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ORIGINAL RESEARCH

Analysis of implementation of Tradable Green Certificates system in a competitive electricity market: a game theory approach

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Abstract This paper investigates three models to implement Tradable Green Certificates (TGC) system with aid of game theory approach. In particular, the competition between thermal and renewable power plants is formulated in three models: namely cooperative, Nash and Stackelberg game models. The price of TGC is assumed to be determined by the legislative body (government) which is fixed. Numerical examples presented in this paper include sensitivity analysis of some key parameters and comparison of the results of different models. In all three game models, the parameters that influence pricing of the TGC based on the optimal amounts are obtained. The numerical examples demonstrate that in all models: there is a reverse relation between the price of electricity and the TGC price, as well as a direct relation between the price of electricity and the share of green electricity in total electricity generation. It is found that Stackelberg model is an appropriate structure to implement the TGC system. In this model, the supply of electricity and the production of green electricity are at the highest level, while the price of electricity is at the lowest levels. In addition, payoff of the thermal power plant is at the highest levels in the Nash model. Hence this model can be an applicatory structure for implementation of the TGC system in developing countries, where the number of thermal power plants is significantly greater than the number of renewable power plants.

Keywords Green electricity · Tradable Green Certificate · Game theory · Renewable energy

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Introduction

In the energy sector, climate change and energy security are significant factors affecting policies, regulations and investment (REN21 2012; Bazilian et al. 2011). With respect to growing concerns about climate changes, many countries have pursued policies to develop clean energy and set mandatory targets for renewable-source and low-carbon emission. For instance, European Union (EU) proposes a goal of 20 % share of renewable energy sources in the Union's total energy consumption by 2020 (Zhou 2012).

In global primary energy, the share of renewable energy could increase from the current 17 to 30 or 75 %, and in some nations exceed even 90 %, until 2050 (Johansson et al. 2012). Renewable energy (RE) considerably influences over many areas such as: strengthening economic growth to promote industrial development and employment, contribute to the transition toward a low carbon development growth for reduction of the greenhouse gas emissions, enhancement of technology diversification and hedging against fuel price volatility to increase supply adequacy, and facilitating the access to electricity to promote rural development and social welfare (Azuela and Barroso 2012; Fargione et al. 2008).

Electricity industry is one of the most important sources of pollution and RE plays a key role in the electricity generation. Most nations have pursued some policies to support the electricity generation from the renewable

energy sources as one of the ways to curb global warming. In this regard, two of the most common practices are feed-in tariff and TGC systems (Tamás et al. 2010).

Some studies tried to answer the question of how does the feed-in tariff could affect selection of the energy resources. For example, Mahmoudi et al. (2014) proposed a computational framework for helping the government to determine the optimal taxes and subsidies for each individual electric power plant in a competitive electricity market, regarding the emitted pollutants of the power plants.

Taxes and subsidies on some technologies may help the government to achieve sustainable development objectives. The existing literature on TGC proposes that when the substantial investments in RE are already in place and the technologies are at a mature stage, switching to implementation of a TGC system is an appropriate alternative (Ciarreta et al. 2014).

A TGC system is introduced as renewable portfolio standards (RPS) or renewable obligations (RO) recognized in the RE Sector where the producers, retailers, consumers and distributors are required to accept obligation of a certain share in the production or consumption of electricity from renewable sources (Aune et al. 2012). The main objective of the TGC system is increasing the share of credit for green electricity generation from renewable sources, with the minimum possible cost for the government (Vogstad 2005).

Tamás et al. (2010) showed TGC system more efficient from feed-in tariff. RPS laws or TGC system use in 25 countries at national level and 54 states/provinces in the United stated, Canada, and India (REN21 2014). The Renewable Obligation was introduced in the UK in 2002 to support generation of green electricity. The RO target started at 3 % for the first period 2002–2003, increased annually by 1 % until it reach to 15.4 % in 2015–2016 (Zhou 2012). The UK increased the level of support for offshore wind producers under its green certificate scheme to 0.26 USD/KWh. At the beginning of 2012, the Norwegian–Swedish TGC market lunched to develop renewable capacity to produce 26/4TWh up to 2020. Romania implemented new law aimed at limiting the capacity expansion, growth of new players and more interesting for investors of TGC market (REN21 2014).

In this paper, competition of the power plants is modeled in the electricity market and the TGC system under producers' obligations. Therefore, some models are developed for two situations: competitive (Nash and Stackelberg equilibriums) and cooperative situations. Furthermore, adopting a numerical example, the impact of minimum share of electricity supply from RE sources and price of certificates on total supply and price of electricity, moreover, payoff and production of the power plants.

The reminder of the paper is organized as follows. "Literature review" section briefly discusses the related literature. "Prerequisites and assumptions" section describes the prerequisites and assumptions. "Model formulation" section provides the formulations of power plants problems. "Game theory models" section presents three game theory models for implementation of TGC system. "Numerical examples and sensitivity analysis" section discusses a numerical examples along with a set of sensitivity analyses. "Conclusion" section provides the conclusions and several directions for future research.

Literature review

TGC are financial assets provided for green electricity producers for the amount of green electricity measured and fed into the electricity grid. The TGC may be considered as a market-oriented environmental subsidy (Vogstad 2005; Boots 2003). In other words, the renewable power plants that generate electricity from RE (green electricity), benefit from a double source of income, from the sale of both physical electricity and green certificates (Farinosi et al. 2012).

A system of TGC is both an economic mechanism that supports RE production and a regulatory instrument available for public authorities to reach a specified goal for RE production. The market for TGC consists of supply and demand for certificates (Nielsen and Jeppesen 2003). Demand is created by a politically determined target for the share of electricity production or consumption from RE. Based on the policies of each country, any point on the electricity supply chain can be required to obligation of the set of targets. As shown in Fig. 1, the obligation can be placed at: supply, transmission, distribution and consumption electricity (Mitchell and Anderson 2000).

