*}{\alpha}$ (23)

For Scenario II (Wind follower): $Q_{j\_Wind}^* = \frac{P_0 + REC - C_{vj} - \alpha Q_i^*}{\alpha}$ (24)

Table 6. Calculated values of $Q^*_{j\_Solar}$ and $Q^*_{j\_Wind}$ for Ghadir Mehriz solar power plant and Binaloud wind power plant

Scenarios	**Variable ↓ / Year →**	**2020**	**2021**	**2022**	**2023**
I	Optimal Stackelberg equilibrium production of the follower power plant (Ghadir solar)	24,500	23,114	23,795	22,616
II	Optimal Stackelberg equilibrium production of the follower power plant (Binaloud wind)	378	469	58,485	56,864

Source: *Research calculations based on the Stackelberg competition model.Million Rials*

Finally, based on the Stackelberg equilibrium output levels derived for both the leader and follower power plants, the market equilibrium price was calculated according to:

- For Scenario I (Solar): $P^*_{\mathrm{I}} = P_0 - \alpha(Q^*_i + Q^*_{j\_Solar})$ (25)
- For Scenario II (Wind): $P^*_{\mathrm{II}} = P_0 - \alpha(Q^*_i + Q^*_{j\_Wind})$ (26)

By substituting the corresponding parameter values from Table (2) and the computed optimal outputs, the equilibrium prices were determined and are reported in Table (7).

Scenarios	Variable ↓ / Year →	2020	2021	2022	2023
I	Stackelberg equilibrium price (P^*_{I})	238,593	581,830	913,495	990,104
II	Stackelberg equilibrium price (P^*_{II})	238,642	581,875	913,287	989,899

Source: *Research calculations based on the Stackelberg competition model.Million Rials*

Based on the computed Stackelberg equilibrium values of Q^*_i, $Q^*_{j\_Solar}$, $Q^*_{j\_Wind}$, P^*_{I}, and P^*_{II}, the equilibrium profits of both the leader and the follower units were calculated for Scenario I (Solar) and Scenario II (Wind). The results of these calculations are presented in Table (8), reflecting the Stackelberg equilibrium outcomes for both leader and follower under the two policy scenarios.

Table 8. Values of π^*_i,$\pi^*_{j\_Solar}$, and $\pi^*_{j\_wind}$ under the simultaneous implementation of PFR and REC policies

Scenarios	Variable ↓ / Year →	2020	2021	2022	2023
both scenarios	Stackelberg profit of Damavand combined-cycle power plant	7,338,626	18,344,966	12,206,447	1,782,904
I	Stackelberg profit of Ghadir Mehriz solar power plant	6,764,461	14,000,350	22,202,997	22,773,488
II	Stackelberg profit of Binaloud wind power plant	88,961	260,386	54,964,749	57,664,059

Source: *Research calculations based on the Stackelberg competition model. Million Rials*

(c) *Social Welfare under the Joint Implementation of PFR & REC*

In this step, following Equation (17), consumer surplus (CS) was first computed using the parameter values reported in Table (2). Subsequently, the social welfare level was estimated under both scenarios. Accordingly, we have:

For Scenario I (Solar follower):

$$CS_{\text{I}} = P_0\left(Q_i^* + Q_{j\_Solar}^*\right) - \frac{\alpha}{2}\left(Q_i^* + Q_{j\_Solar}^*\right)^2 - P^*\left(Q_i^* + Q_{j\_Solar}^*\right) \tag{27}$$

For Scenario II (Wind follower):

$$CS_{\text{II}} = P_0\left(Q_i^* + Q_{j\_wind}^*\right) - \frac{\alpha}{2}\left(Q_i^* + Q_{j\_wind}^*\right)^2 - P^*\left(Q_i^* + Q_{j\_wind}^*\right) \tag{28}$$

Table 9. Consumer surplus under the simultaneous implementation of PFR and REC in Scenarios I and II

