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Optimization of Renewable Energy Investment Costs in the Private Sector Considering Government Support Policies

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ABSTRACT

Global experience indicates that the implementation of attractive tariff schemes has led to an increased share of bioenergy and renewable energy sources in the energy distribution network. When properly designed, such policies can ensure cost recovery for producers and investors in the renewable energy sector. Accordingly, this paper seeks to propose a model, based on a game theory approach, to maintain the profit levels of stakeholders. In this context, the leader model incorporates government subsidies, while the follower model represents the profit levels of renewable energy producers. The proposed model aims to identify optimal subsidy policies by considering various factors, thereby sustaining the private sector's motivation to invest in renewable energy production. The results demonstrate that an increase in government support through different policy interventions leads to higher profit margins for companies. On the other hand, as the number of renewable energy producers (companies) grows, the total government subsidies increase, prompting policymakers to implement measures that enhance market competition and thereby reduce corporate profitability.

Keywords: *Renewable Energy, Investment Cost, Energy Production, Game Theory, Stackelberg*

1. Introduction

Global warming, population growth, and the depletion of fossil fuels have prompted governments to maximize the use of renewable energy sources (Zhang et al., 2022). Statistics from the past two decades also indicate a significant increase in the adoption of renewable energy capacity among countries. For example, solar power generation in the United States rose from 495 GWh in 2000 to 145,598 GWh in 2022. The growing utilization of renewable energy is similarly evident in other developed nations such as China, India, and Brazil, according to available data. There is a rising emphasis on the use of renewable energy in both developed and developing countries. More specifically, the unique advantages of renewable and clean energy sources—such as environmental compatibility and inexhaustibility—compared to fossil fuels have driven increased demand for these alternative resources. Projections suggest that in the coming years, the use of clean energy will surpass traditional methods based on fossil fuel consumption (Khalili et al., 2025; Xie & Lin, 2025).

In the 1980s and early 1990s, only a few countries around the world had tools and policies in place to support the development of renewable energy. However, between 1998 and 2005—and especially from 2005 to 2010—many societies across the globe began formulating strategies and policies aimed at promoting bioenergy-based systems. The number of countries with targets or policies supporting such energy sources increased from 55 in 2005 to 119 by early 2011(Lin & Zhu, 2019; Murshed, 2020). Many of these policies focused on the renewable energy sector, resulting in significant impacts on market development, increased investment, and the growth of the renewable energy industry in these countries(Yi et al., 2019).

The impacts of these policies have not been uniform in practice, and some have proven more effective than others in advancing renewable energy, particularly bioenergy. The success of such policies depends not only on the choice of policy itself but also on how it is formulated and implemented. Overall, the global renewable energy market continues to experience fluctuations, as policymakers still face the challenge of setting achievable and realistic targets and linking them to appropriate long-term policy mechanisms to meet those goals (Lund, 2009).

The most important and commonly adopted forms of renewable energy policies worldwide include the following:

1. Setting guaranteed feed-in tariffs for renewable electricity
2. Establishing a renewable portfolio standard (RPS) to determine the share of renewables in the national energy mix
3. Providing upfront capital subsidies and grants
4. Offering investment tax credits
5. Granting tax exemptions or value-added tax (VAT) exemptions
6. Providing production tax credits (PTC) for electricity generation
7. Conducting public tenders or auctions
8. Implementing net metering schemes
9. Issuing green certificate standards

The use of government support mechanisms for renewable energy production has attracted considerable attention from researchers around the world, leading to a wide range of studies in this field. For instance, Marousek et al. (Maroušek et al., 2015) evaluated the overall effectiveness of subsidy policies implemented by the European Union for various renewable energy sources that received subsidies during the first and second decades of the 21st century. Zhao et al. (Zhao et al., 2014) assessed the costs and benefits of renewable energy subsidies in China. Their analysis revealed that the average subsidy cost was 0.248 yuan/kWh between 2006 and April 2011, distributed among different categories of renewable energy. Yang et al. (Yang et al., 2019) investigated the effect of government subsidies on renewable energy investment. Their findings indicated that government subsidies have a positive threshold effect on renewable energy investment in China. When energy intensity and credit availability are higher, and the level of economic development is below a certain threshold, the share of government subsidies in renewable energy investment significantly increases. Moreover, monetary subsidies and tax incentive policies can promote investment in renewable energy, with tax incentives having a more substantial impact. Government subsidies are also identified as the primary driving force behind the development of small, medium, and micro-sized renewable energy enterprises. Myojo and Ohashi (Myojo & Ohashi, 2018) proposed an empirical framework aimed at incentivizing renewable energy production, with a specific focus on consumer subsidies for the installation of residential solar photovoltaic systems in Japan. In another study, Martelli et al. (Martelli et al., 2020) introduced a novel optimization approach based on a real-world (bi-level) decision-making process to determine optimal renewable energy subsidies and carbon taxes for small- and medium-scale multi-energy systems. Finally, Chang et al. (Chang et al., 2020) measured net technical efficiency, scale efficiency, and overall investment efficiency of input-output factors for renewable energy producers using the Data Envelopment Analysis (DEA) method, specifically the Bunker-Charnes-Cooper (BCC) model. Their study explicitly examined the impact of government subsidies and tax incentive policies on the investment performance of renewable energy companies using panel data from Chinese renewable energy producers.