The TGC are generated by producers of green electricity. A certificate is issued for a certain amount of the green electricity generated. The size of certificate can be 1 MW/h or higher units of the green electricity produced. The certificates can be sold by the renewable power plant separately from the physical electricity. Every entity in the electricity supply chain like producers (except the green electricity producers), distributors, retailers, importers and

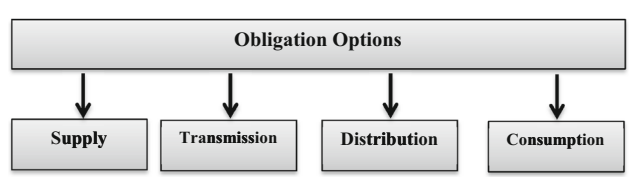

Fig. 1 Obligation option

consumers can be obliged to purchase a certain portion of the certificates from a renewable power plant. Financial market for the certificates may be created from interaction between the green electricity producer (as the TGC supplier) and the obligated entity (as the TGC demand). For instance, because the customer's obligation is considered in Denmark (Nielsen and Jeppesen 2003), interaction between customers and green electricity producers creates a market for TGC. In this approach, the consumers are obliged to consume a minimum quota of the green electricity, by purchasing the related certificates.

In designing of the TGC system, there are four mechanisms to organize the demand for certificates (Schaeffer et al. 2000):

1. An obligation on an entity in the electricity supply chain, to purchase a certain number of certificates within a certain period,
2. Setting a fixed price at which the certificates can be sold to a certain actor,
3. A tendering process aiming at buying the certificates,
4. Voluntary demand.

There are a few formal analyses of the TGC system (Tamás et al. 2010). Amundsena and Mortensen (2001) investigated the electricity and TGC markets in the case of Denmark assuming a perfect competition. They showed that an increase in the mandatory quota of the green electricity decreases the total supply and increases the electricity price. In the same case and method, Jensen and Skytte (2003) demonstrated that there is a linear relationship between the electricity price and the certificate price. They showed that the linear coefficient depends on the mandatory quota of green electricity by assuming a perfect competition on the certificates market and monopolistic competition on the electricity market. In a case study of Italy, Lorenzoni (2003) explained a formal implementation of the TGC system in 2002 and showed possible trends of the quantity and price of the certificates in the coming years. Verbruggen (2004) described details of the TGC system in some regions of Belgium and analyzed the established TGC system in Flemish region.

Ford et al. (2007) used system dynamics method to anticipate the price of certificate in a market TGC, to promote generation of the electricity from wind energy. They concluded that the certificate price climbs rapidly in the early years after a market opens. After a few years, it would lead to this fact that the electricity generated from the wind energy exceeds the requirement. Zhou and Tamas (2010) investigated the influences of integrating the production of green and thermal electricity on performance of the TGC system. They assumed that both the electricity and the certificate markets are imperfect. They showed that total supply of the electricity is greater under integration than when in disintegration; whereas, the price of TGC in an integrated market is higher than that of the disintegrated market.

Colcelli (2012) by quality method discussed the problem of legal nature of TGC in Italy and concluded that TGC be regarded as good. Currier (2013) examined a Cournot electricity oligopoly operated under TGC system with producer obligation. He calculated parametric optimal percentage requirement using Bound branches algorithm to sure maximum social welfare. Fagiani et al. (2013) by system dynamic approach analyzed the performance of feed-in tariff and TGC markets. They simulated electricity market a period which cover 39 years from 2012 to 2050 in case of Spain and showed Tariffs could obtain better efficiency but also low effectiveness or over-investment, moreover, TGC performances benefit from higher social discount rates. Ciarreta et al. (2014) analyzed implementation of TGC system in Spain. They modeled interaction between the electricity pool and TGC market and analyzed this, through solving a sequential game. They studied the retailer regulation design that would give lead to a decreasing TGC demand and simulated the impact of same regulation on the TGC price.

Currier and Sun (2014) investigated performance of TGC system in electricity market under alternative market structure. They demonstrated that an oligopolistic market structure may create more welfare than a competitive market structure. Fagiani and Hakvoort (2014) analyzed the impact of regulatory changes on TGC price volatility in Swedish market and a bigger Swedish/Norwegian market. By econometrics approach, they showed regulatory change harms TGC market and bigger Swedish/Norwegian market has not resulted in lower volatility yet.

Most researchers investigated the electricity market and the TGC market with economic analysis and systems dynamic methods. Moreover, most of the previous researches have concentrated on implementation of the TGC systems in a specific country. To the best of authors' knowledge, there is no research in this context which adopts the game theory approach. Analysis based on game theory approach helps to policy makers for market structure design for electricity and TGC market. Some studies consider to market structure in the case of imperfect and perfect competition generally by simple economic method. In this paper, we aim model market structure of electricity and TGC markets in case of imperfect competition Cournot oligopoly and monopoly under fixed TGC price policy.

Prerequisites and assumptions

For simplicity of this research, we concentrate on interaction of two power plants: green and thermal electricity producers. These power plants compete together in the

electricity markets under the TGC system. Under the TGC system, a thermal electricity producer is obliged to acquire a minimum number of green certificates. This number corresponds to a percentage (quota) of the yearly thermal electricity generated.

It is assumed that the minimum quota and price of the certificates are set by the lawgiver. This means that the price of certificates is fixed and not determined by the market equilibrium of supply and demand.

Assumptions

The proposed models in this paper are based on the following assumptions:

1. Power plants have no limitation on consumption of the resources.
2. The price of certificates is only at fixed prices in the long term similar to the former feed-in tariffs.
3. The electricity price is set under a national supply and demand mechanism (in the local market).
4. There are no limitations on the supply and demand for the electricity as well as the certificates.
5. There are no excess supply and demand in the markets of electricity and certificates.

Notations

Before describing the payoff functions for the companies, the indices, parameters and decision variables are explained below:

Parameters

α the minimum mandatory quota (percentage) of green electricity, $0 \leq \alpha \leq 1$;
π_R the profit function of renewable power plant;
π_T the profit function of thermal power plant;
π the total payoff of centralized power plant, $(\pi = \pi_R + \pi_T)$;
C_T the cost function of thermal power plant;
C_R the cost function of renewable power plant;
P_c the price of green certificates (\$/MWh), $P_c > 0$;
γ the cap price of electricity, $\gamma > 0$;
β the price elasticity of electricity supply; $\beta > 0$.