Scenarios	Variable ↓ / Year →	2020	2021	2022	2023
I	Consumer surplus (before the simultaneous implementation of REC & PFR)	999,527	1,050,345	655,553	82,970
	Consumer surplus (after the simultaneous implementation of REC & PFR)	5,547,218	25,253,547	18,324,322	4,625,561
II	Consumer surplus (before the simultaneous implementation of REC & PFR)	999,526	1,050,345	655,550	82,967
	Consumer surplus (after the simultaneous implementation of REC & PFR)	5,552,079	25,280,619	18,338,145	4,632,038

Source: *Research calculations based on the Stackelberg competition model. Million Rials*

Based on the calculated values of consumer surplus (CS) and the Stackelberg equilibrium profits of the leader and follower units (π_i^* , $\pi_{j\_Solar}^*$, $\pi_{j\_wind}^*$), the social welfare level was estimated according to the social welfare function defined in Equation (15). Thus, we have:

- For Scenario I (Solar): $w_{\text{I}} = CS_{\text{I}} + \pi_i + \pi_{j\_Solar}$
- For Scenario II (Wind): $w_{\text{II}} = CS_{\text{II}} + \pi_i + \pi_{j\_wind}$

This formulation enables the quantitative assessment of welfare impacts resulting from the joint implementation of PFR and REC policies, providing a comprehensive measure of economic efficiency across the two renewable technology scenarios.

Table 10. Social welfare affected by the simultaneous implementation of PFR & REC in Scenarios I and II

Scenarios	Variable ↓ / Year →	2020	2021	2022	2023
I	Social welfare (before the simultaneous implementation of REC & PFR)	14,300,222	33,137,428	35,641,965	27,388,289
	Social welfare (after the simultaneous implementation of REC & PFR)	23,400,641	89,756,576	77,155,012	36,614,930
II	Social welfare (before the simultaneous implementation of REC & PFR)	8,611,001	20,133,211	67,511,655	61,461,729
	Social welfare (after the simultaneous implementation of REC & PFR)	16,730,003	76,043,648	109,930,587	71,511,978

Source: *Research calculations based on the Stackelberg competition model. Million Rials*

(d-1) ***Graphical Analysis and Economic Interpretation of the Model Results***

The results of the Stackelberg equilibrium model for the two competitive scenarios,

(1) the competition between Damavand Combined Cycle Power Plant and Ghadir Mehriz Solar Power Plant, and

(2) the competition between Damavand Combined Cycle Power Plant and Binaloud Wind Power Plant,

demonstrate that the joint implementation of Renewable Energy Certificate (REC) and Power Fuel Rate reform (PFR) policies exerts significant effects on production levels, profitability, and overall social welfare.

In general, a comparison of the two scenarios reveals that although conventional power plants maintain a production advantage in the short run, government support policies create a new competitive pathway for solar and wind power plants. This structural shift is clearly reflected not only in the profitability and market share of renewable units but also in the improvement of social welfare.

The results underscore that REC strengthens the economic position of renewable producers through additional revenue streams, while PFR realigns the cost structure of fossil-based generation, thereby enhancing the relative competitiveness of renewable energy sources.

From a policy perspective, this combination represents an effective transitional strategy for gradually shifting from fossil fuels toward clean energy sources in Iran and comparable energy markets. It highlights how well-calibrated pricing and certificate mechanisms can facilitate market-driven decarbonization while preserving economic efficiency.

The case study analysis also reveals that the qualitative behavior of generating units and welfare impacts remain consistent with the patterns identified through both sensitivity and Monte-Carlo simulations. In particular, the directionality of responses to REC and PFR continues to align with theory: increasing REC strengthens renewable output and revenue, while raising PFR reduces thermal output and shifts profitability in favor of renewable units. This consistency across deterministic, stochastic, and case-based settings confirms that the model does not exhibit excessive sensitivity to parametric variation and possesses strong structural robustness.

