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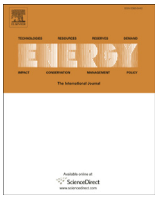

Time-Of-Use pricing in an energy sustainable supply chain with government interventions: A game theory approach

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ABSTRACT

In this study, the game theory approach has been used to perform Time-Of-Use (TOU) pricing for renewable and conventional energy supply chains with government intervention to achieve sustainable development goals. Also, a Demand Response Program (DRP) based on TOU pricing has been implemented to improve the profits of power producers and the energy consumption pattern of end customers. Decision variables included the price of conventional and renewable energy during low- and high-load periods, tax rate, and subsidies. These variables are determined in three scenarios with the goals of maximizing government revenue, maximizing social welfare, minimizing environmental impacts, and under two-game structures of cooperative and Nash between the producers. The equilibrium solutions of each game for the three scenarios were obtained by backward induction. The results showed that decisions related to energy prices and tariffs play a major role in achieving the goals of sustainable development, profits of supply chain members, and success in meeting consumer demand. For all three scenarios, the government revenue function and the social welfare functions earn higher values in the Nash game than in the cooperative game, but the environmental impacts and the producers' profit function earn respectively lower and higher values in the cooperative game.

1. Introduction

In recent years, increasing public attention to environmental and social concerns and rising support for legal regulations reflecting these concerns have pushed businesses towards creating sustainable supply chains to maintain their competitive advantages [1,2].

Sustainability is generally defined as “the utilization of existing resources to meet the needs of the present generation without compromising the ability of future generations to meet their own needs” [3]. sustainability through focus on economic consideration, social responsibility and environmental sustainability affects all human behavior, and decisions. Accordingly, readers of this study can explore other definitions of sustainability into papers: [4–6]. The development of renewable energy technologies and the rising global demand to use renewable energies to reduce greenhouse gas emissions have had positive impacts on the pursuit of economic, environmental, and social goals of sustainable development [7–9].

In regards to electricity supply chains, governments can use a variety of measures and policies including financial incentives and tax schemes to promote the use of renewable energies and reduce the use of fossil fuels [10–14]. However, these energy policies need to ensure access to diverse, safe, and sustainable sources of energy at competitive prices. In competitive electricity markets, aside from pursuing sustainable development goals, power generation companies must also compete in lowering prices to maintain and increase their market share. Indeed, pricing has significant implications for the interests of all participants in the electricity market and plays a key role in energy sustainable development [15,16].

In China, the CPC Central Committee and the State Council have proposed using Price-Based Demand Response (PBDR) and Demand Side Management (DSM) programs to modify electricity pricing mechanisms to accelerate energy market reform, creating competition in the power generation sector, and promote diversification in the electricity market [15]. Demand Response (DR) is a DSM program with economic and environmental objectives that are designed to balance supply and demand in the electricity grid,

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power consumption optimize, implement time-dependent electricity prices, improve energy efficiency, and reduce the energy purchase cost [17,18]. The core of a DR program could be a PBDR scheme defining different prices for different periods to encourage customers to consume less power during peak periods or shift consumption to off-peak periods. According to the research of [15,19], PBDR strategies include TOU pricing,RTP, (Critical Peak pricing) CPP, (extreme day pricing) EDP, Peak Time Rebate pricing, Inclining Block Rate (IBR) and Day-Ahead Dynamic Pricing (DADP). One of the most widely used PBDR schemes is the Time-Of-Use (TOU) pricing. TOU pricing is easy to be implemented and has great effect on load shifting. Its effectiveness on load shifting has been widely recognized that many areas have implemented TOU pricing for a long time [15,18]. The goal of TOU pricing is to modify the consumption pattern to make it more evenly distributed by reducing peak demand and shifting demand to off-peak hours [20]. This study seeks to answer the following questions:

- What is the optimal pricing strategy, using game theory approach, for renewable and conventional energy supply chains with government intervention?
- How DSM techniques can be utilized, with the help of the game theory, to modify the consumption pattern of an electricity supply chain?
- How do the financial incentives provided by the government, including subsidies and taxes, affect supply chain decisions?
- How does the demand for renewable and conventional energy in low-load and high-load periods and the profit of renewable and conventional energy producers change with the government's strategies?
- What is the optimal strategy of the government, renewable and conventional energy producers, and consumers in terms of price, demand, profit, environmental impacts, and social welfare?

To answer the raised questions, this article presents a Stackelberg game model with a leader-follower structure. In the first level of this model, the government acts as the leader of the game. In the second level, two-game structures are considered: (i) a cooperative game between renewable and conventional energy producers and (ii) a non-cooperative (Nash) game between them. For each structure, decisions of the government and supply chain members are determined in three scenarios reflecting the government's focus in pursuing sustainability goals. In each scenario, one of the three sustainability goals is considered as the objective function and the other two are considered as constraints with certain thresholds for optimizing that objective function. It is assumed that part of the consumers tends to use renewable energy and part of the consumers tend to use conventional energy. Therefore, this allows consumers to get their energy consumption from a conventional or renewable energy producer. Increasing the demand of consumers in each sector, it depends on the price and the amount of subsidies and taxes of the government. The government subsidizes renewable energy consumption to increase the propensity to buy from renewable energy producers and taxes conventional energy consumption to reduce the propensity to buy from conventional energy producers. Also, DSM is performed through the implementation of a price-based demand-response program.

The rest of this article is organized as follows: Section 2 reviews the literature, Section 3 presents the problem definition and assumptions and the proposed model, Section 4 provides a numerical example and its equilibrium solutions followed by an analysis of the results, and Section 5 provides a summary of conclusions and some suggestions for future research.

2. Literature review

Considering the subject of the paper, which is electricity pricing in conventional and renewable energy supply chains with government intervention using the game theory approach. The literature is reviewed in two sections, one dedicated to electricity pricing and the other to government intervention in sustainable supply chain management. In the end, the gaps in the research literature and the contributions of this paper to the literature are discussed.

2.1. *Energy pricing in electricity markets*

Pricing is an extremely important economic factor from both empirical and theoretical points of view for all kinds of markets. In electricity markets, electricity price decisions are key determinants of the profits of all market participants [15,21]. Given the diverse structure of electricity markets, over the years, many studies have been conducted to model strategic interactions and pricing options in these markets.

In one of these studies, Maharjan et al. [22] proposed a Stackelberg game between retailers and end consumers in a smart grid to maximize retailers' revenue from the market and reduce consumer bills. They also used a DSM program to increase the reliability of the power supply. In another study, Srinivasan et al. [23] examined the effect of half-hourly real-time pricing (RTP), TOU pricing, and day-night (DN) pricing strategies in smart grids in the Singapore electricity market. Their results showed that dynamic pricing based on the game theory is a good demand-side management strategy. In a study by Zugno et al. [24], they proposed a two-level model for retailers' participation in an electricity market with a demand response program. In this study, a Stackelberg game was defined between retailers (leaders) and consumers (followers) in a dynamic pricing environment. Yang et al. [15] examined electricity pricing options for residential use in China with an emphasis on the importance of the price-based demand response model (PBDR) as one of the largest demand response programs. This study also provided a detailed review and discussion of PBDR strategies in demand-side management. Nojavan and Zare [25] proposed an optimization model based on deterministic and interval optimization approaches for determining retail electricity prices in smart grids using RTP, TOU, and fixed pricing (FP) schemes. Their results showed that the average retail profit is higher in TOU and RTP schemes than in FP. A DRP was also implemented to improve the load pattern and increase retailers' profits. Aizenberg and Voropai [26] proposed a pricing model for electricity retail markets with Bertrand competition and provided a solution for load curve optimization for multiple consumers and an electricity company. Yang et al. [27] proposed a game theory-based model for optimizing TOU pricing strategies (as a DSM method) for conventional energy sources. The results of this study showed that using the optimal TOU price will reduce the costs of utility companies, increase profits, and level consumer demand. Peng and Tao [28] introduced a model for the cooperative game between electricity retailers in the presence of renewable sources in China's spot electricity market. Their results showed that the cooperative game model improves the competitiveness of electricity retailers in the spot market. In a study by Finn and Fitzpatrick [29] on the promotion of renewable energy consumption through PBDR programs and RTP schemes, the results showed that shifting demand toward the periods when electricity prices are low will increase the consumption of renewable energies, including wind power. Azad and Ghotbi [30] proposed a Cournot model for hourly pricing of renewable electricity in a deregulated retail market based on the game theory. In this model, members of the market were considered to be small suppliers, consumers, and the electricity grid. Fang et al. [10] developed an evolutionary game model for renewable energy generation and transmission under government regulations in the Chinese electricity market and proposed an equilibrium strategy between the government, fossil-energy power plants, and power grids. In a study by Kok et al. [9], investigated the effect of pricing policies (e.g. flat pricing versus peak pricing) on a company's investment in two competing energy sources (renewable and conventional) with a focus on the level of investment in renewable sources. They also examined the effect of direct subsidization (e.g., tax credit) and indirect subsidization (e.g., carbon tax) on investment and carbon emissions levels. The results of this study showed that pricing policies play a significant role in sustainability decisions. Gaba et al. [19] Investigated the impact of participation of residential consumers' in price-based (PB) and incentive-based (IB) DR programs using a non-cooperative game. Their findings showed that participation in PB and IBDR program benefits both the utility and the consumers. Ma et al. [31] proposed a Nash bargaining-based cooperative planning for multi-agent energy system. Their findings showed, cooperative model improve the benefits of both each participant and the cooperative alliance. Gao and Ma [32] proposed a pricing method for DR using game theory. In their model, a Stackelberg game was considered between retailers and consumers and a noncooperative game among consumers. Their numerical results showed the effectiveness of the proposed pricing method.