Decision variables

P_e the wholesale price of electricity (\$/MWh), $P_e > 0$;
q_T the quantity production of electricity from non-renewable energy sources (MW), $q_T \geq 0$;
q_R the production of electricity from renewable energy sources (MW), $q_R \geq 0$;
Q the total supply of electricity (MW), $Q \geq 0 (Q = q_T + q_R)$.

Model formulation

Producer of renewable power

We adopted profit functions proposed by Currier and Sun (2014), and considering relation between wholesale price and end-user price of electricity explained by Amundsen and Bergman (2012). In their model, producer of green electricity can sell both electricity generated on the electricity market as well as certificates on separate market. The cost of renewable power plant is function of electricity generated from renewable sources. Therefore, profit maximization problem for renewable power plant can be formulated as follows:

$$\text{Max} \quad \pi_R = [P_e + P_c]q_R - C_R(q_R)$$
$$\text{S.t:}$$
$$q_R \geq 0 \tag{1}$$

This means that a renewable producer can receive P_c for each unit in addition to the electricity price. Cost of the renewable producer is dependent only on the actual amount of electricity production. Under the TGC system, a renewable producer would receive per unit "subsidy" P_c.

Producer of thermal power

A producer of the thermal power can sell the electricity generated in the electricity market. It is obligated to supply a certain proportion of the green electricity from total electricity supplied on the grid. It can fulfill their obligation by either supplying the green electricity or by purchasing the TGC.

The cost of a thermal power plant is a function of the electricity generated from the non-renewable sources. Therefore, the profit maximization problem for the producer of thermal power is as follows:

$$\text{Max} \quad \pi_T = [P_e - P_c\alpha]q_T - C_T(q_T)$$
$$\text{S.t:}$$
$$q_T \geq 0 \tag{2}$$

Thermal producer can receive P_e for each unit of electricity. Cost of the thermal power is dependent only on the actual amount of the electricity production. It is obligated to payment for buying the TGC from the renewable pro-

ducer, to compensate for the unfulfilled requirement. Therefore, the thermal producer under the TGC system virtually pays a per unit "tax" αP_c as in Eq. (2). In our model, only a thermal power plant is obligated to hold a number of the TGC equal to α times its production.

Cournot model

According to the Cournot model, the price is a function of the production quantity. Kreps and Scheinkman (1983) discussed that if the producers first determine their capacity, and only later are allowed to set a price, the outcome will be the Cournot equilibrium.

Thus, it can be assumed that the electricity price is a function of the total electricity generated by the renewable and non-renewable sources.

$$P_e = \gamma - \beta Q = \gamma - \beta(q_R + q_T) \tag{3}$$

where γ the cap is the price of electricity and β is the price elasticity of the electricity supply. Meanwhile, $Q = (q_R + q_T)$ is the total electricity supply. It is assumed that $\beta > 0$.

Cost function

It is assumed that the cost function of the power plants is a quadratic function. The cost functions for the renewable and thermal power plant can be described as follows:

$$C_R(q_R) = a_R q_R^2 + b_R q_R + c_R \tag{4}$$

$$C_T(q_T) = a_T q_T^2 + b_T q_T + c_T \tag{5}$$

In Eqs. (4) and (5), it is assumed that $a_R, b_R, a_T, b_T > 0$, and the marginal production costs are increasing. Jensen and Skytte (2003) used the same model for the cost function of the power plants.

Profit maximization problem for power plants

Substituting Eqs. (3), (4) and (5) into Eqs. (1) and (2), the problems of power plants can be described as follows.

The profit maximization problem for the producer of green electricity is given below:

$$\text{Max} \quad \pi_R = [\gamma - \beta(q_R + q_T)]q_R + P_c q_R - a_R q_R^2 - b_R q_R - c_R$$

S.t:

$$q_R \geq 0; \quad a_R, b_R > 0 \tag{6}$$

The profit maximization problem for the producer of thermal power is given below:

$$\text{Max} \quad \pi_T = [\gamma - \beta(q_R + q_T)]q_T - P_c q_T - a_T q_T^2 - b_T q_T - c_T$$

S.t:

$$q_T \geq 0; \quad a_T, b_T > 0 \tag{7}$$

Game theory models

Nash equilibrium

Nash equilibrium (NE) solution is one of the fundamental solution concepts in the game theory. NE solution is where the strategy of each player is the best response against strategies of the rivals. Because of deviation from NE would lead to reduction of player's profit, none of the players has motivation to reject this strategy. The NE of the game is defined as follows (Krause et al. 2006):

In a game of n players, the strategy profile $P^* = (P_1^*, \ldots\ldots, P_n^*)$ is a NE if for all I $i = \{1, \ldots\ldots, n\}$ there is:

$$U_i = (P_1^*, \ldots\ldots, P_n^*) \geq (P_1^*, \ldots\ldots, P_{i-1}^*, P_i, P_{i+1}^*, \ldots\ldots P_n^*) \tag{8}$$

where U_i is the utility function of the ith player.

Several algorithms have been developed for computing of NE. The interested reader may refer to Krause et al. (2004) and Porter et al. (2008). In this study, an NE approach is used for the Cournot game to calculate the price equilibrium of the electricity in a competitive market under a green certificate system.

Based on the NE, q_T^* and q_R^* will be obtained from Eqs. (6) and (7) first, then with substitution of q_T^* and q_R^* into π_R and π_T, respectively, the maximum profit of the power plant will be obtained as π_T^*, π_R^*.

