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A game theoretic approach for tradable white certificates regarding energy rebound and government intervention

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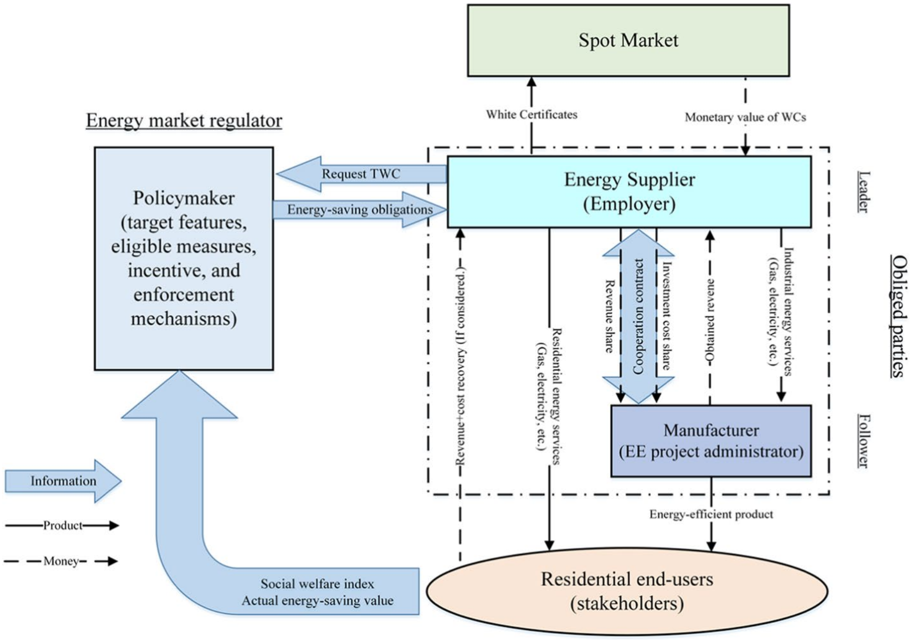
Abstract
In recent decades, many government administrations have tracked energy efficiency programs (EEPs) against environmental concerns. This was done so that it could potentially be useful as a supportive mechanism for smart technologies applied under the smart city concept. To facilitate this, tradable white certificates (TWCs) have been implemented as popular financial instruments used by energy-intensive sectors to boost cleaner production. In this study, we address an industrial EEP development with a TWC instrument as a multi-agent problem. We study this problem for the first time in the context of a supply chain that includes a manufacturer, an energy producer, and household energy consumers. Furthermore, we explore a new monopolistic pricing model for energy services and energy-efficient products, regarding the rebound effect, energy consumption, and social welfare. Additionally, we discuss two revenue-cost-sharing contracts and compare them as contracts using a comprehensive parametric and experimental analysis. The results show that the second proposed contract has some advantages over the first one. However, the second contract leads to less production than the first one does, while at the same time leading to less social welfare. Also, the findings suggest that the second investigated contract is a more appropriate instrument for the obligated parties than the first one when the aim is to improve the performance of TWC schemes. These findings can provide better circumstances for governance to optimize the critical parameters' level on TWC schemes with the lowest analytical cost.

Extended author information available on the last page of the article

Graphical abstract



Keywords Pricing · Energy efficiency · White certificate · Smart city · Supply chain contracts · Game theory

Abbreviations

GHG	Greenhouse gas
EEP	Energy efficiency program
TWC	Tradable white certificate
CSR	Corporate social responsibility
CS	Consumer surplus
ES	Energy-saving value
SCR	Supply chain revenue

List of symbols

s	Index of energy supplier
m	Index of producer
S	Stackelberg equilibrium
I	The first contract
II	The second contract
α	The potential market base of the product (product)
β	The energy cross-price elasticity (1/\$)
η	The conversion coefficient of energy demand to appliance demand defined as $0 < \eta < 1$ (product/MWh)
c_p	The production cost of the home appliance (\$)
c_s	The energy generation and associated costs (\$)