2.2. Government intervention for sustainable supply chain management

Recently, many studies have been performed on the optimization of government decisions in green supply chain management, such as how they use incentive and penalty policies to encourage environment-friendly production. In one of these studies, Zhu et al. [33] examined the games between government and businesses in green supply chain management. Their results showed that subsidies and penalties have a direct impact on the outcome of the game. Hafezalkotob [34] modeled the competition and cooperation between two manufacturers in the presence of government interventions. In this model, the goal was to set government tariffs in such a way as to facilitate achieving sustainability goals in a competitive market. Zhang and Wang [35]developed a competitive model based on a Stackelberg game for the green and non-green supply chains. These researchers showed how government tariffs can be set to guide organizations toward sustainability. Sinayi and Rasti [36] studied the pricing of green products based on environmental and social welfare goals in a sustainable supply chain with government interventions using the game theory approach. In a study by Madani and Rasti-Barzoki [37], they presented a competitive model for green and non-green supply chains with government intervention. In this study, pricing policies, government tariffs, and their impact on the profits of supply chain members were examined. Pakrooh et al. [38] proposed a model for pricing fossil fuels (including gasoline, gas, and electricity) with government intervention, with a focus on how to reform energy policy to reduce CO2 emissions. Yao et al. [39] proposed a model based on the Stackelberg game theory for optimizing company strategies and profits in an electricity market comprised of the government, power companies, and customers. In a study by Liu et al. [11], they proposed a game theory-based model for optimizing renewable multi-energy systems. Using this model, these researchers investigated the impact of government subsidy strategies on the reduction of carbon emissions and the penetration of renewable energies as a result of a lower propensity to use fossil energy. Jamali and Rasti-Barzoki [14] proposed a game-theoretic approach for examining licensing contracts and government support strategies in renewable electricity supply chain. Their findings showed the government strategies provide more development of technology than the cooperation strategy between the two suppliers. Also, research Yi et al. [40], Xin-gang et al. [41], Xin-gang and Yu-qiao [42] analyzed competition between the conventional supplier and renewable energy supplier under government intervention. Yi and et al. [40] examined support schemes of government under renewable and conventional producers strategies in electricity competitive market of China with the approach of evolutionary game theory. They simulated the evolutionary game model of electricity producers taking China's wind power industry as an example and most of the data are collected from the China Statistical Yearbook. Also, in study of Xin-gang et al. [41] was examined game between China's thermal and green power producers as an example to analyze the development of the renewable energy power industry under support schemes of government. in study of Xin-gang and Yu-qiao [42] the evolution process of renewable and conventional producers' behaviors is simulated under of government support schemes in China as an example. Their results showed that with the implementation of government strategies, the uncertainties of the behavior of power producers is gradually reduced.

Table 1 provides a summarized description of previous articles in the research literature and their assumptions and compares them with the current study.

To the best of the authors’ knowledge, this is the first study to examine the impact of subsidies and taxes on demand for renewable and conventional energy in such environments. Another contribution of this study is the examination of the competition in renewable and conventional electricity supply chains for the purpose of optimal pricing and achieving sustainable development goals.

The contributions of this article to the research literature are as follows:

1. Investigating the competition between renewable and conventional energy supply chains based on three scenarios of government in cooperative and non-cooperative (Nash) game structures.
2. Examining the impact of government intervention in the form of subsidizing/taxing demand to increase the propensity to use renewable energy.
3. Considering a DRP with TOU pricing based on the game theory approach in the competing renewable and conventional energy supply chains.
4. Considering three scenarios for the government focus (maximization of government revenue, maximization of social welfare, and minimization of environmental impacts) in its intervention in renewable and conventional energy supply chains and providing managerial insights.

3. Problem definition and modeling

In this study, Time-Of-Use (TOU) pricing is performed in a competitive market comprised of conventional and renewable energy supply chains where the government intervenes in the competition of chains members through taxing and subsidization. In both supply chains, renewable and conventional energy

Table 1
A comparison among the current paper with the previous studies.

Study	Demand side management	TOU pricing	Game Theory	Government intervention	Effect of subsidy on Consumer Behavior	Effect of tax on Consumer Behavior	Sustainable Development			Renewable energy	Conventional energy	energy Supply chain	
							Government revenue	social welfare	environmental impacts			Competition	Cooperation
[22]	✓		✓							✓	✓		
[23]	✓	✓	✓							✓	✓		
[24]	✓		✓							✓	✓		
[25]	✓	✓								✓	✓		
[24]			✓								✓	✓	
[27]	✓	✓	✓								✓		
[29]	✓		✓							✓			
[30]			✓							✓			
[10]			✓	✓						✓	✓		
[9]		✓								✓	✓		
[34]			✓	✓	✓	✓	✓	✓	✓				
[36]			✓	✓	✓	✓	✓	✓	✓				
[37]			✓	✓	✓	✓							
[38]			✓	✓							✓		
[39]			✓	✓						✓	✓		
[11]			✓	✓						✓			
[14]			✓	✓						✓		✓	✓
Current study	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

producers decide the selling price of electricity in low and high-load periods. In this problem, different demand functions are considered for the demand for renewable and conventional energy in low and high-load periods. It is assumed that part of the consumers tends to use renewable energy and part of the consumers tend to use conventional energy. In addition, it is assumed that demand in each period has a downward slope relative to its own price and an upward slope relative to the price of another producer in the same period. Also, it is assumed that demand in each period has an upward slope relative to prices in another period.

In this problem, government intervention is considered to be a key component in the competition between renewable and conventional energy supply chains. The decisions of each producer affect not only the profitability and demand of other producers but also the decisions of the government, which decisions of the government also affect the decisions of the producers. Therefore, the optimal decisions of supply chain members are considered to be a function of government tariffs. To encourage the use of renewable energy, the government subsidizes renewable energy generation to help reduce final renewable energy prices and simultaneously penalizes conventional energy generation through additional taxation to increase final conventional energy prices and thus reduce customer propensity to use this type of energy. Taxes and subsidies are considered as two decision variables for the government. The three main sustainable development goals of the government are defined as maximizing government revenue, maximizing social welfare, and minimizing environmental impact. Taxes and subsidies and other decision variables of the supply chains are determined based on these three goals. To analyze the interactive situations and the players' behavior, the problem is solved through the game theory method with the Stackelberg model. The game is assumed to be in the leader-follower format with Nash (decentralized) and cooperative (centralized) game structures and is solved by backward induction. For each structure, three scenarios are defined for the government. In each scenario, one of the government's goals is considered as the objective function and the other two government goals are considered as constraints. Similar to Refs. [21,43], the objective function must be optimized such that the objectives that are considered as constraints do not exceed the assumed threshold.

In the Nash game structure, the government is considered to be the leader and the two producers are followers. A Nash game is played out between the two producers (followers) to determine their best responses to each other. In this game, players have the same power, and decisions are made simultaneously (Fig. 1). In this structure, first, the selling prices of renewable and conventional electricity for low and high-load periods are determined. Knowing the prices offered by producers, the government, as the leader, then determines the amounts of subsidies and taxes that are to be allocated in the three scenarios by backward induction. In the cooperative game structure, the government is the leader, and conventional and renewable energy producers are integrated as followers (Fig. 2). In this structure, the two producers cooperate with each other and determine the selling prices of renewable and conventional electricity in low and high-load periods as followers together. Then, the government, as the leader, determines the subsidies and taxes in the three scenarios by backward induction.

The next sub-sections describe the problem notations and assumptions then, the model is presented based on these assumptions.

3.1. Notations

Notations that are used in this study are defined as follows:

Indices	
i	Index of low load and high load periods $i \in \{l, h\}$
l	Low load period
h	High load period
j	Producers $j \in \{r, n\}$
Parameters	
ρ	Percentage of consumers who purchase energy from the renewable energy producer
β	Sensitivity of demand to its own price in its own period, i.e. self-price elasticity (MWh/\$)
λ_j	Environmental impacts of producer j (tonCO2/MWh)
θ_1	Demand's sensitivity in low-load period to energy price of high-load period (MWh/\$)
θ_2	Demand's sensitivity in high-load period to energy price of low-load period (MWh/\$)
y	Sensitivity of the demand in its own period to the price of other producer,i.e. Cross-price sensitivity coefficient (MWh/\$)
c_j	Cost of generating one unit of electricity by the producer j (MWh/\$)
α_i	Market base for the energy in period i (MWh)
L_R	The lower bound revenue for the government (\$)
L_E	The upper bound of environmental impact for the government (tonCO$_2$)
L_S	The lower bound of social welfare for the government (\$)
Decision Variables	
s	The considered subside by the government (MWh/\$)
t	The considered tax by the government (MWh/\$)
p_{ji}	Selling price of producer j in period i (MWh/\$)
Demand and profit functions	
D_{ji}	Demand from producer j in period i (MWh)
π_r	Profit function of renewable energy producer (\$)
π_n	Profit function of conventional energy producer (\$)
π_{SW}	Government function for social welfare goal (\$)
π_{RG}	Government function for revenue generation goal (\$)
π_{EG}	Government function for environmental impacts goal (tonCO$_2$)

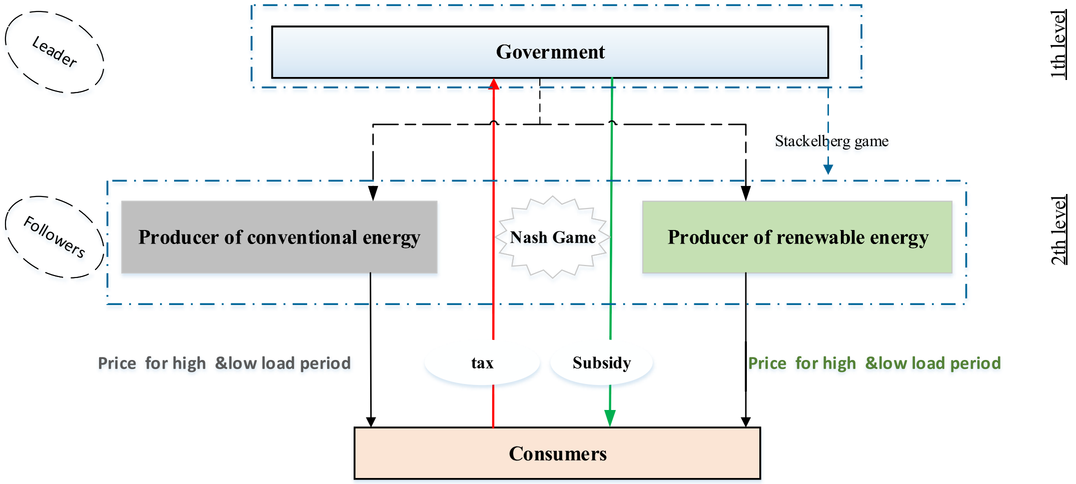


Fig. 1. The nash structure.

3.2. Assumptions

The model is created based on the following assumptions:

Assumption 1. The demand function for each producer in each period is linear and positive, and for both low and high load periods, demand is dependent on price, tax rate, and subsidy rate [9,43,44].