Proposition 1 *If the profit function of the power plants is concave, the optimal amounts of production for the green and thermal power plants in the Nash model are*

$$q_{R[N]}^* = \frac{AP_c + B\beta + 2a_T C}{2D + 2\beta^2} \tag{9}$$

$$q_{T[N]}^* = -\frac{P_c(2\alpha a_R + 2\beta\alpha + \beta) + \beta(-b_R + 2b_T - \gamma) + 2a_R(b_T - \gamma)}{2D + 2\beta^2} \tag{10}$$

where $A = \alpha\beta + 2a_T + 2\beta$, $B = -2b_R + b_T + \gamma$, $C = -b_R + \gamma$, $D = 2a_R a_T + 2a_R\beta + 2a_T\beta + \beta^2$. *[N] Denotes the optimum amounts in the Nash model.*

Proof of all the propositions are given in "Appendix". Substituting Eqs. (9) and (10) into Eqs. (6) and (7), an optimal payoff of the renewable and thermal power plants is obtained in the Nash game model as follows:

$$\pi^*_{R[N]} = (AP_c + B\beta + 2a_T C)\left[\gamma - \beta\left(\frac{P_c(2\alpha a_R + 2\beta\alpha + \beta) + \beta(-b_R + 2b_T - \gamma) + 2a_R(b_T - \gamma) + AP_c + B\beta + 2a_T C}{(2D + 2\beta^2)^2}\right) - \frac{a_R(AP_c + B\beta + 2a_T C)}{(2D + 2\beta^2)^2} - \frac{b_R + P_c}{2D + 2\beta^2}\right] - c_R \tag{11}$$

$$\pi^*_{T[N]} = \left(\frac{P_c(2\alpha a_R + 2\beta\alpha + \beta) + \beta(-b_R + 2b_T - \gamma) + 2a_R(b_T - \gamma)}{2D + 2\beta^2}\right)\left[\gamma - \frac{a_t}{2D + 2\beta^2} + P_c\alpha - b_T - \beta\left(\frac{-P_c(2\alpha a_R + 2\beta\alpha + \beta) - \beta(-b_R + 2b_T - \gamma) - 2a_R(b_T - \gamma) + AP_c + B\beta + 2a_T C}{2D + 2\beta^2}\right)\right] - c_T \tag{12}$$

Since the TGC price is determined by the government and it is fixed to help the government for pricing the TGC, the parameters that influence the price of TGC is found based on the optimal amounts. Substituting $q^*_{R[N]}$ and $q^*_{T[N]}$ into Eq. (3) gives:

$$P^*_{c[N]} = \frac{-P^*_e(2\beta^2 + 2D) - \beta^2(B + b_R - 2b_T - \gamma) - \beta(2Ca_T - 2a_R b_T + 2a_R\gamma) + 2D\gamma}{(A\beta + 2\alpha a_R + 2\alpha\beta + \beta)} \tag{13}$$

Note that $P^*_c = P_c(P^*_e)$. Equation (13) shows that there is a linear relationship between the electricity price and the TGC price in the Nash game model. The linear coefficient is negative and depends on the minimum quota of the green electricity (α).

Cooperative game

In this section, a cooperative game approach is applied to the problem of thermal–green power plants with respect to the TGC system. Using this approach, the thermal and renewable power plants work together to determine Q and P_e. It is possible to examine whether the thermal power plant allocates a portion of its capacity to produce the green electricity to get more profit considering a situation in which it competes with renewable power plants or not? To calculate the optimal amounts under a cooperative situation, the new model will be obtained from summation of Eqs. (6) and (7).

$$\begin{aligned} \text{Max} \quad \pi = {} & [\gamma - \beta(q_R + q_T)]q_R + P_c q_R - a_R q_R^2 \\ & - b_R q_R - c_R + [\gamma - \beta(q_R + q_T)]q_T \\ & - P_c q_T - a_T q_T^2 - b_T q_T - c_T \\ \text{S.t}: & \\ & q_R, q_T \geq 0; \quad a_R, a_T, b_R, b_T > 0 \end{aligned} \tag{14}$$

Hessian matrix of π in Eq. (14) is: $H = \begin{bmatrix} -2\beta - 2a_R & -2\beta \\ -2\beta & -2\beta - 2a_T \end{bmatrix}$; the utility function π is a concave function on (q_R, q_T) if and only if the Hessian matrix H is negative definite.

Proposition 2 *If* $\det(H) > 0$, *the optimal amounts for production of the green and thermal power plants in the cooperative game model will be:*

$$q^*_{R[C]} = \frac{P_c(A - a_T - \beta) + \beta(B + b_R - \gamma) + a_T C}{D - \beta^2} \tag{15}$$

$$q^*_{T[C]} = \frac{P_c(A - 2a_T - \beta + \alpha a_R) + \beta(B + b_R - \gamma) + a_T C}{D - \beta^2} \tag{16}$$

where [C] *denotes the optimum amounts in the cooperative game model.*

Inserting Eqs. (15) and (16) into (6) and (7), the optimal payoff of the renewable and thermal power plants in the Nash game model are found as follows:

$$\pi^*_{R[C]} = \left(\frac{P_c(A - a_T - \beta) + \beta(B + b_R - \gamma) + a_T C}{D - \beta^2}\right) \left[\begin{array}{l} P_c + C - \beta\left(\dfrac{P_c(\alpha a_R + 2A - 2\beta - 3a_T) + 2\beta(b_R + B + \gamma) + 2a_T C}{D - \beta^2}\right) \\ \qquad - \dfrac{a_R(P_c(A - a_T - \beta) + \beta(B + b_R - \gamma) + a_T C)}{D - \beta^2} \end{array}\right] - c_R \tag{17}$$

$$\pi^*_{T[C]} = \left(\frac{P_c(A - 2a_T - \beta + \alpha a_R) + \beta(B + b_R - \gamma) + a_T C}{D - \beta^2}\right) \left[\begin{array}{l} \gamma - \beta\left(\dfrac{P_c(\alpha a_R + 2A - 2\beta - 3a_T) + 2\beta(b_R + B + \gamma) + 2a_T C}{D - \beta^2}\right) - \\ \dfrac{a_T(P_c(A - 2a_T - \beta + \alpha a_R) + \beta(B + b_R - \gamma) + a_T C)}{D - \beta^2} - b_T - P_c\alpha \end{array}\right] - c_T \tag{18}$$

Similar to the previous section, P_c is calculated by substituting $q^*_{R[C]}$ and $q^*_{T[C]}$ into Eq. (3) as follows:

$$P^*_{c[C]} = \frac{P^*_e(\beta^2 - D) - 2B\beta^2 - 2Ca_T\beta - 2\beta^2 b_R + \beta^2\gamma + D\gamma}{2\beta(\alpha a_R + A - 2a_T - \beta)} \tag{19}$$

Equation (19) indicates that there is a linear relationship between the electricity price and the TGC price in a cooperative game model. The linear coefficient depends on the minimum quota of the green electricity (i.e., α) but the positive or negative linear coefficient depends on other parametric values.