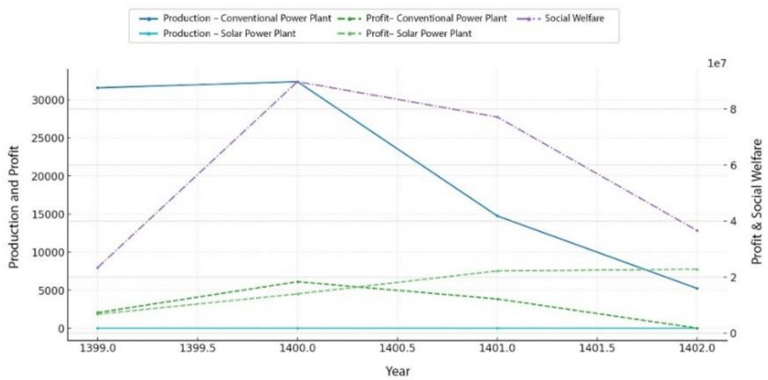

Figure 15. Trends in Production and Profit of the Selected Solar and Conventional Power Plants, and Social Welfare following the Simultaneous Implementation of PFR and REC

Source: *Authors' research findings*

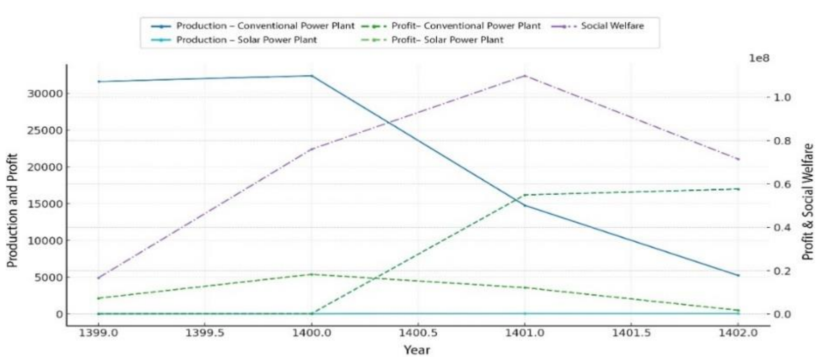

Figure 16. Trends in Production and Profit of the Selected Wind and Conventional Power Plants, and Social Welfare following the Simultaneous Implementation of PFR and REC

Source: *Authors' research findings*

(d-2) ***Comparative Dynamics of Production, Profitability, and Social Welfare, Before and After the Implementation of Supportive Policies (PFR & REC)***

This section separately analyzes the evolution of production, profitability, and social welfare of the selected power plants before and after the joint implementation of the two government support instruments: the Renewable Energy Certificate (REC) and the Power Fuel Rate reform (PFR).

1. ***Production Trend***

The Damavand Combined Cycle Power Plant maintains its quantitative production advantage over the entire period. However, the cost pressure induced by PFR generates a fluctuating and downward trajectory in its production levels.

In contrast, the Ghadir Mehriz Solar Power Plant and Binaloud Wind Power Plant, supported by the REC policy, manage to stabilize their equilibrium market share and record a significant increase in production toward the end of the period.

This pattern aligns well with the economic logic of renewable energy certificates: REC raises the effective marginal revenue of renewable units, encouraging a production shift from fossil-based generation toward clean technologies.

Although renewable production remains lower than that of conventional plants in absolute terms, the policy package enhances their competitiveness in the market.

2. ***Profitability Trend***

The profitability of Damavand Combined Cycle Power Plant shows an initial short-term increase in both scenarios, followed by a notable decline in later years. This is primarily driven by fuel cost pressure due to PFR, which raises equilibrium prices in favor of the follower.

Meanwhile, the solar and wind renewable power plants exhibit a steady and upward profit trajectory under the REC policy. In some years, their profitability surpasses that of the conventional leader, illustrating the critical role of REC in strengthening revenue streams and creating investment incentives in renewable energy.

3. ***Social Welfare Trend***

In both scenarios, total social welfare increases substantially after policy implementation, with the gap between pre- and post-policy levels widening over time. This trajectory confirms the effectiveness of the combined PFR–REC policy mix in:

- Enhancing economic efficiency,
- Reducing environmental externalities, and
- Promoting a more equitable distribution of market benefits.

In essence, the joint application of REC and PFR not only improves the competitive position of renewable power plants, but also generates broad positive welfare effects, strengthening the long-term sustainability of the national energy system.