Assumption 2. Demand's sensitivity in each period to its own energy price is more than the selling price in other periods ($\beta > \theta_1$, $\beta > \theta_2$).

Assumption 3. Demand's sensitivity in each period to its own energy price is more than Sensitivity of the demand to the energy price of other producer in the same period ($\beta > y$)[9].

Assumption 4. renewable energy production costs more than conventional energy production ($c_r < c_n$) [37].

Assumption 5. Demand's sensitivity in low-load period to energy price of high-load period is more than demand's Sensitivity in high-load period to energy price of low-load period ($\theta_1 > \theta_2$).

Assumption 6. Percentage of consumers who purchase energy from the renewable (conventional) energy producer is already known and exogenous.

Assumption 7. governments pay (impose) a subsidy (tax) on the

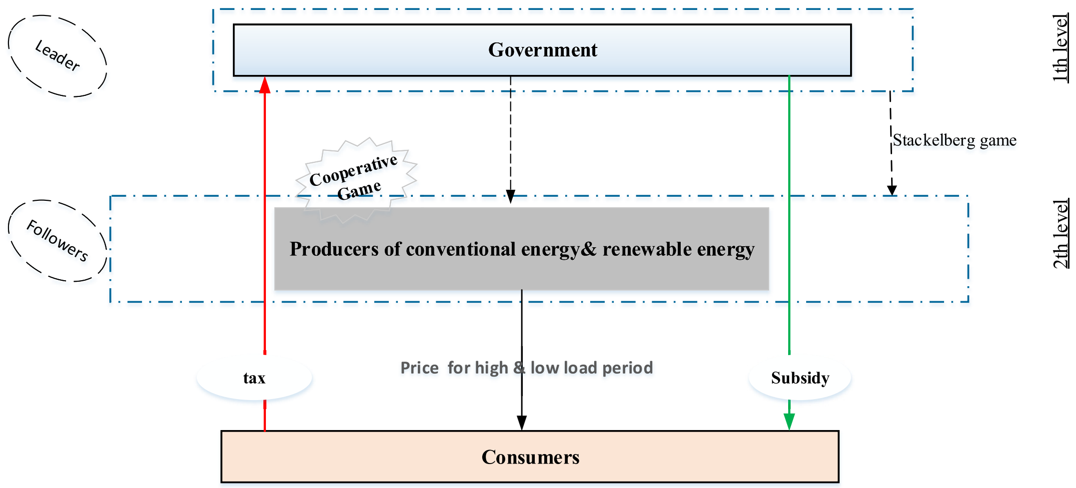


Fig. 2. The cooperative structure.

final price of the renewable (conventional) energy.

3.3. Modeling

In the following Three sub-sections, first, the functions related to renewable and conventional energy producers and then the functions related to the government are presented.

3.3.1. Demand functions

The model of this study uses price-dependent demand functions [9,45]. In this model, demand is considered to be a function of conventional and renewable energy prices in low and high-load periods, subsidies, and taxes as formulated below.

$$D_{rl} = \rho\alpha_l - \beta(p_{rl} - s) + y(p_{nl} + t) + \theta_1 p_{rh} \tag{1}$$

$$D_{rh} = \rho\alpha_h - \beta(p_{rh} - s) + y(p_{nh} + t) + \theta_2 p_{rl} \tag{2}$$

$$D_{nl} = (1-\rho)\alpha_l - \beta(p_{nl} + t) + y(p_{rl} - s) + \theta_1 p_{nh} \tag{3}$$

$$D_{nh} = (1-\rho)\alpha_h - \beta(p_{nh} + t) + y(p_{rh} - s) + \theta_2 p_{nl} \tag{4}$$

Equation (1) is the demand for renewable energy in the low-load period and Equation (2) is the demand for renewable energy in the high-load period. Similarly, Equations (3) and (4) compute the demand for conventional energy in the low-load and high-load periods, respectively. In each of these equations, the first term is the potential demand in the period, the second term is the sensitivity of demand to the final price with the government subsidy/tax taken into account, the third term is the sensitivity of demand to the final price of the other producer with the government subsidy/tax taken into account, and the fourth term is the sensitivity of demand to price changes in the other period.

3.3.2. Producer profit functions

The profit functions of renewable and conventional energy producers in the decentralized structure are presented in Equations (5) and (6), respectively. In these functions, the net profit of each producer is obtained by subtracting its expenses from its revenue.

$$\pi_r = (p_{rl} - c_r)D_{rl} + (p_{rh} - c_r)D_{rh} \tag{5}$$

$$\pi_n = (p_{nl} - c_n)D_{nl} + (p_{nh} - c_n)D_{nh} \tag{6}$$

In the centralized structure, the profit is obtained by summing the profits of renewable and conventional energy producers. The profit function for this structure is presented in Equation (7).

$$\pi_C = \pi_r + \pi_n \tag{7}$$

3.3.3. Government objective function

Following the problem definition, to achieve the goals of sustainable development, the government seeks to maximize its net revenue, maximize social welfare, and minimize environmental impacts as formulated in Equations (8)–(10) respectively [21].

$$\pi_{RG} = (-s)(D_{rl} + D_{rh}) + (t)(D_{nl} + D_{nh}) \tag{8}$$

$$\begin{aligned}\pi_{SW} = & \int_{p_{\mathrm{rl}}-s}^{\frac{\rho\alpha_l + y(p_{\mathrm{nl}}) + yt + p_{\mathrm{rh}}\theta_1}{\beta}} D_{\mathrm{rl}}\mathrm{d}p_l + \int_{(p_{\mathrm{rh}}-s)}^{\frac{\rho\alpha_h + yp_{\mathrm{nh}} + yt + p_{\mathrm{rl}}\theta_2}{\beta}} D_{\mathrm{rh}}\mathrm{d}p_h \\ & + \int_{p_{\mathrm{nl}}+t}^{\frac{(1-\rho)\alpha_l + yp_{\mathrm{rl}} - ys + p_{\mathrm{nh}}\theta_1}{\beta}} D_{\mathrm{nl}}\mathrm{d}p_l + \int_{p_{\mathrm{nh}}+t}^{\frac{(1-\rho)\alpha_h + yp_{\mathrm{rh}} - ys + p_{\mathrm{nl}}\theta_2}{\beta}} D_{\mathrm{nh}}\mathrm{d}p_h + \pi_r + \pi_n\end{aligned} \tag{9}$$

$$\pi_E = (\lambda_r)(D_{rl} + D_{rh}) + (\lambda_n)(D_{nl} + D_{nh}) \tag{10}$$

Equation (8), whereby the government maximizes its revenue, represents the economic aspect of sustainability [34,46]. In this equation, the first term is the cost of subsidizing renewable power generation to increase the consumers' propensity to use renewable energy. The second term of this function determines the income to be earned from the taxation of consumers as a penalty for using conventional energy. Social welfare can be considered as an aspect of sustainability as well as an economic indicator for measuring consumer and producer profits [36,47]. In Equation (9), the social aspect of sustainability is defined as the sum of consumer surplus and profit of renewable and conventional energy producers. Here, consumer surplus is an economic indicator of consumer satisfaction that is determined based on the difference between market price and the maximum purchase price of the two types of energy in low and high-load periods [36,47,48]. The environmental impact of the production of each type of energy is measured by Equation (10) [43].

To optimize each of these objective functions, the other two are considered as constraints for the government. Then the amounts of subsidy to be paid and tax to be collected in Nash and cooperative game structures in the three scenarios are calculated. Table 2 shows the three defined scenarios for Nash and cooperative game structures (derived from Ref. [21]). In Scenario 1, the government maximizes its net revenue by considering a lower bound for social welfare and an upper bound for environmental impacts. In Scenario 2, the government maximizes social welfare by considering a lower bound for its net revenue and an upper bound for environmental impacts. In Scenario 3, the government minimizes environmental impacts by setting a lower bound for social welfare and its net revenue.

4. Equilibrium solutions

Based on the model and functions presented in the previous section, this section presents the optimal strategies and equilibrium solutions for the members of renewable and conventional energy supply chains in decentralized (Nash) and centralized (cooperative) game structures. It should be noted that, hereafter, the symbols $(.)^N$ and $(.)^c$ are used as equilibrium values of the variables in the Nash and cooperative game structures, respectively.

4.1. Decentralized model

In the decentralized model, the renewable and conventional energy supply chains compete with each other. The sequence of decision making of players is presented in Fig. 3. First, the two producers (as followers in the Stackelberg game) engage in the Nash competition to determine the equilibrium prices of renewable and conventional energy in the low and high-load periods. Then, subsidies and taxes under the three scenarios of Table 2 are obtained by backward induction and placing equilibrium solutions in the functions of the government (as the leader of the Stackelberg game). The model of this problem is formulated in Table 3.

Theorem 1. *Optimal prices of renewable and conventional energy producers in low and high-load periods at Nash equilibrium are obtained in* Eqs. (11)–(14).

$$p_{rl}^{N}=\frac{yQ_1Q_{14}-\left(4y\beta Q_0+Q_2\left(8\beta^2+Q_{14}\right)\right)(\theta_1+\theta_2)+2\beta Q_3\left(Q_{14}+2(\theta_1+\theta_2)^2\right)}{Q_4} \tag{11}$$

$$p_{nl}^{N}=\frac{1}{4}\left(-\frac{Q_6}{Q_9}+\frac{Q_{11}}{Q_{10}}-\frac{Q_7}{Q_{12}}+\frac{Q_8}{Q_{13}}\right) \tag{12}$$

$$p_{rh}^{N}=\frac{1}{4}\left(4c_r-\frac{Q_6}{Q_9}+\frac{Q_5}{Q_{10}}+\frac{Q_8}{Q_{13}}+\frac{\alpha_h-\alpha_l+(c_n+c_r)(y-2\beta-2\theta_1)}{Q_{12}}\right) \tag{13}$$

$$p_{nh}^{N}=\frac{1}{4}\left(4c_n-\frac{Q_6}{Q_9}+\frac{Q_{11}}{Q_{10}}-\frac{Q_8}{Q_{13}}+\frac{\alpha_h-\alpha_l+(c_n+c_r)(y-2\beta-2\theta_1)}{Q_{12}}\right) \tag{14}$$

proof. *The proof of* Theorem 1 *is given in Supplementary material. The values Q1 to Q14 can be seen in Supplementary material.*

4.2. Centralized model

In this model, the two producers are integrated, acting together as the follower of the Stackelberg game. The sequence of decision making is presented in Fig. 4. Here, the equilibrium solutions of renewable and conventional energy prices in low and high-load periods are placed in the functions of government (Stackelberg leader). Subsidies and taxes in the three scenarios of Table 2 are then determined accordingly. The formulation of this model is provided in Table 3.