Non-cooperative Stackelberg games

This section considers the relationship between thermal and renewable power plants using a non-cooperative structure. The interaction between these power plants will be regarded as a Stackelberg game, where one of the participants, i.e., the leader, has the initiative and can enforce its strategy on the its rival, i.e., the follower. The leader makes the first move and the follower reacts by playing the best move according to the available information. The objective of the leader is to design its move in such a way as to maximize its profit after considering all the rational moves that can be advised by the follower.

The renewable producer–Stackelberg model takes the renewable power plant as the leader and the thermal power plant as the follower. In this section, the renewable producers first generates electricity and sells it to the distributors then the thermal producers with knowledge about the issued certificates and the remaining market share will produce and sell its electricity to the market. Considering that aim of the TGC system is supporting than increasing the share of the electricity produced from RE, the thermal producer–Stackelberg model is not investigated as a thermal producer leader.

Proposition 3 *The optimal amounts of production of green and thermal power plants in Stackelberg game model are:*

$$q^*_{R[S]} = \frac{AP_c + B\beta + 2a_T C}{2D} \tag{20}$$

$$q^*_{T[S]} = -\frac{P_c(A\beta + 2D\alpha) + \beta^2 B + Ca_T\beta + 2Db_T - 2D\gamma}{4D(\beta + a_T)} \tag{21}$$

where [S] *refers to the optimum amounts in Stackelberg model.*

Inserting Eqs. (20) and (21) into (6) and (7), the optimal payoff of the renewable and thermal power plants in Stackelberg model is obtained as follows:

$$\pi^*_{R[S]} = (AP_c + B\beta + Ca_T) \left[\begin{array}{l} \left(\frac{P_c}{2D}\right) - \frac{a_R + 2Db_R}{4D^2} + \left(\frac{\gamma - \beta}{2D}\right) \\ \left(\frac{(-2D(\alpha P_c + b_T - \gamma) + (AP_c + B\beta + Ca_T)\beta + 2(\beta + a_T)(AP_c + B\beta + Ca_T)}{8D^2(\beta + a_T)}\right) \end{array} \right] - c_R \tag{22}$$

$$\pi^*_{T[S]} = \left(P_c\alpha + \frac{(AP_c + B\beta + Ca_T)\beta}{2D} + b_T - \gamma\right) \left[\gamma - \left(\frac{(\beta + a_T)(2D(P_c\alpha + b_T + \gamma) + \beta(AP_c + B\beta + Ca_T))}{8D(\beta + a_T)^2}\right)\right] - c_T \tag{23}$$

$$P^*_{c[S]} = \frac{-4DP^*_e(\beta^2 + D) - \beta^2(2Ba_T + B\beta + Ca_T) - \beta(2Ca_T^2 - 2Db_T - 2D\gamma) + 4Da_T\gamma}{\beta(2Aa_T + A\beta - 2D\alpha)} \tag{24}$$

Substituting $q^*_{R[S]}$ and $q^*_{T[S]}$ into Eq. (3) gives:
Same as the other models, in Stackelberg game model, there is a linear relationship between the electricity price and the TGC price. The linear coefficient is dependent on the mandatory quota of the green electricity (), but the positive or negative linear coefficient depends on some other parameter values.

Numerical examples and sensitivity analysis

In this section, a number of numerical examples are presented with the aim of illustrating some significant features of the models established in the previous sections. A sensitivity analysis of the main parameters of these models will also be performed. Note that Examples (1–2) illustrate the renewable producer–Stackelberg, Nash equilibrium and cooperative game models, respectively.

Example 1 The changes of $q^*_R, q^*_T, q^*_T, Q^*, P^*_e$ with respect to the changes of α are investigated. Let the parameters be set as below:

$\gamma = 150$; $\beta = 0.4$; $a_R = 0.6$; $a_T = 0.4$; $b_R = 11$; $b_T = 8$; c_T, $c_R = 101$; $P^*_c = 18$.

Table 1 lists the results of this example in three game models. Some important results in the table are also graphically displayed in Figs. 2, 3 and 4.

The results of Example 1 show that in every three models, by increasing α, all q^*_R, π^*_R and P^*_e increase, however, q^*_T, π^*_T, Q^* and π^* decrease. The value of Q^* in the Stackelberg model will be greater than that of the Nash and cooperative models (see Fig. 2). In other words, electricity supply in Stackelberg model is set in the highest level and this can lead to social welfare improvement.

The renewable power plant acquires the maximum payoff in the cooperative model where the payoff of the thermal power plant is minimum. Moreover, the thermal power plant acquires the maximum payoff in Nash model, but the payoff of the renewable power plant is minimum. So, if electricity market structure follows cooperative scenario, thermal power plant will be eliminated from market quickly.

As can be seen from Fig. 4, total payoff of the both power plants in the cooperative model is the highest and the lowest in the Stackelberg model. Additionally, Fig. 3 illustrates that P^*_e will be at the highest level in the cooperative model and at the lowest level in the Stackelberg model. This means end-users' welfare in Stackelberg scenario can be more than other scenarios. As can be observed in Table 1: π^*_R has the lowest value in the Nash game model and the highest value in the cooperative model, while π^*_T is minimum in the cooperative model and maximum in the Nash model. q^*_R shows the lowest value in the Nash model and the highest value in the Stackelberg model, while q^*_T has the lowest value in the cooperative model and the highest value in the Nash model. Therefore,