These case-based findings are broadly consistent with European and Chinese evidence showing that REC markets support renewable deployment only when market design ensures adequate price formation (Liu et al., 2024; Bösch, 2025).

Likewise, the positive welfare gains observed under stronger PFR implementation replicate the outcomes of previous simulation studies linking fossil-fuel price rationalization to higher renewable uptake (Hashemizadeh et al., 2024; Gholami et al., 2024). Together, these parallels reinforce the external validity of the model, suggesting its relevance for similar subsidy-dominant energy systems.

Overall, the theoretical consistency of the results, their compatibility with international empirical literature, and the robustness demonstrated across sensitivity, stochastic, and case-based tests collectively affirm the model's validity. Importantly, the findings demonstrate that implementing PFR alone yields partial market correction, while the combined PFR-REC mechanism induces a stronger equilibrium shift toward renewable deployment, improves profitability, and enhances welfare. These insights are directly aligned with the broader energy-transition literature emphasizing that hybrid policy portfolios yield superior decarbonization and investment outcomes compared to isolated instruments.

6. Conclusion and Policy Recommendations

6.1 Overall Conclusion

This study evaluated the competitiveness of renewable power plants relative to conventional thermal units in Iran's electricity market using a Stackelberg game-theoretic model supported by Monte Carlo simulation and sensitivity analysis. Real operational data from three representative power plants were used to examine the combined effects of Power Fuel Rate (PFR) reform and Renewable Energy Certificates (REC) on market behavior.

The results demonstrate that implementing PFR and REC together substantially increases the output, profitability, and market share of renewable units, while thermal units experience gradual reductions in profit and production due to rising fuel costs. These combined policies improve resource allocation, strengthen incentive structures, and contribute to higher levels of social welfare. The robustness of these findings was confirmed through sensitivity testing and Monte Carlo simulations.

The analysis further reveals that the structural dominance of thermal generation, reinforced by extensive subsidies, limits renewable expansion unless supported by coordinated pricing and incentive reforms. This insight is especially relevant for developing economies where similar institutional and financial barriers persist. The mechanisms simulated in the Stackelberg setting, cost adjustment through PFR and revenue enhancement through REC are broadly applicable in markets where a few dominant thermal generators coexist with emerging renewable entrants.

By integrating PFR and REC within a Stackelberg framework, this study analyzes the strategic behavior of thermal and renewable power plants under simultaneous policy intervention and demonstrates that the joint application of these mechanisms reduces the market dominance of thermal units, enhances renewable generation, and raises overall social welfare. The contributions of the study consist of combining these policy tools in a unified analytical structure, developing an endogenous REC estimation method suited to non-market environments, incorporating sensitivity and Monte-Carlo robustness checks, and validating the model using real operational data from three representative power plants. These elements collectively strengthen the analytical and practical relevance of the findings and position the study as a substantive addition to the literature.

6.2 Policy Recommendations

The results of this study provide several practical policy insights for regulators:

First, integrating PFR and REC generates complementary effects that enhance market efficiency and improve welfare outcomes, highlighting the superiority of coordinated policy design over isolated instruments.

Second, sensitivity analysis shows that moderate, data-driven policy intensities are more effective and stable, supporting a measured transition path rather than abrupt interventions.

Third, the confirmed robustness under uncertainty, through Monte Carlo simulations, indicates that hybrid policy packages can perform reliably even in markets with limited regulatory experience.

Finally, these findings are directly relevant to developing economies like Iran, where coordinated incentives are essential to mobilize investment, reduce dependency on fossil fuels, and support long-term transition objectives.

The analytical outcomes of this study yield several concrete policy implications for energy-sector regulators and decision-makers. First, the joint application of REC and PFR policies demonstrates a complementary effect that enhances both market efficiency and social welfare, suggesting that integrated policy design can outperform single-instrument approaches. Second, sensitivity analysis reveals that moderate and data-driven policy intensities are preferable to extreme values, as they ensure cost-effective transition without destabilizing market equilibrium. Third, the robustness confirmed through Monte Carlo simulations indicates that hybrid policy structures remain effective under uncertainty, underscoring their applicability in energy markets with limited institutional experience. Finally, these insights hold direct relevance for developing economies such as Iran, where creating coordinated incentive schemes can accelerate renewable investment, reduce fossil fuel dependency, and support long-term energy transition goals.