Theorem 2. *Optimal prices of renewable and conventional energy producers in low and high-load periods in the cooperative game are obtained in Eqs.* (15)-(18).

$$p_{rl}^{c}=\frac{1}{4}\left(-\frac{H_4}{H_7}-\frac{H_2}{H_8}-\frac{H_3}{H_9}-\frac{H_1}{H_{10}}\right) \tag{15}$$

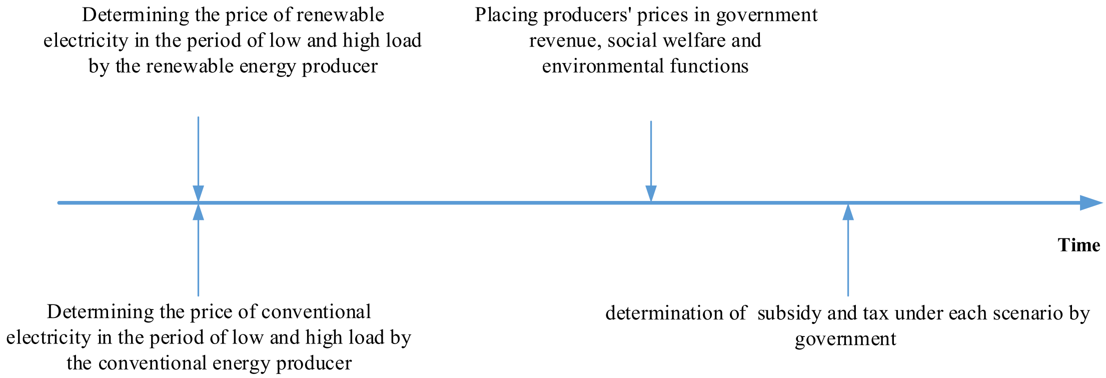


Fig. 3. The sequence of decision-making under the Nash structure.

Table 2
The government scenarios in two Nash and Cooperative structures.

Scenario	Goal	CONSTRAINTS	Subsidy and tax strategy in the Nash game (decentralized)	Subsidy and tax strategy in the Cooperative game (centralized)
1	π_{RG}	π_{SW} π_E	$\begin{cases} \max\limits_{P_{ji}^{N}} \pi_{RG}(s,t) \\ \pi_{SW} \geq L_S \\ \pi_E \leq L_E \end{cases}$	$\begin{cases} \max\limits_{P_{ji}^{c}} \pi_{RG}(s,t) \\ \pi_{SW} \geq L_S \\ \pi_E \leq L_E \end{cases}$
2	π_{SW}	π_{RG} π_E	$\begin{cases} \max\limits_{P_{ji}^{N}} \pi_{SW}(s,t) \\ \pi_{RG} \geq L_R \\ \pi_E \leq L_E \end{cases}$	$\begin{cases} \max\limits_{P_{ji}^{c}} \pi_{SW}(s,t) \\ \pi_{RG} \geq L_R \\ \pi_E \leq L_E \end{cases}$
3	π_E	π_{RG} π_{SW}	$\begin{cases} \min\limits_{P_{ji}^{N}} \pi_E(s,t) \\ \pi_{RG} \geq L_R \\ \pi_{SW} \geq L_S \end{cases}$	$\begin{cases} \min\limits_{P_{ji}^{c}} \pi_E(s,t\big)\Big) \\ \pi_{RG} \geq L_R \\ \pi_{SW} \geq L_S \end{cases}$

Table 3
Problem solving models.

Scenario	Problem Solving Model in Decentralized Mode (Nash)	Problem Solving Model in centralized Mode (Cooperative)
1	$\begin{cases} \max\limits_{s,t} \pi_{RG} \\ \pi_{SW} \geq L_S \\ \pi_E \leq L_E \\ \begin{cases} Max\pi_r \\ p_{ji}^{N} \\ Max\pi_n \\ p_{ji}^{N} \\ \pi_r > 0, \pi_n > 0, p_{ji}^{N} > c_j \end{cases} \end{cases}$	$\begin{cases} \max\limits_{s,t} \pi_{RG} \\ \pi_{SW} \geq L_S \\ \pi_E \leq L_E \\ \begin{cases} Max\pi_c \\ p_{ji}^{c} \\ \pi_c > 0, p_{ji}^{c} > c_j \end{cases} \end{cases}$
2	$\begin{cases} \max\limits_{s.t} \pi_{SW} \\ p_{ji}^{N} \\ \pi_{RG} \geq LR \\ \pi_E \leq LE \\ \begin{cases} Max\pi_r \\ p_{ji}^{N} \\ Max\pi_n \\ p_{ji}^{N} \\ \pi_r > 0, \pi_n > 0, P_{ji}^{N} > c_j \end{cases} \end{cases}$	$\begin{cases} \max\limits_{s.t} \pi_{SW} \\ p_{ji}^{C} \\ \pi_{RG} \geq LR \\ \pi_E \leq LE \\ \begin{cases} Max\pi_c \\ P_{ji}^{c} \\ \pi_c > 0, p_{ji}^{c} > c_j \end{cases} \end{cases}$
3	$\begin{cases} \min\limits_{s,t} \pi_E \\ \pi_{RG} \geq L_R \\ \pi_{SW} \geq L_S \\ \begin{cases} Max\pi_r \\ p_{ji}^{N} \\ Max\pi_n \\ p_{ji}^{N} \\ \pi_r > 0, \pi_n > 0, P_{ji}^{N} > c_j \end{cases} \end{cases}$	$\begin{cases} \min\limits_{s,t} \pi_E \\ \pi_{RG} \geq L_R \\ \pi_{SW} \geq L_S \\ \begin{cases} Max\pi_c \\ p_{ji}^{c} \\ \pi_c > 0, p_{ji}^{c} > c_j \end{cases} \end{cases}$

$$p_{rh}^{c} = \frac{1}{4}\left(4c_r + \frac{H_4}{H_7} - \frac{H_5}{H_8} - \frac{H_3}{H_9} - \frac{H_1}{H_{10}}\right) \tag{16}$$

$$p_{nl}^{c} = \frac{1}{4}\left(\frac{H_4}{H_7} - \frac{H_2}{H_8} - \frac{H_6}{H_9} - \frac{H_1}{H_{10}}\right) \tag{17}$$

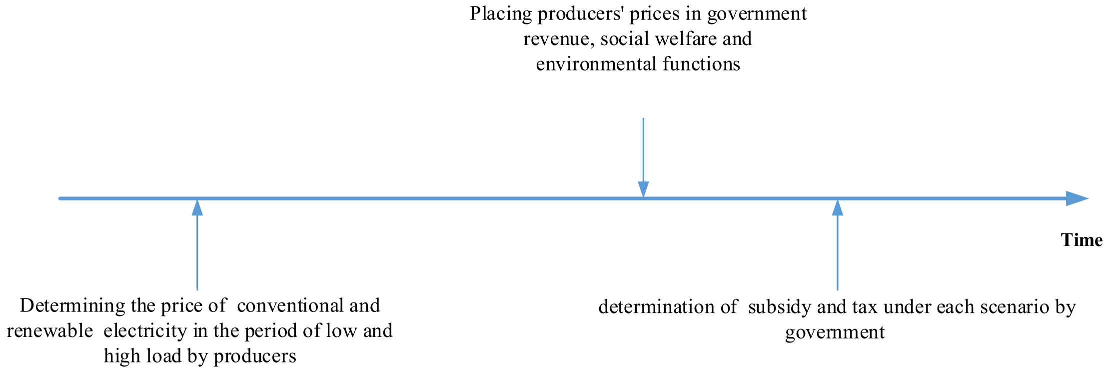


Fig. 4. The sequence of decision-making under the cooperative structure.

$$p^c_{nh} = \frac{1}{4}\left(4c_n - \frac{H_4}{H_7} - \frac{H_5}{H_8} - \frac{H_6}{H_9} - \frac{H_1}{H_{10}}\right) \tag{18}$$

Proof. *The proofs of Theorem 2 is given in Supplementary material. The values H1 to H14 can be seen in Supplementary material.*

In both of Nash and cooperative structures By placing equilibrium solutions in the demand and profit functions, their equilibrium value can be obtained in terms of government tariffs .

5. Analytical results and managerial insights

The analysis of the results is presented in two sections: parametric sensitivity analysis and numerical analysis. Also, at the end of this section, some management insights are provided.

5.1. Parametric analysis

This section examines the effect of some important parameters such as the base market demand in low-load and high-load periods and the cost of renewable and conventional electricity generation on the prices of renewable and conventional energy in the Nash game structure (the conclusions drawn for the Nash game also apply to the cooperative game).

$$\frac{dp^N_{rh}}{d\alpha_h} = \frac{1}{4}\left(\frac{-1+2\rho}{y+2\beta-\theta_1-\theta_2} - \frac{1}{y-2\beta+\theta_1+\theta_2} + \frac{1}{-y+2\beta+\theta_1+\theta_2} + \frac{-1+2\rho}{y+2\beta+\theta_1+\theta_2}\right) \tag{22}$$

5.1.1. Effect of $\boldsymbol{\alpha_l}$ on the renewable energy price in the low-load period

The first-order derivative of the renewable energy price in the low-load period regarding α_l is given in Equation (18).

$$\frac{p^N_{rl}}{d\alpha_l} = \frac{1}{4}\left(-\frac{1}{2y-2\beta+\theta_1+\theta_2} + \frac{1}{-2y+2\beta+\theta_1+\theta_2} - \frac{-1+2\rho}{-2(y+\beta)+\theta_1+\theta_2} - \frac{1-2\rho}{2(y+\beta)+\theta_1+\theta_2}\right) \tag{18}$$

If conditions (19), (20), and (21) are met, then $\frac{dp^N_{rl}}{d\alpha_l} > 0$, meaning that α_l (potential demand in the low-load period) has a positive effect on the renewable energy price in this period [49]. In other words, p^N_{rl} increases with α_l.

$$\frac{\beta\rho + y\left(-1+\rho - \frac{2\beta}{2y-2\beta+\theta_1+\theta_2} + \frac{2\beta}{-2y+2\beta+\theta_1+\theta_2}\right)}{y+\beta} < 0 \tag{19}$$

$$2(y+\beta) < \theta_1 + \theta_2 \tag{20}$$

$$2\beta + \theta_1 + \theta_2 \geq 0 \tag{21}$$

5.1.2. Effect of $\boldsymbol{\alpha_h}$ on the renewable energy price in the high-load period

Equation (22) shows the first-order derivative of the renewable energy price in the high-load period with respect to α_h.