Table 1 Sensitivity analysis of game theory models with respect to α

α	0.05	0.1	0.15	0.2	0.25
Nash game model					
q_R^*	125.80	126.35	126.91	127.46	128.02
q_T^*	103.16	101.88	100.61	99.33	98.06
Q^*	228.96	228.24	227.52	226.80	226.08
π_R^*	7179	7243	7308	7373	7437.67
π_T^*	4581	4466	4353	4241	4129.97
π^*	11,760	11,710	11,661	11,613	11,567.64
P_e^*	58.42	58.70	58.99	59.28	59.57
Stackelberg game model					
q_R^*	166.91	167.65	168.38	169.12	169.85
q_T^*	84.47	83.11	81.76	80.40	79.04
Q^*	251.38	250.76	250.14	249.52	248.9
π_R^*	7649	7717	7786	7855	7924.55
π_T^*	3039	2939	2840	2743	2648.11
π^*	10,688	10,656	10,626	10,599	10,572.66
P_e^*	49.45	49.70	49.94	50.19	50.44
Cooperative game model					
q_R^*	149.06	153.30	157.55	161.79	166.04
q_T^*	24.83	19.95	15.07	10.19	5.31
Q^*	173.89	173.25	172.62	171.98	171.34
π_R^*	11,599.94	11,933.20	12,266.45	12,599.71	12,932.96
π_T^*	1651.10	1297.69	948.68	604.06	263.83
π^*	13,251.05	13,230.89	13,215.13	13,203.76	13,196.79
P_e^*	80.44	80.70	80.95	81.21	81.46

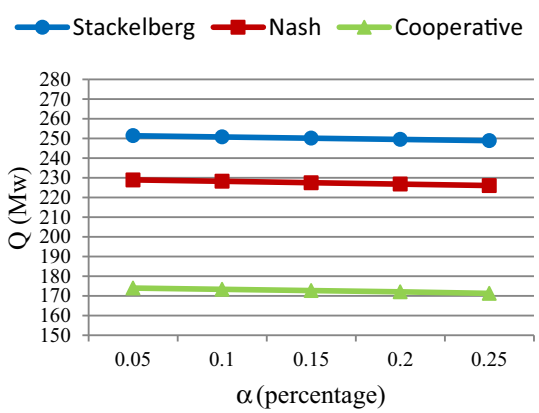

Fig. 2 Changes of total electricity supply versus α

the cost of pollution in the Nash model will be more than other scenarios.

Example 2 In this example, the changes of $q_R^*, q_T^*, \pi_R^*, \pi_T^*, \pi^*, Q^*$ and P_e^* are investigated with the changes of P_c. Let the parameters be set as below:

$$\gamma = 150; \quad \beta = 0.4; \quad a_R = 0.22; \quad a_T = 0.04;$$
$$b_R = 16, \quad b_T = 8; \quad c_T, c_R = 101; \quad \alpha = 0.1.$$

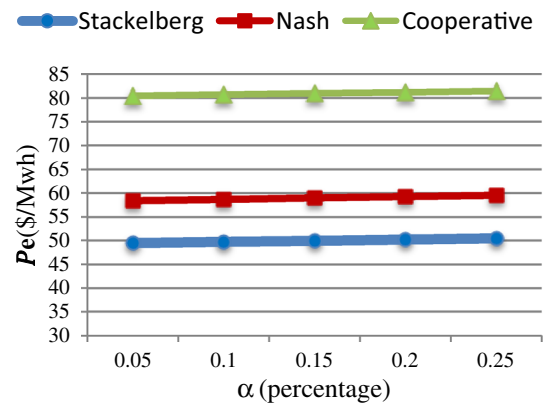

Fig. 3 Changes of price of electricity versus α

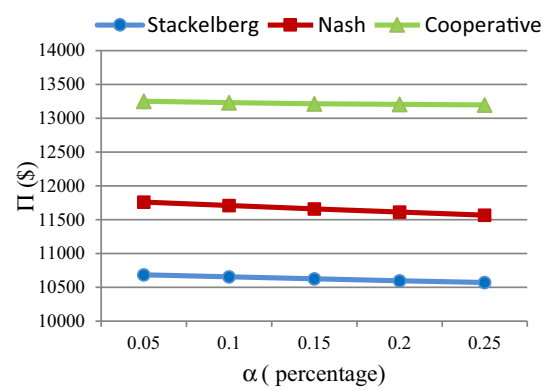

Fig. 4 Changes of total payoff versus α

Table 2 summarizes the results of this example in three models. Some important results of Table 2 are also graphically illustrated in Figs. 5, 6 and 7. As reported in the table, the results of Example 2 show that in each of the three models, increasing P_c^* will reduce P_e^* and q_T^* while increase Q^* and q_R^*. In other words, with TGC increasing the electricity price decreases and electricity supply increases at the same time. So it is expected that implementation of TGC system leads welfare improvement in all scenarios. As expected before from Eqs. (1) and (2), P_c has a direct relation with π_R^* and an inverse relation with π_T^*. In every three models, π^* and π_R^* increases by increasing P_c but π_T^* decreases.

In the Nash and Stackelberg game models P_e^* decreases and Q^* increases faster than the cooperative game model with respect to increasing P_c^*. Results of Examples 1-2 imply that P_e^* has the lowest value in the Stackelberg model and the highest value in the cooperative model (Figs. 3, 5). Q^* has the highest value in the Stackelberg model and the lowest value in the cooperative model (see Figs. 2, 6). Moreover, π^* has the lowest value in the Stackelberg

Table 2 Sensitivity analysis of game theory models with respect to α

P_c	10	30	50	70
Nash game model				
q_R^*	75.52	95.27	115.03	134.79
q_T^*	125.90	114.65	103.39	92.14
Q^*	201	210	218	227
π_R^*	3435	5527	8103	11,164
π_T^*	6874	5682	4603	3634
π^*	10,308	11,209	12,706	14,798
P_e^*	69.43	66.03	62.63	59.23
Stackelberg game model				
q_R^*	91.18	115.04	138.90	162.76
q_T^*	118.78	105.66	92.55	79.43
Q^*	210	221	231	242
π_R^*	3542	5698	8353	11,507
π_T^*	6107	4811	3667	2675
π^*	9649	10,510	12,020	14,182
P_e^*	66.01	61.72	57.42	53.13
Cooperative game model				
q_R^*	30.85	73	116	159
q_T^*	132.18	91	50	9
Q^*	163.03	165	166	168
π_R^*	2120	5918	10,567	16,067
π_T^*	9218	6239	3342	527
π^*	11,338	12,157	13,909	16,594
P_e^*	84.79	84.15	83.5	82.9