The implementation of attractive tariffs and subsidies by governments for renewable energy producers can lead to an increased share of renewable energy in the power distribution network. However, such policies must be designed to both ensure cost recovery for producers and investors in the renewable energy sector, and minimize the amount of subsidies provided. One effective approach to achieving this balance is the use of evolutionary game theory. Several important studies have already applied evolutionary game theory in the context of renewable energy. For example, Liu et al. (Liu et al., 2021) proposed a game-theoretic modeling framework with a strategic solution to optimize the design of multi-carrier energy systems and renewable subsidy strategies. Yi et al. (Yi et al., 2019) developed an evolutionary game theory and system dynamics (SD) model to examine generator strategies in China's wind power industry. Their simulations analyzed the evolution of strategies and the effects of project parameters (subsidies, quotas, and penalties) on power generators and the operations of the tradable green certificate (TGC) market. Zhao et al. (Zhao et al., 2020) developed a game-theoretic model considering relevant stakeholders, including government subsidy policies, producers' environmental quality standards, and customers' environmental awareness (CEA). The study analyzed the factors influencing the strategies of both governments and producers. Fathi and Bakhshoudeh (Fathi & Bakhshoodeh, 2021) examined the economic–environmental effects of targeted energy subsidy policies in Iran's meat market using a game theory framework. They modeled players' welfare using an equilibrium displacement model and considered environmental losses (or benefits) resulting from greenhouse gas emissions based on the behaviors of three players: producers, consumers, and the government. Zhang et al. (Su et al., 2021) studied the effects of three different subsidy schemes using game theory in an agricultural supply chain consisting of a low-cost and a high-cost firm. Their model incorporated new dimensions such as cost factors, market structure, product differentiation, and competition.

The conducted review reveals that in recent years, game theory has emerged as an optimal approach for designing government support policies and identifying factors contributing to cost reduction. Accordingly, this study employs a multi-source renewable energy production approach and applies game theory to analyze and optimize energy production costs for residential buildings. It is worth noting that the proposed model is an innovative framework in the field of building energy, which takes into account the impact of government support policies and the level of allocated subsidies. The main objective of this paper is to take a step toward advancing energy foresight, which comprises a set of efforts aimed at exploring resources, patterns, and drivers of change or stability to envision and plan for possible futures. This approach highlights how future realities (tomorrow) emerge from the dynamics of change or continuity in the present (today).

2. Evolutionary Game Theory

As previously stated, the implementation of attractive tariffs and subsidies by the government for renewable energy producers will lead to an increased share of renewable energy in the power distribution network. However, such policies must be designed in a way that both guarantees cost recovery for producers and investors in renewable energy and minimizes the amount of subsidy provided. Accordingly, this paper presents, for the first time, an investment cost model based on game theory, in which the government's support policies are considered as the leader and renewable energy producers as followers. Game theory involves a set of decisions made by various actors, each seeking to optimize their own payoff function. Consequently, game theory offers a more realistic simulation of stakeholder-driven behavior. It can be highly beneficial for planning, policymaking, and system design, providing insights that are not attainable through traditional engineering methods. In this study, game theory is employed to model government support policies aimed at reducing investment costs in renewable energy.

2.1. Stackelberg Game Model

One of the approaches within evolutionary game theory is the Stackelberg game model, which is commonly used for economic purposes. In the Stackelberg game, the first player—referred to as the leader (or upper-level player)—

makes a move first, followed by the second player—the follower (or lower-level player). These types of games are also known as leader–follower games. This equilibrium model was first introduced by Stackelberg in 1934 (see (Brown et al., 2006). In such games, the first player assumes the role of the leader, and the second player follows the leader's move. The players observe the leader's strategy and then respond accordingly. Therefore, the optimal strategy of the follower is precisely the one predicted by Stackelberg theory (Koh et al., 2020). The structure of the Stackelberg model can be illustrated by assuming two service providers in a default market, offering identical goods or services with equal demand and value within a shared community. Given that both providers operate under the same market conditions, competition arises in terms of increasing individual production levels and maximizing their own profits.