If conditions (23), (24), and (25) are met, then $\frac{dp^N_{rh}}{d\alpha_h} > 0$ and the parameter α_h (potential demand in the high-load period) has a positive effect on the renewable energy price in the high-load period [49]. This means that p^N_h increases with α_h.

$$\rho < -\frac{y\left(y^2 - 4\beta^2 - (\theta_1+\theta_2)^2\right)}{(y+2\beta)(y-2\beta+\theta_1+\theta_2)(-y+2\beta+\theta_1+\theta_2)} \tag{23}$$

$$y > 2\beta + \theta_1 + \theta_2 \tag{24}$$

$$4\beta + \theta_1 + \theta_2 \geq 0 \tag{25}$$

5.1.3. Effect of $\mathbf{c_r}$ on the renewable energy price in the low-load period

The first-order derivative of the renewable energy price in the low-load period with respect to c_r is given in Equation (26).

$$\frac{dp_{rl}^{N}}{dc_r} = -\frac{4\beta\big(\theta_1+\theta_2\big)\big(2\beta\big(\beta-\theta_1\big)-\big(2\beta\big(\beta-\theta_2\big)-\big(\beta-\theta_1\big)\big(\theta_1+\theta_2\big)\big)\big(y^2-4\beta^2-(\theta_1+\theta_2)^2\big)}{16\beta^2(\theta_1+\theta_2)^2-\theta_1+\theta_2\Big)\big(\theta_1+\theta_2\big)(\theta_1+\theta_2)^2\big)^2} \tag{26}$$

If conditions (27), (28), and (29) are met, then $\frac{dp_{rl}^{N}}{dc_r} > 0$ and the parameter c_r has a positive effect on the renewable energy price in the low-load period [47]. In other words, p_{rl}^{N} increases with c_r.

$$y + \sqrt{\frac{(\beta+\theta_1)(-2\beta+\theta_1+\theta_2)^2(2\beta+\theta_1+\theta_2)}{\theta_1^2+\beta(2\beta-3\theta_2)+\theta_1(-\beta+\theta_2)}} > 0 \tag{27}$$

$$\frac{2\beta(\beta+\theta_1)}{3\beta-\theta_1} < \theta_1 + \theta_2 \tag{28}$$

$$y < 2\beta + \theta_1 + \theta_2 \tag{29}$$

5.1.4. Effect of $\mathbf{c_r}$ on the renewable energy price in the high-load period

The first-order derivative of the renewable energy price in the high-load period with respect to c_r is provided in Equation (30).

$$\begin{aligned}\frac{dp_{rh}^{N}}{dc_r} = & -\frac{4\beta(\theta_1+\theta_2)(2\beta(\beta-\theta_1)-(\beta-\theta_2)(\theta_1+\theta_2))}{16\beta^2(\theta_1+\theta_2)^2-\left(-y^2+4\beta^2+(\theta_1+\theta_2)^2\right)^2} \\ & -\frac{(2\beta(\beta-\theta_2)-(\beta-\theta_1)(\theta_1+\theta_2))\left(y^2-4\beta^2-(\theta_1+\theta_2)^2\right)}{16\beta^2(\theta_1+\theta_2)^2-\left(-y^2+4\beta^2+(\theta_1+\theta_2)^2\right)^2}\end{aligned} \tag{30}$$

If conditions (31), (32), and (33) are met, then $\frac{dp_{rh}^{N}}{dc_r} > 0$ and the parameter c_r has a positive effect on the renewable energy price in the high-load period [47]. This means that p_{rh}^{N} increases with c_r.

$$y + \sqrt{\frac{(\beta+\theta_1)(-2\beta+\theta_1+\theta_2)^2(2\beta+\theta_1+\theta_2)}{\theta_1^2+\beta(2\beta-3\theta_2)+\theta_1(-\beta+\theta_2)}} > 0 \tag{31}$$

$$\frac{2\beta(\beta+\theta_1)}{3\beta-\theta_1} < \theta_1 + \theta_2 \tag{32}$$

$$y < 2\beta + \theta_1 + \theta_2 \tag{33}$$

From the above results, the following conclusions can be drawn:

Corollary 1. *Confirming the validity of the model for the competing energy supply chains, any increase in base energy demand in low-load and high-load periods will lead to an increase in the equilibrium price of renewable and conventional energy in both low-load and high-load periods.*

Corollary 2. *Any increase in the cost of renewable energy production will lead to an increase in the selling price of this energy in both low-load and high-load periods so that renewable energy generation can remain cost-effective.*

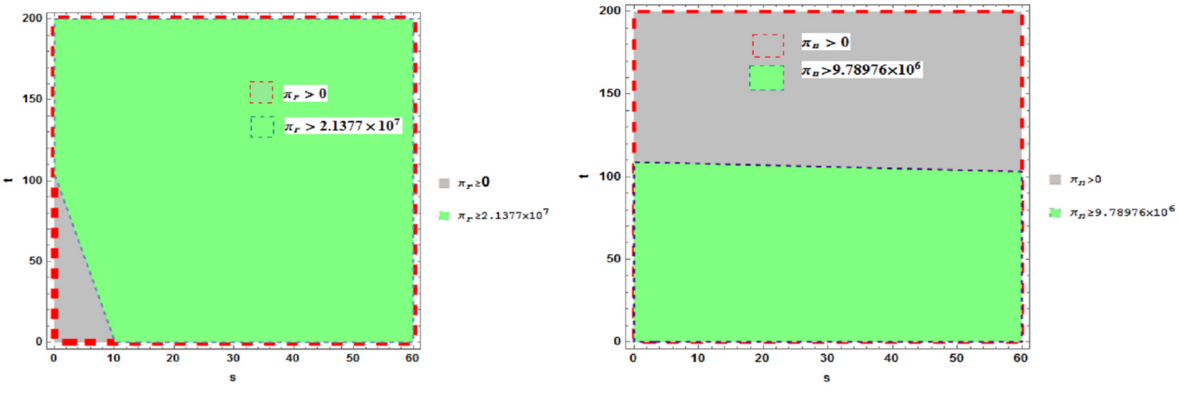
5.2. Numerical example

This section provides a numerical example to illustrate the feasibility of the mathematical model and examine the impact of the government's sustainable development policy on the demands, profits, and pricing policies of renewable and conventional energy producers. Some of the parameters of this example have been derived from Ref. [9], which is a case study conducted in Texas, United States. The rest of the parameters have been set such that profit functions remain concave, demands remain positive, and other model assumptions are also met. The values of the parameters are provided in Table 4.

Although a positive profit function guarantees the concavity of the profit functions of producers, to ensure long-term market competition between producers, it is necessary to define a minimum profit for each producer. In Fig. 5 (a) and (b), the gray zone is the area where producers' profits based on government tariffs are positive, and the green zone is the area where producers expect to

Table 4
The values of the parameters used in the numerical example.

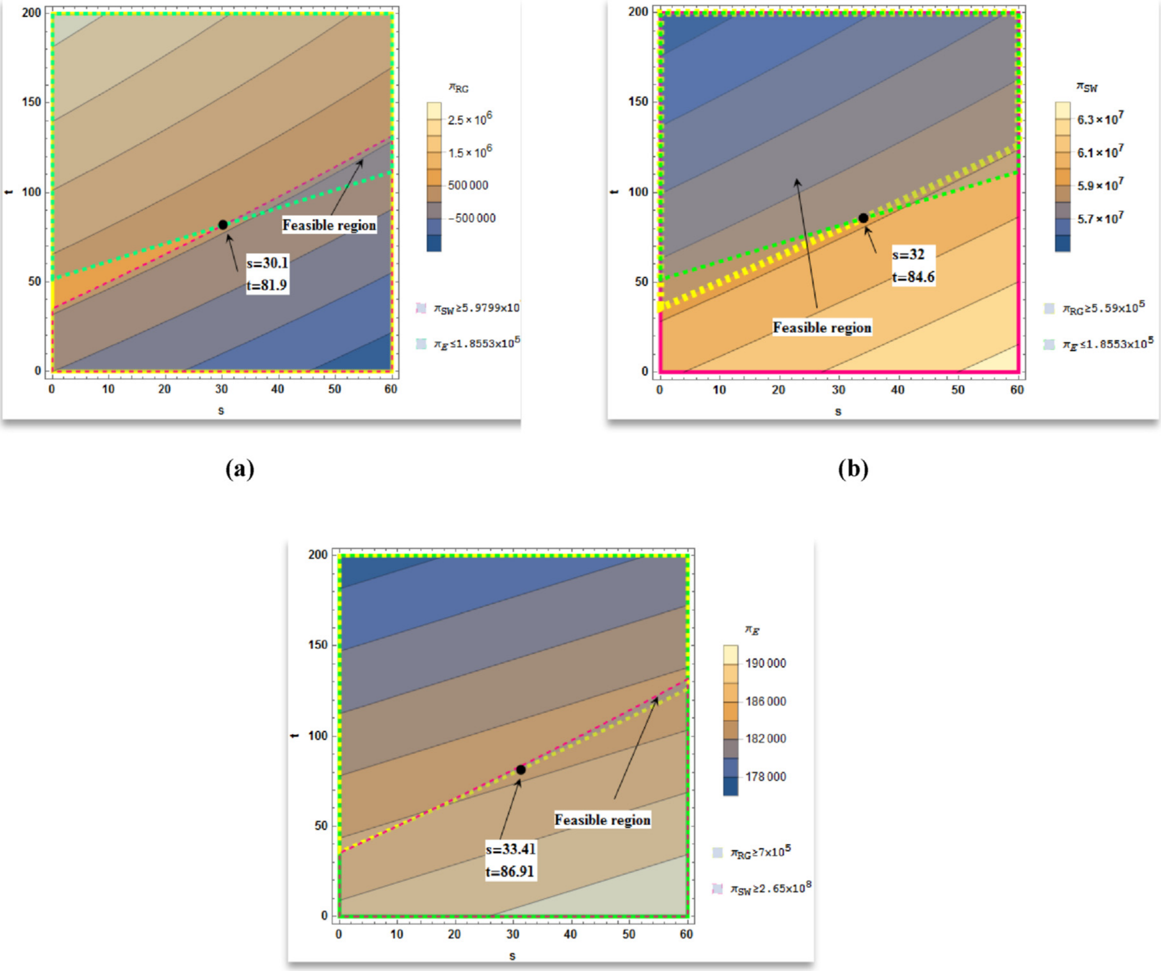
par	Value	Unit	par	Value	Unit	par	Unit	Value
α_h	40000	*MWh*	λ_r	5	*Tonco$_2$/MWh*	L_E^N	*ton co$_2$*	1.8553×10^5
α_l	30000	*MWh*	λ_n	5	*Tonco$_2$/MWh*	L_S^N	*$*	5.9799×10^7
β	13	*MWh/$*	ρ	0.6	-	L_R^C	*$*	5×10^5
y	3	*MWh/$*	c_r	200	*$/MWh*	L_E^C	*ton co$_2$*	1.6×10^5
θ_1	3	*MWh/$*	c_n	142	*$/MWh*	L_S^C	*$*	5.39×10^8
θ_2	1	*MWh/$*	L_R^N	5.59×10^5	*$*			



(a)

(b)

Fig. 5. The feasible region for renewable energy and conventional energy producer's profits.