Based on these insights, the following actions are recommended:

1. Gradual reform of fuel pricing and subsidy removal, with redirected revenues supporting renewable infrastructure development.
2. Establishment of a credible REC market, including a central registry, MRV protocols, trading mechanisms, and purchase obligations to strengthen investor confidence.
3. Institutional and legal reforms, streamlining licensing, enabling financial guarantees, and creating stable long-term policy signals.

4. Eliminating competitive distortions faced by renewables through phasing out preferential pricing and rents for thermal units.

5. Upgrading grid infrastructure to enable higher renewable integration and reduce curtailment risks.

6.3 Future Research Directions

Future studies may complement the present work by assessing additional policy tools, such as concessional finance, tax incentives, and insurance schemes and by employing more advanced modeling approaches including multi-agent frameworks, agent-based modeling, and CGE models. Collecting granular operational data from renewable and thermal plants would also enhance empirical assessments. Furthermore, comparative analyses of alternative competition frameworks (e.g., Cournot, Bertrand, auction models) could help refine market design for different stages of renewable development.

6.4 Final Remarks

The findings confirm the essential role of coordinated policy mechanisms, specifically fuel price reform combined with renewable support instruments in strengthening renewable competitiveness and advancing Iran toward a low-carbon electricity system. The Stackelberg-based analytical framework proposed here is well-suited to Iran's institutional structure and can be adapted to other developing economies with similar characteristics, offering a practical tool for evidence-based policymaking.

Author Contributions

Conceptualization, investigation, formal analysis, and writing of the original draft: Majid Raeofmehr; Supervision and methodological guidance: Zeynolabedin Sadeghi; Scientific consultation: Seyed Abdolmajid Jalaei. All authors have read and approved the final version of the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data used in this study were obtained from publicly accessible statistical platforms and official databases, including the SATBA statistical portal (https://amar.satba.gov.ir/), Tavanir publications (http://www.tavanir.org.ir), the IGMC Statistical Center (https://www.igmc.ir/statistical-center), and the CODAL disclosure system (https://www.codal.ir/). Additional plant-level information was sourced from publicly available documents of the relevant power companies, such as Damavand Power Generation Company (https://damavandpg.co.ir/). All policy parameters and cost-based estimations were derived from official reports and methodological calculations described in the paper.

Acknowledgements
Not applicable

References

Ahmed, Z., Ahmad, M., Rjoub, H., Kalugina, O. A., & Hussain, N. (2022). Economic growth, renewable energy consumption, and ecological footprint: Exploring the role of environmental regulations and democracy in sustainable development. Sustainable Development, 30(4), 595–605.

Andres, P. (2024). Adapting to competition: Solar PV innovation in Europe and the impact of the 'China shock'. Environmental and Resource Economics, 87(11), 3095–3129. https://doi.org/10.1007/s10640-024-00904-8

Bichuch, M., Dayanıklı, G., & Laurière, M. (2024). A Stackelberg mean field game for green regulator with a large number of prosumers. In 2024 IEEE Conference on Control Technology and Applications (CCTA) (pp. 1–8). IEEE. https://doi.org/10.1109/CCTA60798.2024.11108013.

Bo, S., & Tao-zhen, H. (2021). Study on green production decision of heterogeneous power generators under renewable portfolio standards. Operations Research and Management Science, 30(11), 6.

Bösch, J. (2025). Green signals? Assessing price dynamics in the European renewable energy certificate market. Renewable Energy Economics, 61, Article 101852. https://doi.org/10.1016/j.renee.2025.101852 (assuming standard Elsevier style; adjust if different)

Brusiło, P., & Tomski, A. (2025). The dynamic panel gravity model of trade in photovoltaic cell panels in the Asia–Pacific region. Quality & Quantity. Advance online publication. https://doi.org/10.1007/s11135-025-02265-w.