In Stackelberg game theory terminology, the players are referred to as the leader and the follower, who act sequentially. The leader is typically the larger, more established producer or the provider of a higher-quality product, placing them in a superior market position. Consequently, the leader is granted the first-move advantage and is thus referred to as the market leader. Based on this structure, the follower observes and evaluates the leader's decision before determining their own optimal production level. Any player with the potential to gain a competitive advantage may assume the role of the leader, thereby increasing the likelihood of their participation in the market competition.

Heinrich von Stackelberg, a German economist, developed a theory concerning equilibrium in oligopolistic markets. In his model, it is assumed that there are only two groups of firms, each of which can act as either a leader or a follower. If the firms have knowledge of each other's cost functions as well as the market demand function, the follower firm maximizes its profit based on its cost function and the market demand (Koh et al., 2020). As a result of this optimization, the follower's market share is determined. Subsequently, the leader firm maximizes its own profit by incorporating the follower's response into its own profit function, also based on the cost and demand functions. Consequently, the production levels that yield maximum profit for both the leader and follower firms are determined (Salichs et al., 2019).

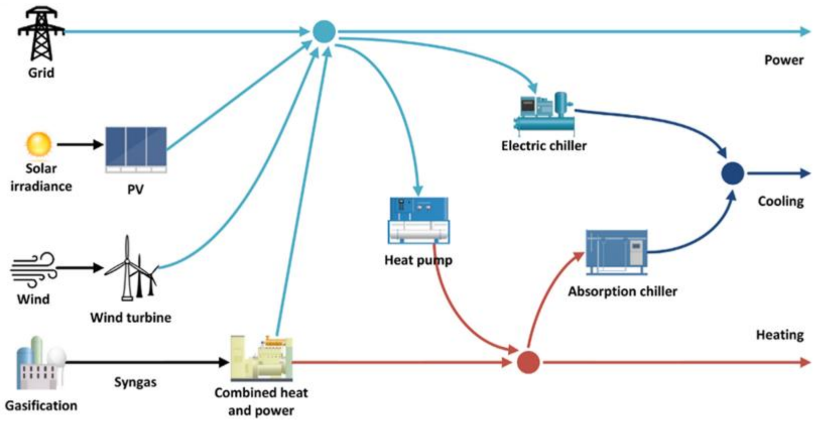
Accordingly, this paper investigates a Stackelberg leader–follower model in which the government acts as the leader and provides subsidies to private-sector producers of renewable energy. In solving the model, it is assumed that the leader's objective is to minimize total costs, while the follower's objective is to maximize the profit from renewable energy production over time. The government is thus modeled as the market leader. Based on this framework, the optimal production levels of renewable energy are determined and compared with actual data, and the government's optimal support policies are evaluated at the computed equilibrium point. In the proposed mathematical model, the leader-level objective function aims to minimize total subsidies, while the follower-level objective function seeks to maximize the profit generated from selling the produced renewable energy to the grid.

To analyze the follower segment in this framework, all technologies employed within a city—including renewable energy generation technologies and related systems such as chillers and other infrastructure required for urban energy needs—must be collectively considered. This comprehensive approach enables a more accurate and realistic estimation of the subsidies to be granted by the government. The rationale is that a portion of the power and heat generated by renewable energy technologies is consumed locally to meet the city's own energy demands, while only the surplus is sold to the national power grid. Therefore, the government must first assess whether the performance of renewable energy technologies implemented in a given region is sufficient to contribute to the national grid. Only if the government determines that the installed technologies have the capacity to support the national electricity supply will it consider providing subsidies. In simpler terms, the government does not offer subsidies to small-scale investors, such as those installing a single solar panel; subsidies are granted only when there is significant capacity to support the broader energy infrastructure.

Evaluating the overall energy performance of an entire city, rather than focusing solely on a single implemented technology within that city, is a more rational and comprehensive approach. This method ensures that all relevant aspects are considered, resulting in more realistic and accurate analyses. Fig. 1 illustrates the set of energy inputs and outputs within a city.

Figure 1

Urban Multi-Energy Network



It should be noted that not all of these technologies may be used simultaneously within a city. However, as illustrated in the figure, a city's energy and heat inputs are supplied through the national electricity grid, renewable energy technologies such as solar and wind power, and combined heat and power (CHP) systems. A portion of this energy is consumed locally for various urban needs, such as cooling (e.g., chillers), heating, and pumping systems, while the surplus energy is sold back to the national power grid.