(a)

(b)

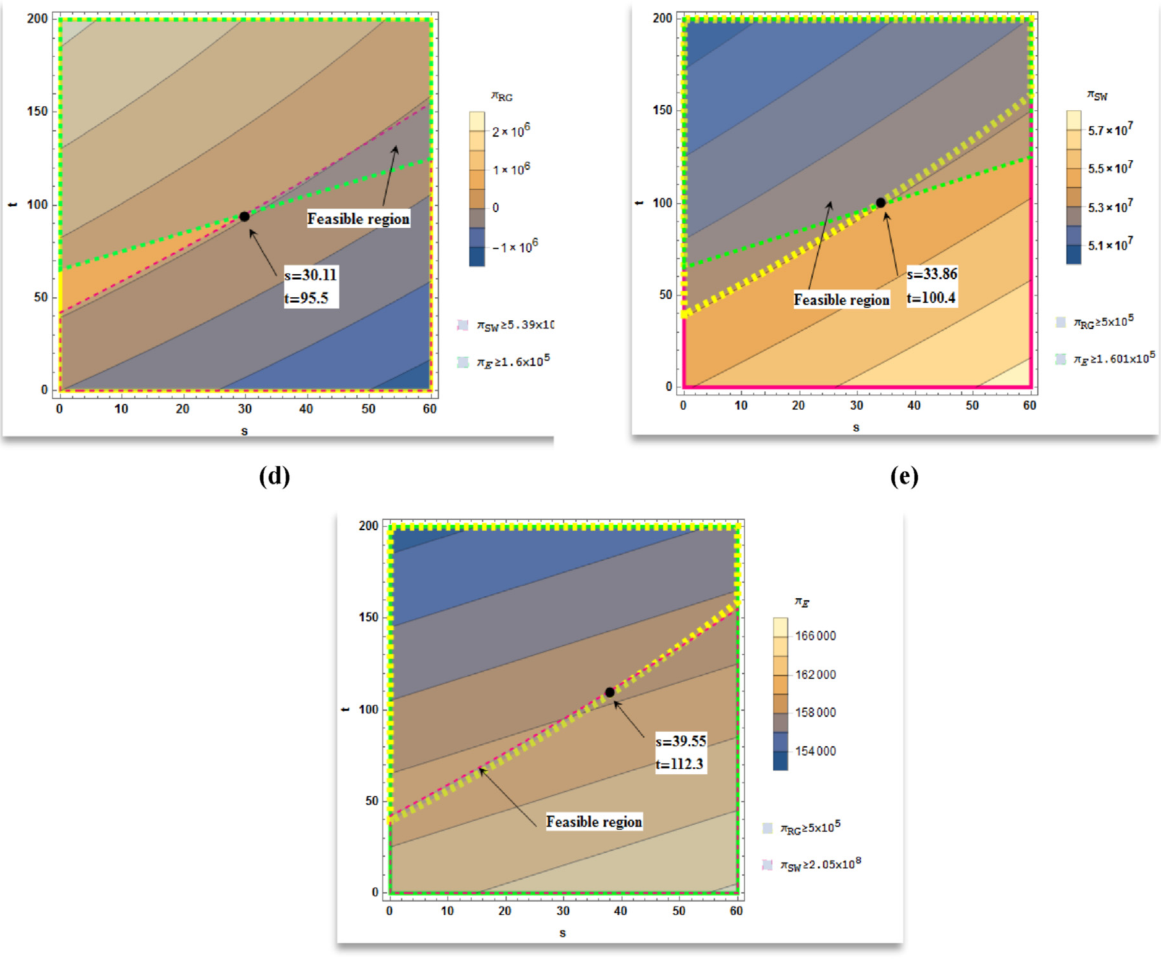
(c)

Fig. 6. Optimal equilibrium solutions for Scenarios 1/2/3 - Nash game structure.

make at least the minimum profit based on government tariffs (Fig. 5(a) Profits of renewable energy producers; Fig. 5 (b) Profits of conventional energy producers).

5.3. Equilibrium solutions of the numerical example

Fig. 6(a and b, c) and 7(d, e, f) shows the equilibrium solutions and the optimal solutions of the numerical example in each



(d)

(e)

(f)

Fig. 7. Optimal equilibrium solutions for Scenarios 1/2/3 - cooperative game structure.

Table 5
Optimal equilibrium solutions for Nash game structure.

Scenario	Government		Renewable manufacturer				Conventional manufacturer			
	s^N	t^N	p_{rl}^N	$(p_{rl}-s)^N$	p_{rh}^N	$(p_{rh}-s)^N$	p_{nl}^N	$(p_{nl}+t)^N$	p_{nh}^N	$(p_{nh}+t)^N$
1	30.1	81.64	1094.47	1064.37	1295.54	1265.44	745.986	827.626	889.959	971.599
2	32	84.6	1095.75	1063.75	1296.81	1264.81	744.152	828.752	888.125	972.725
3	33.41	86.91	1096.7	1063.29	1297.77	1264.36	742.725	829.635	886.698	973.608

Table 6
Optimal equilibrium solutions of demand and profit functions in Nash game structure.

Scenario	Renewable energy		Conventional energy		Manufacturers		Government		
	D_{rl}^N	D_{rh}^N	D_{nl}^N	D_{nh}^N	π_r^N	π_n^N	π_{RG}^N	π_{SW}^N	π_E^N
1	10532.6	11558.6	7103.86	7911.51	2.2084 + 07	1.02081 + 07	5.61E+05	*	*
2	10566.2	11592.2	7059.68	7867.33	2.21399 + 07	1.01536 + 07	*	5.9802 + 07	*
3	10591.5	11617.4	7025.42	7833.07	2.21818 + 07	1.01114 + 07	*	*	185419

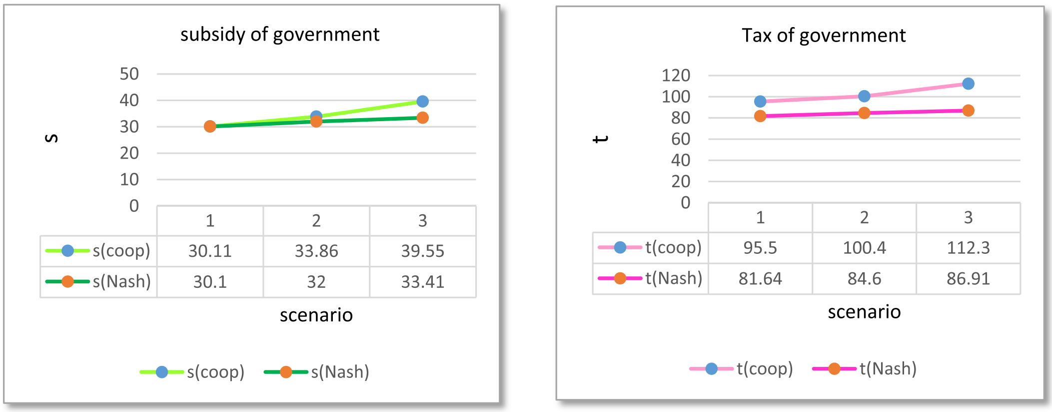
scenario. For all three scenarios, the feasible area is the intersection of the two constraints and the objective function. The government revenue, social welfare, and environmental impact functions are shown in yellow, red, and green, respectively. For each scenario, the contour plot of the government objective is also illustrated. For each scenario, the points at the intersection of the government objective functions are the optimal points for subsidy and tax rates. These figures are used to further explore the results in the next section. The optimal equilibrium solutions in Nash and cooperative game structures in each scenario are presented in Tables 5–8 (The

Table 7
Optimal equilibrium solutions for cooperative game structure.

Scenario	Government		Renewable manufacturer				Conventional manufacturer			
	s^c	t^c	p^c_{rl}	$(p_{rl}\text{-}s)^c$	p^c_{rh}	$(p_{rh}\text{-}s)^c$	p^c_{nl}	$(p_{nl}+t)^c$	p^c_{nh}	$(p_{nh}+t)^c$
1	30.11	95.5	1224.08	1193.97	1444.33	1414.22	899.469	994.969	1067.39	1162.89
2	33.86	100.4	1226.19	1192.33	1446.44	1412.58	896.638	997.038	1064.55	1164.95
3	39.55	112.3	1229.28	1189.73	1449.53	1409.98	889.672	1001.972	1057.59	1169.89

Table 8
Optimal equilibrium solutions of demand and profit functions in the cooperative game structure.

Scenario	Renewable energy		Conventional energy		Manufacturers	government		
	D^c_{rl}	D^c_{rh}	D^c_{nl}	D^c_{nh}	π^c_{COOP}	π^c_{RG}	π^c_{SW}	π^c_E
1	9796.29	10327.9	5849.47	6024.62	3.28894 + 07	528036	*	*
2	9830.13	10357.5	5809.16	5989.97	3.29075 + 07	*	5.39487 + 07	*
3	9888.05	10409.2	5716.31	5911.05	3.28702 + 07	*	*	159623



(a) (b)

Fig. 8. Comparison of subsidies/taxes in Nash and cooperative game structures in the three scenarios.