Calikoglu, U., & Aydinalp Köksal, M. (2022). Green electricity and Renewable Energy Guarantees of Origin demand analysis for Türkiye. Energy Policy, 170, Article 113229. https://doi.org/10.1016/j.enpol.2022.113229

Chen, D., Zhang, Y., Hong, X., Chen, Q. F., & Zhang, J. (2022). Non-cooperative game and cooperative operation of multi-level supply chain under background of carbon emission reduction. IEEE Access, 10, 33015–33025. https://doi.org/10.1109/ACCESS.2022.3153000

Cheng, L., Yu, F., Huang, P., Liu, G., Zhang, M., & Sun, R. (2025). Game-theoretic evolution in renewable energy systems: Advancing sustainable energy management and decision optimization in decentralized power markets. Renewable & Sustainable Energy Reviews, 217, Article 115776. https://doi.org/10.1016/j.rser.2025.115776

Du, J., Shen, Z., Song, M., & Vardanyan, M. (2023). The role of green financing in facilitating renewable energy transition in China: Perspectives from energy governance, environmental regulation, and market reforms. Energy Economics, 120, Article 106595. https://doi.org/10.1016/j.eneco.2023.106595

Fang, M., Li, R., & Zhao, X. (2024). Improving new energy subsidy efficiency considering learning effect: A case study on wind power. Journal of Environmental Management, 357, Article 120647. https://doi.org/10.1016/j.jenvman.2024.120647

Gholami, M., Sadeghi, Z., Jalaee Esfandabadi, S. A. M., & Nejati, M. (2024). Economic and environmental effects of energy transition in Iran by 2050: A dynamic multi-regional computable general equilibrium model. Iranian Journal of Economic Studies, 12(2), 551–584.

Hashemizadeh, A., Ju, Y., & Bambaei Abadi, F. Z. (2024). Policy design for renewable energy development based on government support: A system dynamics model. Applied Energy, 376, Article 124331. https://doi.org/10.1016/j.apenergy.2024.124331

Helgesen, P. I., & Tomasgard, A. (2018). An equilibrium market power model for power markets and tradable green certificates, including Kirchhoff's laws and Nash-Cournot competition. Energy Economics, 70, 270–288. https://doi.org/10.1016/j.eneco.2017.12.013

Jalaee, M. S., Sadeghi, Z., Jalaee, S. A., Nejati, M., & Yaghoobi, M. A. (2025). An analysis of macroeconomic responses to energy price reforms along Iran's decarbonization path: A computable general equilibrium (CGE) modeling approach. Iranian Journal of Economic Studies, 13(2), 515–542.

Ji, C.-Y., Tan, Z.-K., Chen, B.-J., Zhou, D.-C., & Qian, W.-Y. (2024). The impact of environmental policies on renewable energy investment decisions in the power supply chain. Energy Policy, 186, Article 113987. https://doi.org/10.1016/j.enpol.2024.113987

Langer, L., Brander, M., Lloyd, S. M., Keles, D., Matthews, H. D., & Bjørn, A. (2024). Does the purchase of voluntary renewable energy certificates lead to emission reductions? Journal of Cleaner Production, 478, Article 143791. https://doi.org/10.1016/j.jclepro.2024.143791

Lin, B., & Huang, C. (2022). Analysis of emission reduction effects of carbon trading: Market mechanism or government intervention? Sustainable Production and Consumption, 33, 28–37. https://doi.org/10.1016/j.spc.2022.06.008

Liu, D., Jiang, Y., Peng, C., Jian, J., & Zheng, J. (2024). Can green certificates substitute for renewable electricity subsidies? A Chinese experience. Renewable Energy, 222, Article 119861. https://doi.org/10.1016/j.renene.2023.119861

Liu, H., & Han, P. (2024). Renewable energy development and carbon emissions: The role of electricity exchange. Journal of Cleaner Production, 439, Article 140807. https://doi.org/10.1016/j.jclepro.2023.140807

Ma, X., Pan, Y., Zhang, M., Ma, J., & Yang, W. (2024). Impact of carbon emission trading and renewable energy development policy on the sustainability of electricity market: A Stackelberg game analysis. Energy Economics, 129, Article 107199. https://doi.org/10.1016/j.eneco.2023.107199