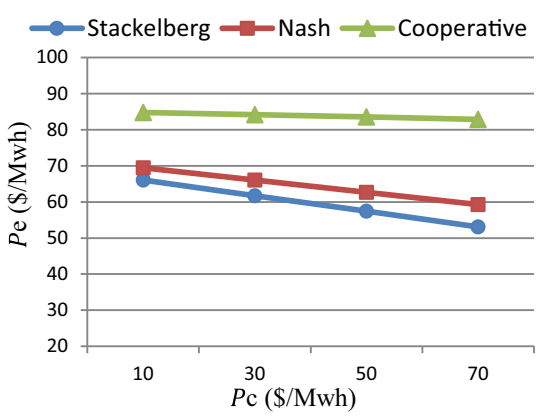

Fig. 5 Changes of electricity price versus P_c

model and the highest value in the cooperative model (Figs. 4, 7).

Example 3 In this example, the changes of α versus P_c in three Nash, Stackelberg and cooperative game models [i.e., Eqs. (13), (19), (24)] are evaluated. Let:

$$\gamma = 150; \quad \beta = 0.4; \quad P_e = 50; \quad a_R = 0.6; \quad a_T = 0.04; \quad b_R = 11, \quad b_T = 8; \quad c_R = 80, \quad c_T = 20.$$

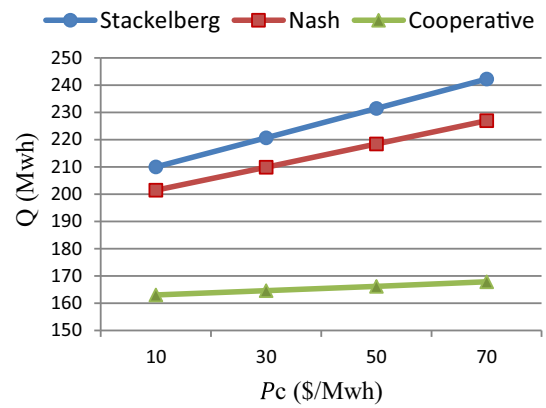

Fig. 6 Changes of supply of electricity versus P_c

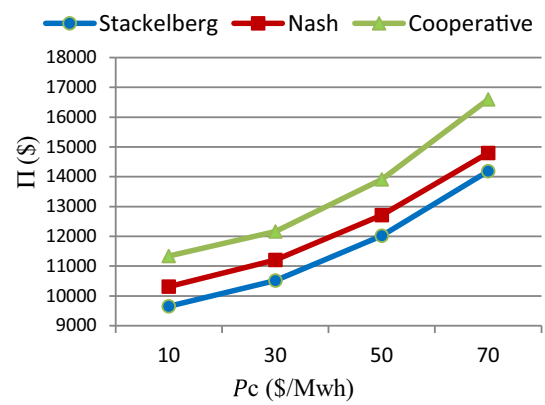

Fig. 7 Changes of total payoff versus P_c

Figure 8 depicts the results of this example in the models. The obtained results show that by increasing, certificate price P_c^* increases in the cooperative and Stackelberg game models while P_c^* decreases in the Nash game model. In the cooperative game model, P_c^* is the highest level in comparison with the other models.

The results of this example can be stated as follows: in the countries which their electricity market structures follow the Nash model, when the green electricity share increases, certificates price decreases and this leads to reduction of renewable power plants profit. This may signify that the TGC system has no appropriate incentives to produce green power sufficiently. Because in this case, renewable producer earned low profit from TGC sale.

The results of this paper can be useful for both public and private investors in the green electricity generation and other electricity producers. Therefore, the policy makers of government may adopt these models to design an implementation structure of the TGC system and to determine the objectives for generation of the green electricity.

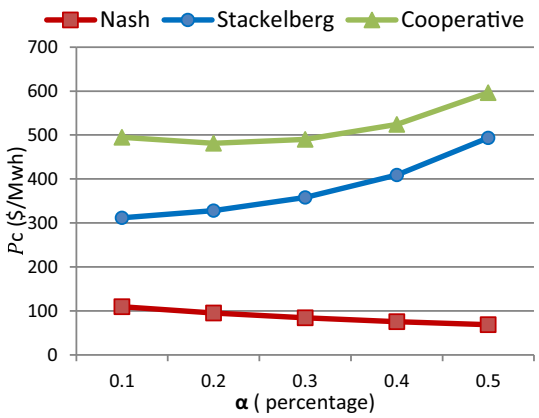

Fig. 8 Changes of P_c versus α

Pricing of the TGC is a challenging problem for the government, the parameters which are effective on the TGC price were shown in various game models. Finally, we summarize the numerical example results of game theory models for TGC system. Table 3 draws a comparison among optimal values of the models.

Conclusion

This paper considers the problem of interaction between the thermal and renewable power plants under TGC system conditions. We proposed three game theory models for TGC system, namely: cooperative, Nash and renewable-producer–Stackelberg models. These models were analyzed to implement the TGC system under the producer's obligation, assuming fixed prices for the certificates. Through a comprehensive sensitivity analysis, the effect of some main parameters of the model on the thermal and the renewable's decisions were evaluated. We showed that there is a reverse relation between price of the electricity and price of the certificates. In addition, price of electricity has a direct relation with the minimum quota. We found that the electricity supply in the cooperative game is at the lowest level, while the price of electricity is at the highest level. In the Stackelberg model, the price of electricity is at the lowest level and the supply of electricity and the production of green electricity are greater than the other models. In the Nash model, the payoff of the thermal power plant is at the maximum level and the payoff of the renewable power plant is at the minimum level.

There are several directions for the future research. First, producer's obligation option in the TGC system is considered, while the other obligation in the TGC system is both challenging and interesting. Second, time constraints were not considered for validation of the certificates. Using time variables in modeling of the TGC system can yield useful results. Third, this paper considers national trade in the electricity market and the TGC system. It is found that modeling the international trade in both of the markets with the game theory approach is interesting. Finally, applying other game theory's models to analyze implementation of the TGC system can be considered. For example, modeling of the TGC system in the incomplete information mode by Bayesian models is both interesting and challenging.