2.2. Decision-Making Strategy for the Leader (Government)

In this strategy, the government formulates its policy for each city individually. It takes into account both the renewable energy generation capacity and the internal consumption and demand of each city before deciding whether to allocate subsidies. The government provides financial support through capital reimbursement and performance-based incentives to promote the adoption of renewable energy. The optimal subsidy amount is calculated based on the level of energy production. Capital reimbursement refers to the partial repayment of expenditures related to investments in renewable technologies—such as photovoltaic systems, combined heat and power (CHP) units, and wind turbines—at the city level. Under this strategy, to qualify for capital reimbursement, the output of each renewable energy technology must exceed a predefined threshold, which is determined by the government. For example, if the energy output of solar power plants exceeds a certain level, the government will provide support to those production units. Otherwise, no capital reimbursement will be granted for that renewable technology. The following categorization can be used to model these alternatives:

$$\begin{bmatrix} y_{i,e} \\ P_{i,e}^{nom} \geq P_{i,e}^{trs} \\ PBI_{i,e} = \beta^{R}{}_{i,e} \end{bmatrix} \vee \begin{bmatrix} \neg y_{i,e} \\ P_{i,e}^{nom} < P_{i,e}^{trs} \\ PBI_{i,e} = 0 \end{bmatrix} \quad i \in I, e \in \Theta_1 \tag{1}$$

Here, $y_{i,e}$ is a binary variable that indicates whether the output of a renewable technology e used in city iii (i.e., $P_{i,e}^{nom}$) exceeds a predefined threshold. If it does, then PBI_i represents the optimal amount of subsidy granted for that specific technology e. In essence, PBI_i refers to the performance-based incentives provided by the government to each city, based on the aggregate production of renewable energy from all technologies deployed within that city. The total subsidy allocated by the government can be formulated as a function of the amount of electricity produced. This is represented by equations (2) and (3):

$$\mathrm{PBI}_i = \sum_{e \in \Theta_1} \beta^{R}{}_{i,e}(\Pi_{i,e}) \quad i \in I \tag{2}$$

$$\Pi_{i,e} = \sum_{d \in D} \Omega_d \sum_{h \in H} P_{i,e}^{d,h} \quad i \in I, e \in \Theta_1 \tag{3}$$

where Ω_d denotes the number of days during which each renewable energy technology is utilized annually in a given city. $P_{i,e}^{d,h}$ represents the output power of technology (e) in city (i) at hour h of design day d. Additionally, D and H are the index sets representing the design days (d) and the hours (h) within each design day, respectively.

In this process, the government's objective is to provide incentives to cities to encourage greater adoption of renewable energy technologies and to reduce greenhouse gas emissions to a predetermined target level (i.e., $GHGmax$).

This objective is ensured by constraints represented in equations (4) and (5):

$$\sum_{i\in I}\sum_{e\in \Theta_1}\sum_{d\in D}\Omega_d\sum_{h\in H}\left(P_{i,e}^{d,h}+Q_{i,e}^{d,h}\right) \geq \sum_{i\in I}\sum_{e\in \Theta_1}\sum_{d\in D}\Omega_d\sum_{h\in H}L_{i,e}^{d,h} \quad (4)$$

$$\sum_{i\in I}\sum_{d\in D}\Omega_d\sum_{h\in H}\left(\sum_{e\in \Theta_1}\left(\varepsilon_e P_{i,e}^{d,h}+\varepsilon_{im}P_{i,grid}^{d,h}\right)\right) + \sum_{e\in \Theta_2}\varepsilon_e Q_{i,e}^{nom} \leq GHGmax \quad (5)$$

ε_e denotes the greenhouse gas emissions over the operational period of renewable technology e, ε_{im} represents the emission intensity of the electricity grid, and θ is the desired penetration fraction of renewable energy. $Q_{i,e}^{d,h}$ corresponds to the thermal output power of technology e in city i, while $P_{i,grid}^{d,h}$ indicates the amount of electricity imported into city i from the national grid. $Q_{i,e}^{nom}$ is the nominal capacity or size of renewable technology e in city i (i.e., the capacity of the renewable power plant installed in each city). $L_{i,e}^{d,h}$ represents the energy demand of type c, including cooling, heating, and electricity for city i, where CCC is the index set for energy carriers.

Eq. (4) states that the thermal and electrical output from the renewable technologies utilized in the studied city must exceed the local consumption demand, enabling the government to use the surplus energy to reduce reliance on fossil fuels. Eq. (5) indicates that the greenhouse gas emissions generated by the renewable technologies and other equipment producing heat and electricity within the city must be below the maximum emission level set by the government in order for subsidies to be granted to that city. If both conditions are outlined in Eqs. (4) and (5) are met for a city, the government will decide to allocate subsidies to that city.