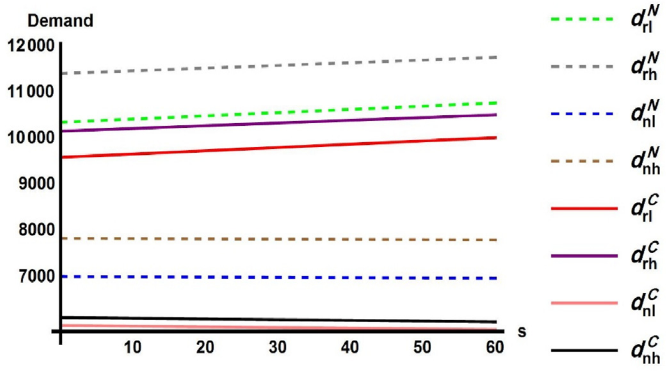


Fig. 9. Comparison of change in demand with changes in subsidy in Nash and cooperative game structures.

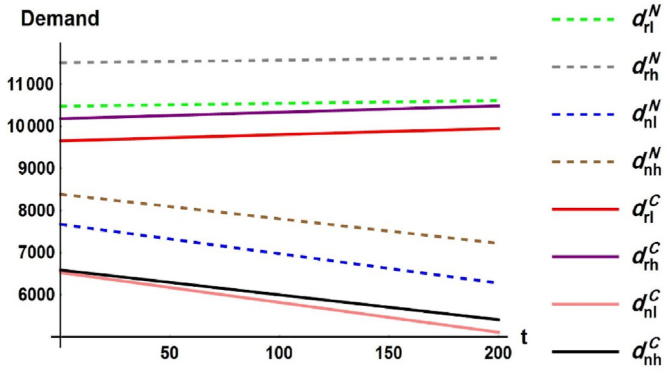
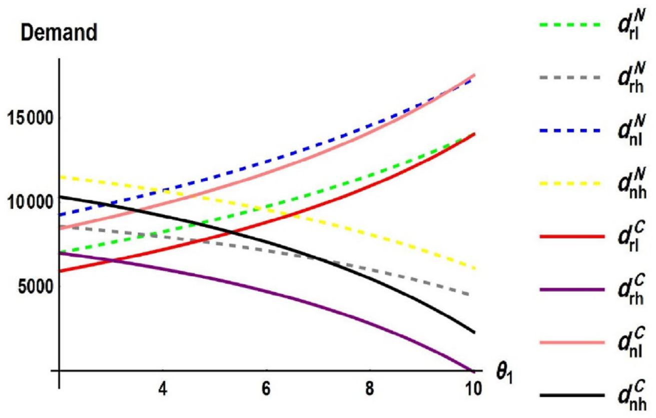


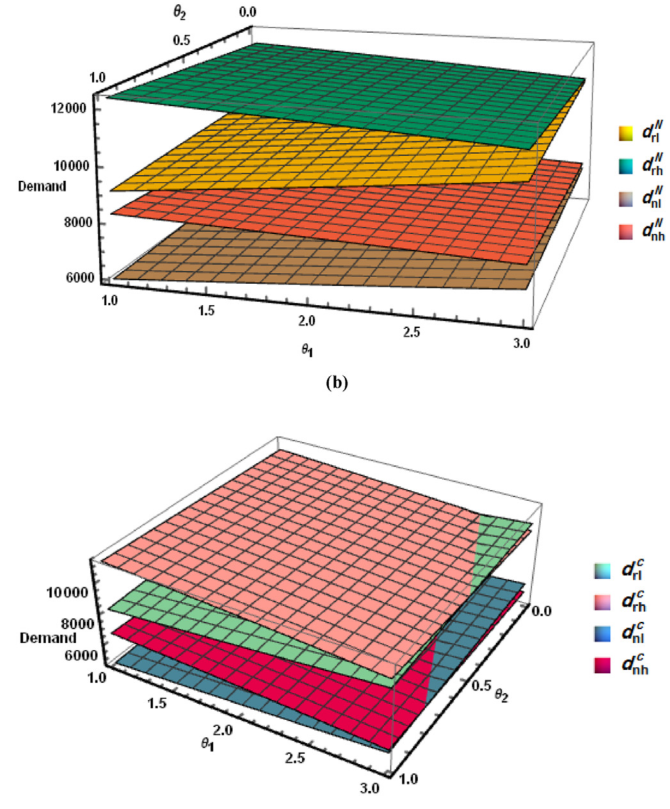
Fig. 10. Comparison of change in demand with changes in tax in Nash and cooperative game structures.

values marked with a star in Tables 6 and 8 are the upper and lower bounds considered for the government functions.).

Based on the numerical results presented in Tables 5 and 7, prices in the Nash structure are lower than prices in the cooperative structure, hence in Tables 6 and 8, demand in Nash structure is more than cooperative structure. Considering to social welfare and government revenue functions are also depend on demand, the government revenue and social welfare functions gain higher values in the Nash game structure than in the cooperative game structure (where producers are integrated), but the environmental effect function takes lower values when renewable and conventional energy producers collaborate.



(a) Demand shift with changes in θ_1



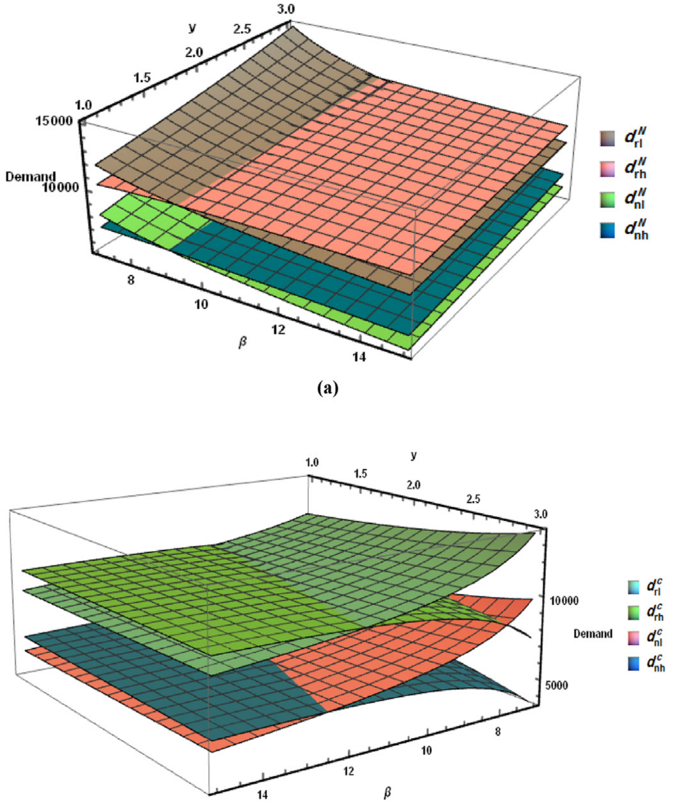
(b)

(c)

Fig. 11. Demand changes with changes in θ_1 and θ_2 in the Nash/cooperative game structure.

As shown in Fig. 8 (a) and (b), in both cooperative and Nash game structures, subsidies, and taxes are highest in Scenario 3, where the government is focused on minimizing environmental impacts. After this scenario, scenario 2, where the government seeks to maximize social welfare, has the highest of subsidies and taxes.

Corollary 3. *In both Nash and cooperative game structures, the government should consider higher amounts of subsidies and taxes to achieve the goal of minimizing environmental impact and maximizing social welfare. The subsidies and taxes needed for minimizing environmental impacts are higher than those needed for maximizing social welfare and government revenue.*



(a)

(b)

Fig. 12. Comparison of change in demand with changes in y and β in Nash/cooperative game structure.

Corollary 4. *In all three scenarios, the value of subsidies and taxes needed in the cooperative game structure is greater than in the Nash game structure.*

In Fig. 9 for the equilibrium tax value in Scenario 1, demand for renewable energy increases, and demand for conventional energy decreases with the increasing subsidy in both game structures. Also, in both game structures, demand for renewable energy is higher than demand for conventional energy.

Corollary 5. *Demand is higher when renewable and conventional energy producers compete with each other than when they cooperate. Also, the higher the subsidy given to encourage consumers to use renewable energy, the greater will be the demand for renewable energy in both low-load and high-load periods.*

as shown in Fig. 10, for the optimal subsidy value in scenario 1, demand for renewable energy increases, and demand for conventional energy decreases with the increasing tax in both game structures.

Corollary 6. *the higher the tax imposed on conventional energy consumers, the lower will be the demand for conventional energy, and the greater will be the demand for renewable energy in both low-load and high-load periods. In general, tax policy results in a lower propensity to use conventional energy compared to renewable energy.*

In Fig. 11 (a), it can be seen that as θ_1 (elasticity of demand in low-load period relative to the specified price for the high-load period) increases, in both Nash and cooperative game structures, demand shifts from high-load (peak) periods to low-load periods.