Appendix

Proof for Proposition 1 If the second order driven for Eq. (6) is negative, the profit function of green producer will be concave. The first-order condition for Eq. (6) is:

$$\frac{\partial \pi_R}{\partial q_R} = (P_c + \gamma) - (\beta q_T + 2\beta q_R + 2a_R q_R + b_R) = 0. \tag{25}$$

Equation (26) is negative if $(P_c + \gamma) < (\beta q_T + 2\beta q_R + 2a_R q_R + b_R)$. The second-order condition for Eq. (6) is as follows:

$$\frac{\partial^2 \pi_R}{\partial^2 q_R} = -(+2\beta + 2a_R). \tag{26}$$

Since the amounts of β and a_R are positive, the second-order condition is negative $\left(\frac{\partial^2 \pi_R}{\partial^2 q_R} < 0\right)$; therefore, the profit function of the green producer is concave.Similarly, if the second order driven for Eq. (7) is negative, the profit function of the thermal producer will be concave. The first-order condition for Eq. (7) is as follows:

$$\frac{\partial \pi_T}{\partial q_T} = \gamma - (2\beta q_T + \beta q_R + P_c \alpha + 2a_T q_T + b_T) = 0. \tag{27}$$

Table 3 Comparison of three game theory models

Profit of power plants	Amount of generated electricity	Price of electricity and TGC
$\pi^*_{R[C]} > \pi^*_{R[S]} > \pi^*_{R[N]}$	$q^*_{R[S]} > q^*_{R[C]} > q^*_{R[N]}$	$P^*_{e[C]} > P^*_{e[N]} > P^*_{e[S]}$
$\pi^*_{T[N]} > \pi^*_{T[S]} > \pi^*_{T[C]}$	$q^*_{T[N]} > q^*_{T[S]} > q^*_{T[C]}$	$P^*_{c[C]} > P^*_{c[S]} > P^*_{c[N]}$
$\pi^*_{[C]} > \pi^*_{[N]} > \pi^*_{[S]}$	$Q^*_{[S]} > Q^*_{[N]} > Q^*_{[C]}$	

Equation (27) is negative if $\gamma < (2\beta q_T + 2\beta q_R + \alpha P_c + 2a_T q_T + b_T)$. The second-order condition for Eq. (7) yields:

$$\frac{\partial^2 \pi_T}{\partial^2 q_T} = -(2\beta + 2a_T). \tag{28}$$

Since the amounts of β and a_T are positive, the second-order condition is negative $\left(\frac{\partial^2 \pi_R}{\partial^2 q_R} < 0\right)$; hence, the profit function of the thermal producer will be concave. From solving Eqs. (28) and (26), it follows that the optimal production of power plants are:

$$q^*_{R[N]} = \frac{AP_c + B\beta + 2a_t C}{2D + 2\beta^2}, \quad q^*_{T[N]} = -\frac{P_c(2\alpha a_R + 2\beta\alpha + \beta) + \beta(-b_R + 2b_T - \gamma) + 2a_R(b_T - \gamma)}{2D + 2\beta^2}. \quad \square$$

Proof for Proposition 2 The first-order condition for profit function of the power plants in Eq. (18) yields:

$$\frac{\partial \pi_R}{\partial q_R} = P_c + \gamma - 2\beta(q_T + q_R) - 2a_R q_R - b_R = 0, \tag{29}$$

$$\frac{\partial \pi_T}{\partial q_T} = \gamma - 2\beta(q_T + q_R) - \alpha P_c - 2a_R q_T - b_T = 0. \tag{30}$$

Solving Eqs. (29) and (30), we have:

$$q^*_{R[C]} = \frac{P_c(A - a_T - \beta) + \beta(B + b_R - \gamma) + a_T C}{D - \beta^2}.$$

$$q^*_{T[C]} = \frac{P_c(A - 2a_T - \beta + \alpha a_R) + \beta(B + b_R - \gamma) + a_T C}{D - \beta^2}. \quad \square$$

Proof for Proposition 3 To solve the model, q_T is first obtained as a function of q_R, then the order condition is first examined for a profit function of the thermal power plant of Eq. (30); the best response strategy of thermal power plant is computed as follows:

$$q_T = \frac{\alpha P_c + q_R + b_T - \gamma}{2(\beta + a_T)}. \tag{31}$$

Inserting Eq. (31) into Eq. (7) gives:

$$\pi_R = P_c q_R + \left[\gamma - \beta - \left(-\frac{\alpha P_c + \beta q_R + b_T - \gamma}{2(\beta + a_T)} + q_R\right)\right] q_R - a_R q_R^2 - b_R q_R - c_R. \tag{32}$$

The first-order condition for Eq. (32) yields:

$$\frac{\partial \pi_R}{\partial q_R} = P_c - \beta\left(-\frac{\beta}{2(\beta + a_T)} + 1\right) q_R + \gamma - \beta\left(-\frac{\alpha P_c + \beta q_R + b_T - \gamma}{2(\beta + a_T)} + q_R\right) - 2a_R q_R - b_R = 0. \tag{33}$$

The profit function of the renewable power plant is concave if the second-order condition for Eq. (33) is negative. The second-order condition for the renewable power plant gives:

$$\frac{\partial^2 \pi_R}{\partial^2 q_R} = -\frac{2a_R a_T + 2a_R \beta + \beta^2}{\beta + a_T}. \tag{34}$$

Regarding the assumption and parameter values, Eq. (34) is negative. Therefore, the profit function of the renewable power plant in this section is found to be concave. From Eq. (33), it follows that the optimal green electricity production is:

$$q^*_{R[S]} = \frac{AP_c + B\beta + 2a_T C}{2D}.$$

Inserting $q^*_{R[S]}$ into Eq. (31), the optimal black electricity production is:

$$q^*_{T[S]} = -\frac{P_c(A\beta + 2D\alpha) + \beta^2 B + Ca_T\beta + 2Db_T - 2D\gamma}{4D(\beta + a_T)}. \quad \square$$

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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