Now, assuming that the two aforementioned conditions are met for a given city, the government aims to allocate subsidies to that city in the most optimal manner. Naturally, minimizing the amount of subsidy is in the government's favor. As such, the government seeks to ensure that its subsidies are as low as possible while still achieving its objectives. Accordingly, the leader's (government's) objective function is defined as follows (Eq. (6)):

$$C_{gov}^{sub}=\sum_{i\in I}PBI_i \quad (6)$$

2.3. Decision-Making Strategy for the Follower

In this section, the energy balance and the follower's objective function are formulated for the renewable energy technologies deployed within a city, including photovoltaic systems, combined heat and power (CHP) units, and wind turbines.

-Modeling of Renewable Energy Technology

In this thesis, it is assumed that the only technology employed in the city under study is photovoltaic solar panels. The equations related to electricity generation by photovoltaic panels are expressed as follows (Eq. (7)):

$$\begin{cases} T_{i,c}^{d,h}=T_{i,air}^{d,h}+G_i^{d,h}\left(\dfrac{NOCT-20}{0.8}\right) \\ I_{i,c}^{d,h}=G_i^{d,h}\left(I_{sc}+a\left(T_{i,c}^{d,h}-25\right)\right) \\ V_{i,c}^{d,h}=V_{oc}-bT_c^{d,h} \\ P_{i,PV}^{d,h}=\dfrac{V_{i,c}I_{i,c}}{V_{oc}I_{sc}}P_{i,PV}^{nom} \quad i\epsilon I, d\epsilon D, h\epsilon H \end{cases} \quad (7)$$

$P_{i,PV}^{d,h}$ represents the output power of the photovoltaic panels, which depends on the solar irradiance $G_i^{d,h}$. $T_{i,c}^{d,h}$ denotes the ambient temperature, NOCT is the nominal operating cell temperature of the photovoltaic panels, and $T_{i,c}^{d,h}$ is the cell temperature of the photovoltaic panels. $I_{i,c}^{d,h}$ and $V_{i,c}^{d,h}$ correspond to the current and voltage of individual photovoltaic cells, respectively. V_{oc} and I_{sc} denote the open-circuit voltage and short-circuit current, respectively. The coefficients a and b represent the temperature coefficients for voltage and current. Finally, $P_{i,PV}^{nom}$ is the nominal power rating of the photovoltaic panels installed in a city.

-Energy Balance in a Multi-Energy System (in an Urban Area)

In a city, multiple renewable energy technologies can be utilized. Additionally, some technologies within the city's integrated energy system require input fuel (such as cooling and heating systems, including chillers and pumps). It is therefore necessary to first define a relationship between the required input fuel and the corresponding output power for these types of technologies.

$$F_{i,e}^{d,h}=\frac{Q_{i,e}^{d,h}}{COP_e} \quad \forall i\epsilon I, d\epsilon D, h\epsilon H \quad (8)$$

Where $F_{i,e}^{d,h}$ denotes the input fuel required for technologies such as chillers and pumps, $Q_{i,e}^{d,h}$ represents the output power of these technologies, and COP_e is their coefficient of performance. For all the aforementioned technologies, Eqs. (9) and (10) must be satisfied to represent their output power and energy performance.

$$P_{i,e} \leq P_{i,e}^{nom} \leq P_{i,e}^{max} \quad (9)$$

$$Q_{i,e} \leq Q_{i,e}^{nom} \leq Q_{i,e}^{max} \quad (10)$$

Where $P_{i,e}^{nom}$ and $P_{i,e}^{max}$, represent the nominal and maximum electrical power capacities of the technologies used in a city, and $Q_{i,e}^{nom}$ and $Q_{i,e}^{max}$ denote the nominal and maximum cooling or heating capacities of the corresponding technologies.

As previously stated, a multi-energy system in cities is designed to supply electricity, cooling, and heating. However, the system—comprising renewable energy technologies—is configured in such a way that it generates surplus electricity beyond the city's internal demand, allowing this excess to be sold. Considering the energy needs of a city along with its production and consumption capacities, the energy balance equation for cooling and heating is defined as shown in Eq. (11).

$$\sum_{e} P_{i,e}^{d,h} - \sum_{e} F_{i,e}^{d,h} - Ex_{i,c}^{d,h} \geq L_{i,c}^{d,h} \quad \forall i,d,h,c = \{electricity\} \quad (11)$$

Moreover, the heating and cooling energy produced by the generation technologies in a city must be equal to the sum of the heating and cooling energy absorbed by the respective consumer technologies, as well as the heating and cooling demand of end-users. In Eq. (11), $Ex_{i,c}^{d,h}$ represents the excess energy or heat generated—i.e., the energy exceeding the city's consumption needs—which is sold to the government by the technologies operating within the city.