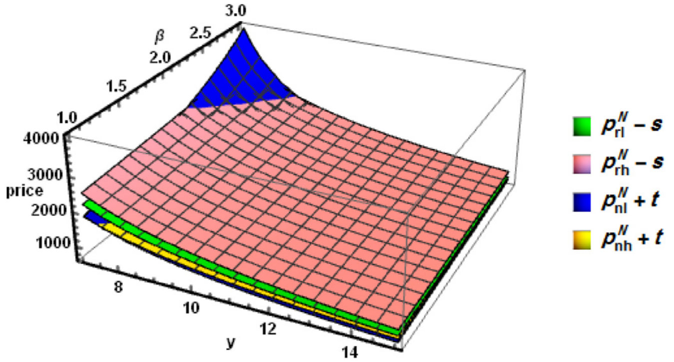
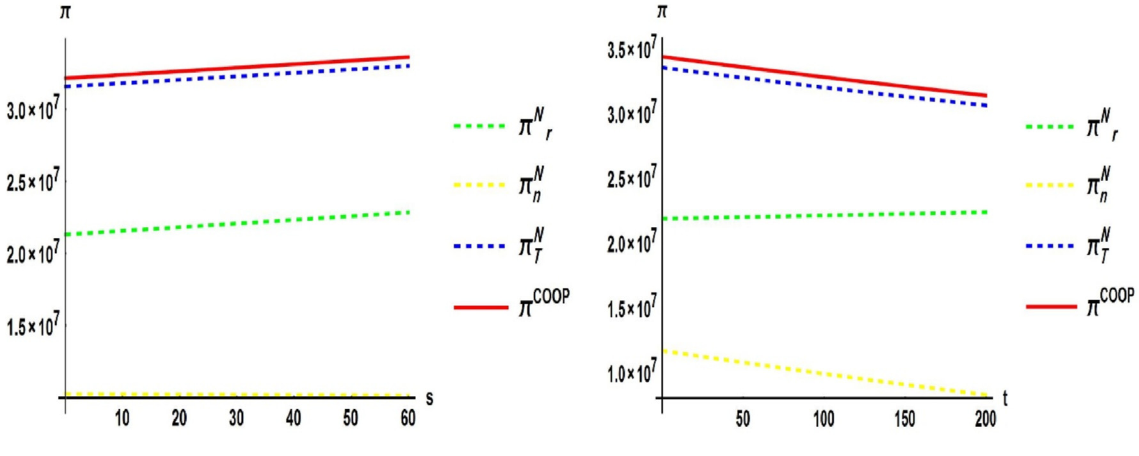


Fig. 13. Changes in end-price with changes in y and.β

Corollary 7. *The greater the ɵ$_1$ coefficient is than ɵ$_2$, the greater will be the demand elasticity (shift from high-load to low-load period) and the more effective will be the demand side management in modifying the consumption pattern, which will lead to increased profits for producers and consumers.*

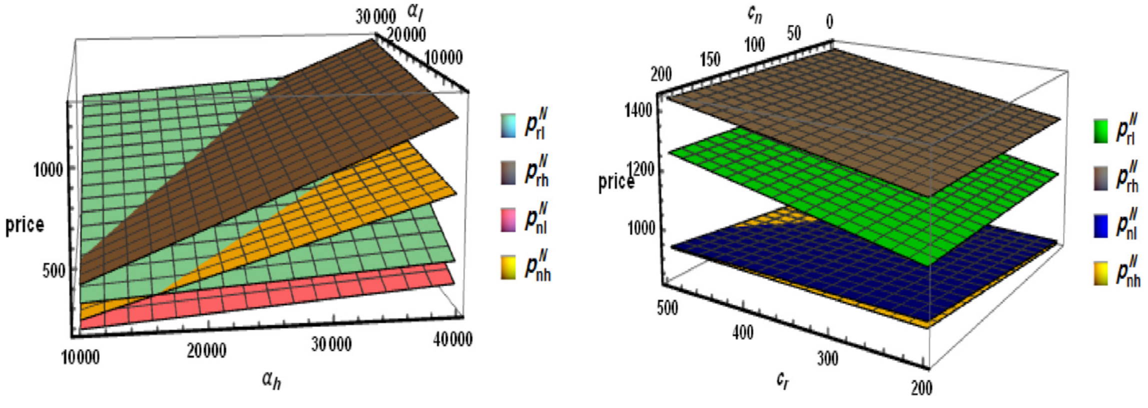
As shown in Fig. 12 (a) and (b), in both Nash and cooperative games, demand shifts from high-load to low-load periods with increasing y and decreasing β.

Corollary 8. *Applying the TOU pricing scheme reduces consumption in high-load periods (as consumers try to avoid peak prices), leading to demand-side management. Also, in both Nash and cooperative games, it results in higher demand for renewable energy than for conventional energy.*



(a) (b)

Fig. 14. Changes in profit with chang in subsidy/tax.



(a) (b)

Fig. 15. Changes in price with changes in a) α_l and α_h b) c_r and.c_n

Also, as shown in Fig. 11 (b) and (c), demand shifts from high-load periods to low-load periods with the increase in ɵ$_1$ and the decrease in ɵ$_2$ (elasticity of demand in high-load period relative to the price set for the low-load period) in the Nash and cooperative game structures, respectively.

Fig. 13 shows the changes in the final price that the consumer has to pay based on government tariffs in the Nash game structure (the same is also true for the cooperative game).

Corollary 9. *Reducing the price cross-sensitivity coefficient and increasing the self-price sensitivity coefficient increase the final* *consumer prices. This has more effect on the price of conventional energy than on the price of renewable energy (these changes cause the demand for renewable energy to exceed the demand for conventional energy* (Fig. 12 (*a*))

As Fig. 14 (a) demonstrates, increasing subsidies increases the profit of the renewable energy producer by affecting demand for renewable energy. Increasing subsidies also reduces the profit of the conventional energy producer by decreasing conventional energy consumption. The shared profit of producers in the cooperative game is greater than their total profit in the Nash game and increases with increasing subsidies. As shown in Fig. 14 (b), in the Nash game, increasing the tax rate decreases the profit of the conventional energy producer (because of lower propensity to use conventional energy) but increases the profit of the renewable energy producer. The total profit of the producers in both Nash and cooperative game structures decreases with the increase in tax.

Corollary 10. *In the Nash game structure, increasing the subsidy increases the profit of the renewable energy producer and decreases the profit of the conventional energy producer. Increasing the subsidy also increases the profits of the producers in the cooperative game structure.*

Corollary 11. *In the cooperative game, increasing the tax rate reduces the profit of the conventional energy producer and increases the profit of the renewable energy producer.*

As shown in Fig. 15 (a), in the Nash game, as α_l and α_h increase, so do the prices of renewable and conventional energy in both low-load and high-load periods (confirming Corollary 1). Also, as potential demand in low-load and high-load periods increase, the price for the high-load period increases more than the price for the low-load period.

Corollary 12. *The higher the energy demand is, the higher is the price increase for both renewable and conventional energies in the low-load and high-load periods. This price increase is more pronounced in the high-load period.*

In Fig. 15 (b), it can be seen that in the Nash game structure, as c_r increases, so does the price of renewable energy in low-load and high-load periods (confirming Corollary 2). With the increase in c_n, the price in the high-load period increases more than the price in the low-load period. The same conclusions regarding c_r and c_n are also true for the cooperative game.

Corollary 13. *The higher the cost of renewable and conventional energy production, the higher the prices to increase the profit of producers.*

5.4. Managerial insights

Insight 1: The government's strategy in the pursuit of sustainable development goals affects the profits of energy producers, demand for conventional and renewable energy, and prices of these energies in low-load and high-load periods in both Nash and cooperative games, and the government can increase the propensity to use renewable energy through taxation and subsidy measures.

Insight 2: By classifying demand in multiple periods, one can identify the factors that increase the low-load demand and decrease the high-load demand and use this knowledge to improve the consumption pattern.

Insight 3: In both Nash and cooperative games, renewable energy consumption exceeds conventional energy consumption. The demand for renewable energy is higher in the Nash game than in the cooperative game. However, the selling price of electricity is higher in the cooperative game than in the Nash game. As a result, the producers make more profit in the cooperative game structure than in the Nash game structure.

Insight 4: The shared profit of the producers in the cooperative game is greater than their total profit in the Nash game structure. The environmental impact function also gains better values in the cooperative game. However, the government revenue and social welfare functions gain better values in the Nash game structure.

Therefore, the decision that whether competition between producers should be a cooperative game or a Nash game should be made based on which sustainability goal is of higher priority for the government. If the top priority of the government is to minimize environmental impacts, then the recommended approach is to nurture cooperation between producers, especially since they will earn more profit in a cooperative game.

6. Summary and conclusion

In this paper, the game theory approach was used to perform TOU pricing for low-load and high-load periods in a competitive energy market containing both renewable and conventional energy supply chains in the presence of government interventions. The energy supply chain as a whole was assumed to be consisting of a renewable energy producer, a conventional energy producer, and some consumers. The government and the producers were considered as respectively the leader and the followers of a Stackelberg game, which was modeled with two Nash and cooperative game structures. It was assumed that the government pursues sustainable development through three goals of maximizing revenue, maximizing social welfare, and minimizing environmental impacts. After defining three scenarios, each representing focus on one of these three goals, the optimal tax and subsidy rates under these three scenarios in two Nash and cooperative game structures were determined and then optimal values of other variables including prices, demand, and producers' profits were obtained by backward induction.

The results showed that TOU pricing for the leveling of consumption pattern for demand-side management purposes resulted in a shift in demand from high-load periods to low-load periods in both Nash and cooperative modes. Also, In all three scenarios, government tariffs were higher in the cooperative game than in the Nash game. The environmental impacts function had a smaller value when the two producers were integrated (Approximately 14% reduction), but the government revenue function and the social welfare function had greater values when producers were not cooperative (Approximately 6% and 10% increase, respectively). This means that setting up a more competitive environment to draw more revenue for the government will result in less desirable environmental impacts. Thus, if minimizing environmental impacts is a higher priority, it is preferred to create a cooperative relationship between producers.

In all three scenarios, demand was higher in the Nash game than in the cooperative game. However, because of the higher selling price of electricity in the cooperative game compared to the Nash game, the producers make more profit in the cooperative game structure. For each of the nash or cooperative structures, when the government pursues a social welfare goal (Scenario 2), total profits of producers is at a maximum value, compared to the other two scenarios. Also, the higher the subsidy given to encourage consumers to use renewable energy, the greater will be the demand for renewable energy in both low-load and high-load periods and the higher the tax imposed on conventional energy consumers, the lower will be the demand for conventional energy, and the greater will be the demand for renewable energy in both low-load and high-load periods. Therefore, in both Nash and Cooperative game structures, the optimal demand for renewable energy was higher than that for conventional energy.

Based on the results of the current study and in order to benefit from the results, it is recommended that the government optimally develop renewable energy using subsidies and taxes. Also encourage the propensity for cooperation between producers in order to reduce costs, environmental impacts and increase the profits of producers of renewable and conventional energy.

Since energy is a strategic commodity and uncertainty in energy supply poses threats to the economy, future studies are recommended to examine the competition between energy producers while taking into account factors such as energy availability and security. Also, considering the intermittent nature of renewable energy sources, which prevents them from competing with conventional energy sources, it is crucial to invest in storage technologies in renewable energy supply chains to ensure supply reliability, and this assumption should be considered in future research. Furthermore, considering the diverse economic and environmental impacts of carbon control policies such as carbon tax, carbon offset, and cap-and-trade policy have different effects on the energy supply chain, future studies in the area of energy pricing are best to be done with such policies taken into account.

Credit author statement

Sima Amiri-Pebdani: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization, Investigation. Mahdi Alinaghian: Supervision, Validation, Writing – review & editing. Soroush Safarzadeh: Validation, review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.124380.

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