Mohamed, E. F., Abdullah, A., Jaaffar, A. H., & Osabohien, R. (2024). Reinvestigating the EKC hypothesis: Does renewable energy in power generation reduce carbon emissions and ecological footprint? [Preprint]. Research Square. https://doi.org/10.21203/rs.3.rs-3940236/v1

Molaei, M. A., & Rezaee, H. (2016). The effect of power plant fuel price adjustment on the generation capacity of wind power plants in comparison to other power plants: A system dynamics approach. Journal of Economic Research (Tahghighat-e Eghtesadi), 51(1), 229–247.

Monavariyan, A., Vatankhah Moghaddam, S., Shah Hoseini, M. A., Vaezi, S. K., & Noorollahi, Y. (2020). Designing of policy making model of renewable energy development in Iran. Iranian Journal of Public Policy, 6(2), 115–134.

Morris, J., Reilly, J. M., & Paltsev, S. (2010). Combining a renewable portfolio standard with a cap-and-trade policy: A general equilibrium analysis (Report No. 187). MIT Joint Program on the Science and Policy of Global Change. https://dspace.mit.edu/handle/1721.1/57560

Mousavi Dorcheh, M., & Karimian Khuzani, H. (2022). Evaluating the policy mix of renewable energy development in Iran. Journal of Science and Technology Policy, 15(2), 55–74.

Nepal, R., Liu, Y., Dong, K., & Jamasb, T. (2024). Green financing, energy transformation, and the moderating effect of digital economy in developing countries. Environmental and Resource Economics, 87(12), 3357–3386. https://doi.org/10.1007/s10640-024-00922-6.

Pajooyan, J., Mohammadi, T., Esmaeelniya, A., & Ghafourian, E. (2023). Analyzing the effects of fuel price reform on electricity industry’s financial balance, employing a simulation of the function of the market. Journal of Financial Economics, 17(62), 277–316. https://sid.ir/paper/1054700/en

Panny, J., & del Río, P. (2025). Renewable energy cooperation in Europe: Taking stock and looking forward. Renewable Energy Economics, 61, Article 101820.

Song, M., Wang, Y., & Long, Y. (2022). Investment and production strategies of renewable energy power under the quota and green power certificate system. Energies, 15(11), Article 4110. https://doi.org/10.3390/en15114110

Tsao, Y.-C., Ai, H. T. T., Lu, J.-C., & Wang, C. (2024). Game theory-based electricity pricing decisions incorporating prosumer energy preferences and renewable portfolio standard. Energy, 306, Article 132418. https://doi.org/10.1016/j.energy.2024.132418

Wang, B., Li, C., Ban, Y., Zhao, Z., & Wang, Z. (2025). A multi-market equilibrium model considering the carbon–green certificate mutual recognition trading mechanism under the electricity market. Energy, 330, Article 136902. https://doi.org/10.1016/j.energy.2025.136902

Wang, H., Li, Y., & Bu, G. (2023). How carbon trading policy should be integrated with carbon tax policy, Laboratory evidence from a model of the current state of carbon pricing policy in China. Environmental Science and Pollution Research, 30(9), 23851–23869. https://doi.org/10.1007/s11356-022-23900-6.

Wu, X., Ye, Q., Chen, L., Liao, H., & Wang, W. (2024). Electricity market clearing for multiple stakeholders based on the Stackelberg game. Frontiers in Energy Research, 12, Article 1342516. https://doi.org/10.3389/fenrg.2024.1342516.

Xiang, K., Chen, J., Yang, L., Wu, J., & Shi, P. (2024). Equilibrium interaction strategies for integrated energy system incorporating demand-side management based on Stackelberg game approach. Energies, 17(14), Article 3603. https://doi.org/10.3390/en17143603.

Xu, G., Yang, M., Li, S., Jiang, M., & Rehman, H. (2024). Evaluating the effect of renewable energy investment on renewable energy development in China with panel threshold model. Energy Policy, 187, Article 114029. https://doi.org/10.1016/j.enpol.2024.114029