2.3. Selection of the Objective Function for the Follower

The total capital expenditure in a multi-energy system (C_i^{CAPAX}) for a given city can be calculated by summing the unit cost (ϕ_e) of each technology employed in the city, as expressed in Eq. (12).

$$C_i^{CAPAX} = \sum_{e\in\Theta} C_{i,e}^{CAPAX} = \sum_{e\in\Theta_1} \phi_e P_{i,e}^{nom} + \sum_{e\in\Theta_2} \phi_e Q_{i,e}^{nom} \quad i\epsilon I \quad (12)$$

$$C_i^{PRS} = \sum_{d\in D} \Omega_d \sum_{h\in H} c_{im} P_{i,grid}^{d,h} \quad i \in I \quad (13)$$

On the other hand, it is sometimes necessary for a city to purchase electricity from the power grid. The cost of electricity purchase from the grid ($Q\&M$) is evaluated using the electricity import price ($C_{i,f}^{Q\&M}$).

$$C_{i,f}^{Q\&M} = \sum_{e\in\Theta_1} \Psi_e P_{i,e}^{nom} + \sum_{e\in\Theta_2} \Psi_e Q_{i,e}^{nom} \quad \forall i \in I \quad (14)$$

Where Ψ_e represents the unit cost of each technology. The total annual operational cost for the city under study is obtained by summing the costs associated with electricity purchases and the operation and maintenance costs of the technology units.

$$C_i^{OPEX} = C_i^{PRS} + C_{i,f}^{Q\&M} \quad (15)$$

Each of the cities under study can sell their surplus electricity and heat to the integrated national system. The revenue generated from the sale of excess electricity and heat (C_i^{REV}) is calculated using their respective electricity market prices (cx_c).

$$C_i^{REV} = \sum_{d\in D} \Omega_d \sum_{h\in H} cx_c Ex_{i,c}^{d,h} \quad \forall i \in I \quad (16)$$

The total cost over the study period for each city is calculated by subtracting the government subsidies granted and the revenue from the sale of surplus electricity and heat from the sum of the total operational and capital expenditures, as follows:

$$C_i^{npc} = C_i^{CAPAX} + \sum_{y\in LT} C_i^{OPEX} - \sum_{y\in LT} C_i^{REV} - PBI_i \forall i \in I \quad (17)$$

3. Solution Strategy

In this approach, the government first announces its subsidy strategy, after which the cities under consideration, where investors are present, respond with their optimal reactions to the government's subsidy policy. Since the government and the cities interact strategically in this context, the most suitable solution method is the Stackelberg approach. Equation (18) formulates a bilevel (two-level) optimization problem:

$$\boldsymbol{P_0} \quad \min_{x_L, y_L} \mathrm{F}(x_L, y_L, x_F) \tag{18}$$
$$s.t.\ G_i(x_L, y_L, x_F) \le 0 \quad i = 1, \dots\dots, m$$
$$H_j(x_L, y_L, x_F) = 0 \quad j = 1, \dots\dots, n$$
$$solve\ x_F\ with\ x_L, y_L$$
$$\min_{x_F} f(x_L, y_L, x_F)$$
$$s.t.\ g_{i'}(x_L, y_L, x_F) \le 0 \quad i' = 1, \dots\dots, m'$$
$$h_{j'}(x_L, y_L, x_F) = 0 \quad j' = 1, \dots\dots, n'$$

Where x_L represents the rate of performance-based incentives. y_L is a binary variable indicating whether the size of a renewable technology is below the threshold value, in which case no capital reimbursement is provided by the government. Additionally, x_F corresponds to the size of the utilized technologies and their operational costs. The response of each studied city depends solely on the leader's (government's) action and the energy demands of that specific city, and is independent of other cities under consideration. Therefore, the objective function $\boldsymbol{P_0}$ is defined as the total net cost aggregated over all the studied cities.

In this study, the follower's objective is defined based on the leader's objective such that the follower's strategy for the objective function must depend metrically on the subsidy. One of the solutions is to minimize the total cost, where the follower's objective is to reduce expenses. Given the bilevel structure of the objective function $\boldsymbol{P_0}$, it cannot be solved directly using conventional optimization methods. However, since there are no binary variables at the lower level problem, it can be replaced by the Karush–Kuhn–Tucker (KKT) conditions. (In mathematical optimization, the KKT conditions are first-order necessary conditions for a solution to be optimal in a nonlinear convex optimization problem. When the primal problem is convex, the KKT conditions hold for optimal points of both the primal and dual problems, i.e., the duality gap is zero. The KKT conditions play a crucial role in optimization.) These conditions include the stationarity condition (Equation (19)), primal feasibility (Equations (20) and (21)), dual feasibility (Equation (22)), and the complementary slackness condition (Equation (23)), and are expressed as follows:

$$\boldsymbol{P_1} \quad \min_{x_L, y_L, x_F} \mathrm{F}(x_L, y_L, x_F) \tag{19}$$
$$s.t.\ G_i(x_L, y_L, x_F) \le 0 \quad i = 1, \dots\dots, m$$
$$H_j(x_L, y_L, x_F) = 0 \quad j = 1, \dots\dots, n$$
$$\frac{\partial f}{\partial x_L} - \sum_{i'=1}^{m'} \mu_{i'} \frac{\partial g_{i'}}{\partial x_L} - \sum_{j'=1}^{n'} \lambda_{i'} \frac{\partial h_{i'}}{\partial x_L} = 0$$
$$g_{i'}(x_L, y_L, x_F) \le 0 \quad i' = 1, \dots\dots, m' \tag{20}$$
$$h_{j'}(x_L, y_L, x_F) = 0 \quad j' = 1, \dots\dots, n' \tag{21}$$
$$\mu_{i'} \ge 0, \quad i' = 1, \dots\dots, m' \tag{22}$$
$$\mu_{i'} g_{i'}(x_L, y_L, x_F) = 0, \quad i' = 1, \dots\dots, m' \tag{23}$$

Reformulating the lower-level problem using the KKT conditions transforms the bilevel problem $\boldsymbol{P_0}$ into a single-level mixed-integer nonlinear programming problem (P1). To reduce the computational burden caused by bilinear terms, each complementary slackness condition can be linearized by introducing binary variables and applying the big-M formulation as follows:

$$\begin{cases} \mu_{i'} \le z_{i'} M_3 & i' = 1, \dots\dots, \imath \\ -g_{i'}(x_L, y_L, x_F) \le (1 - z_{i'}) M_4 & i' = 1, \dots\dots, \imath \end{cases} \tag{24}$$

where $z_{i'}$ is a binary variable indicating whether the constraint $g_{i'}(x_L, y_L, x_F)$=0 is active or not. M_3 and M_4 are sufficiently large constants used in the big-M formulation

Now, simultaneous optimization of the optimal amount of government subsidies and the costs related to the technologies used in the examined cities can be performed. The structure of the proposed algorithm for solving this problem is such that initially all possible responses provided by the leader level are considered as a set of initial candidate solutions. Then, for each of these leader responses, the follower level solves its own problem, and the resulting set of follower responses is stored as a new set corresponding to each member of the leader's solution set. Finally, each response from this new set is substituted back into the leader-level model and the objective function value is calculated. Among all the obtained results, the solution with the best numerical value is selected as the optimal solution to the problem. The steps of this algorithm can be presented as pseudocode in Table 1.

Table 1

Implementation Steps of the Proposed Algorithm for the Game-Based Method

Step	Work Process
1	Developing Various Decision-Making Strategies at the Leader Level (Determining All Possible Valid Responses)
2	The values of the leader-level decision variables for each strategy generated in Step 1 are stored in the strategy set.
3	Solving the Follower-Level Problem for Fixed Values of Leader-Level Variables Based on the Strategy Set
4	The values of the decision variables generated for the follower level in Step 3 are stored in the initial solution set.
5	Each of the decision variables in the strategy and initial solution sets is incorporated into the leader model, and the leader model is evaluated (without optimization) for each member of the sets.
6	The best response is selected as the final solution based on the value of the leader model's objective function and the structure defined in Step 5.

A critical consideration in implementing this algorithm is that, in large-scale numerical instances, it is not feasible to generate all possible responses for the leader (due to both methodological limitations and the need to reduce the computational burden, given the limited access to high-performance computing systems). As the size of the numerical examples increases, the number of potential responses at the leader level grows significantly, making the generation of all valid responses practically impossible. Therefore, it appears desirable to consider only a subset of responses as the strategies to be evaluated. However, determining an appropriate set of strategies presents a new challenge. If several suitable strategies are not selected, part of the solution space containing the optimal response may be overlooked, potentially compromising the effectiveness of the algorithm. To address this, a suitable policy for generating high-quality strategies must be established. In this study, the desired strategies are first generated using a solution-based local search algorithm, and then Steps 2 through 6 of the algorithm are implemented. Local search is a metaheuristic approach used for computationally challenging optimization problems. It is applicable to problems that can be framed as finding a solution that maximizes a given criterion among a set of feasible solutions.

4. Results and discussion

As mentioned, global experience has shown that implementing attractive tariffs leads to an increased share of bioenergy and renewable energy in the energy distribution network. If properly designed, this policy guarantees cost recovery for producers and investors in the renewable energy sector. In Section 2, game theory was examined to propose a balanced approach for government subsidies and investor revenues in the renewable energy domain. Ultimately, separate objective functions were defined for each of the goals. Using the Stackelberg game model, a joint objective function combining the two aforementioned goals was formulated (P0). However, since the defined objective function consisted of two heterogeneous parts (a bi-level objective function where the upper level included binary variables and the lower level continuous variables), it was necessary to homogenize it by defining binary variables for the continuous part, resulting in the objective function P1. Due to the presence of nonlinear terms in P1, which increase computational time and cost, these nonlinear terms were linearized (based on equations 8 to 17). Finally, by substituting the linearized terms into function P1, the final objective function can be obtained.

Now, using the final objective function, it is possible to optimize and estimate the subsidy amount as well as the profit for the utilized technologies. The final objective function should be minimized, and due to the presence of binary variables, the Stackelberg game model is the most suitable approach. This section presents the results of solving the proposed model. Table 2 provides the model parameters used for the solution.

Table 2

Numerical Values Used for Model Solution

Value	Note	parameter
1	Number of Cities Studied	i
1	Number of Renewable Energy Producers (Companies)	e_1
10	Number of Non-Renewable Technologies (such as Chillers, Pumps, and CHP)	e_2
2	Number of Policies Implemented for Government Subsidy Allocation (Including Incentives and Return on Investment for Investors)	-

In this study, it is assumed that the only renewable energy technology utilized in the city under investigation is solar panels. Accordingly, the output power is calculated using Equation (7). Other technologies, such as chillers, pumps, and CHP systems, are considered at a level of 10 in the city under study.

The results of both the leader and follower models, based on the final binary objective function and optimized using the Stackelberg game model, were obtained for a city with the characteristics specified in Table 3.

Table 3

Optimal Values of the Leader and Followers Mode

Value (Cost per Unit)	Model
333021	Leader (Minimum Subsidy Amount)
96949	Follower (Maximum Profit from Renewable Energy Production)

One of the topics that can be examined is the impact of increasing renewable energy technologies (more precisely, increased investment in renewable energy within a city) on the amount of government subsidies granted and the maximum profit obtained from renewable energy production. Accordingly, a sensitivity analysis of the model has been conducted to assess the effect of the number of renewable energy producers (e_1), assuming that the quantities of other non-renewable technologies (such as chillers, pumps, and CHP units) remain constant, on the subsidy allocations and the results of the leader and follower models. The results are presented in Table 4.

Table 4

Sensitivity Analysis of Renewable Energy Producer (e_1)

Follower (Maximum Profit from Renewable Energy Production)	Leader (Minimum Subsidy Level)	Number of $\boldsymbol{e_1}$
11526	157207	5
13968	170782	7
16104	214433	10
19227	276707	20

The results in Table 4 indicate that with an increase in the number of renewable energy producers, despite the rise in government subsidies and company profits, the rate of increase in company profits slows down, reflecting the competitive nature of the market.

In this section, the implementation steps of the proposed algorithm based on the Stackelberg game method were carried out to make necessary decisions grounded in foresight development, aiming to reduce the costs of renewable energy production and improve responsiveness to customer demand. Accordingly, new variables were defined considering the prices set within the government's subsidy policies for renewable energy production. The results indicate that with an increase in the number of renewable energy producers and, consequently, the amount of government subsidies paid, governments adopt measures to enhance competitiveness in the production sector, thereby reducing company profitability to a level that fosters competition among them. In other words, the approach presented in this section establishes a balance between the subsidies granted by the government and the profit levels of solar energy producers such that companies earn reasonable profits while the subsidy amount maintains a competitive market environment.

5. Conclusion

In this study, game theory is employed to determine the optimal level of investment in renewable energy production, taking into account government support policies. A cooperative strategy is adopted to analyze the impact of leader (government) and follower (renewable energy producers) roles. The decision-making process, grounded in foresight development, is implemented through a six-step algorithm aimed at reducing renewable energy production costs and enhancing responsiveness to customer demand. The modeling framework incorporates newly defined variables based on government subsidy policies and predetermined pricing mechanisms for renewable energy production. The results indicate that in a cooperative game with the government acting as the main leader, not only can the renewable energy producers' profits increase, but demand can also be met while reducing sales costs. Moreover, it is shown that higher levels of government subsidies, driven by supportive policy measures, lead to increased profitability for renewable energy producers. Conversely, as the number of renewable energy producers rises and government subsidy payments increase, governments may implement strategies to foster a more competitive production environment, thereby reducing individual firm profitability while maintaining incentives for continued energy production.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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