e	The product's energy use before energy efficiency enhancement (MWh)
e_p	The input energy of the production process before energy efficiency improvements (MWh)
e_0	The miscellaneous energy consumption of household end-users (Except the energy consumption of energy-consuming products) (MWh)
u	The environmental worth of primary energy recourses ($/MWh)
h	The energy efficiency investment on the production process per energy efficiency unit ($)
r	The household energy rebound of efficiency enhancement ($0 < r$)
r_p	The industrial rebound of energy efficiency enhancement ($0 < r_p$)
δ_p	The relative efficiency improvement rate of the production process ($0 < \delta_p < 1$)
t_r	The manufacturer's revenue share from TWC benefits ($0 < t_r < 1$)
d	The manufacturer's cost share of energy price deduction ($0 < d < 1$)
t_c	The manufacturer's cost share of energy efficiency investment ($0 < t_c < 1$)
v_0	The estimated financial value (or reference price) of a TWC per efficiency rate in the spot market (Regardless of the amount of energy-savings) ($/MWh)
δ	The efficiency level of the product ($0 < \delta < 1$)
q	The production volume of energy-efficient products before efficiency improvements (product unit)
q_0	The production volume of energy-efficient products by other manufacturers (product unit)
p_m	The industrial energy price ($/MWh)
p_c	The household energy price ($/MWh)
p	The selling price of the appliance ($)
v_t	The estimated financial value of a TWC in an energy efficiency market ($/MWh)
e_{Tm}	The energy consumption of the manufacturer (MWh)
e_{Tc}	The energy consumption of end-users (MWh)
q_T	The number of produced efficient appliances after efficiency improvements (product)
π_s	The profit function of the energy producer ($)
π_m	The manufacturer's profit function ($)

1 Introduction

Given rising concerns about the environment among government officials, sustainability measures have gained traction in industrial firms in recent years (Balsalobre-Lorente et al., 2023; Ezbakhe & Pérez-Foguet, 2020; Gunnarsdottir et al., 2022; Zhou & Huang, 2016). For example, the European Union has considered an energy efficiency target for energy-intensive sectors—a target that reduces these sectors' energy consumption by about 30—35% by 2030 (Fawcett et al., 2019). Due to the growth of energy consumption and the limitations of energy resources, however, energy management in energy-heavy sectors is falling short of meeting sustainability goals (Ünal et al., 2022). Therefore, energy sectors such as electricity and natural gas—41.6% and 37.4% of the world's total energy consumption, respectively—have a greater incentive to be efficient by adopting new energy-efficient equipment or processes (Xu et al., 2022).

On the one hand, recently, there has been a remarkable interest in smart technologies that can be used in cities (Ejaz et al., 2017; Lauri, 2021; Mattoni et al., 2017). So many countries are trying to promote policies related to the smart city concept and the projects that can facilitate this trend. Developing countries such as India and China are scheduling to invest in these types of projects. On this matter, almost 70% of the mentioned projects are defined in the safety, energy, and transport sectors (CHOI et al., 2020; Ejaz et al., 2017).

On the other hand, energy production from renewable and non-renewable resources around the world has been increasing significantly in recent decades. Therefore, the growth of energy consumption can be seen, as well as the growth of energy production. Greenhouse gas (GHG) emissions are currently produced mainly by energy-consuming sectors such as households and energy production industries (Bertoldi, 2010; Jiakui et al., 2023). Given this, governments have been adopting energy efficiency programs (EEPs), such as replacement programs and energy price reforms in industrial, commercial, and household sectors, to improve energy productivity in these sectors (Monstvilas et al., 2023). In keeping with this, industrial EEPs address production processes, known to be the most energy-intensive processes. The ammonia (Manrique et al., 2018), iron and steel (Chen et al., 2018), and metal casting industries (Carabalí et al., 2018) are some examples of industries that can benefit most from new efficient technologies and methods embedded in industrial EEPs. In these programs, energy efficiency instruments have been adopted already by governments and eco-friendly organizations to control the described circumstances appropriately (Sueyoshi et al., 2019). Some financial and non-financial policies that usually are applied in these programs include energy price reforms, tax subsidy systems, rebate programs, energy education, and energy-labeling schemes (Gill & Lang, 2018). These policies could help the governance to tackle the mentioned challenges in a relatively short-term horizon.

The main aim of the present study is to examine EEP for the industrial and residential sectors, to improve the energy-saving performance of efficient appliances and production processes that can be used in smart cities. It may lead to behavioral changes in end-users via increased social welfare. This EEP would consist of a product manufacturer and an energy producer so that they could coordinate a tradable white certificates (TWC) scheme. Furthermore, considering the benefits of TWC schemes for energy suppliers and the energy-saving investment in innovation for manufacturers, two contracts are proposed to be shared between themselves. This strategy can, as an incentive policy, motivate manufacturers to use more efficient facilities under TWC schemes. This study also investigates the individual and mutual effects of some common incentive mechanisms, to improve the economic aspect of sustainable development through TWC schemes. Additionally, government intervention is addressed under the proposed contracts.

Hence, we pose the research questions in this work as follows:

(i) To what degree does a TWC scheme affect the decision-making of energy policy-makers of a smart city and the strategic management of an appliance supply chain?
(ii) Which one of the supply chain contracts leads to more energy savings and emissions reduction under the TWC scheme?
(iii) How much can rebound effects impact the equilibrium decisions and the agents' profits in this problem?
(iv) How can the energy producer and the product manufacturer share their TWC scheme's costs and benefits, to maximize their utilities under the proposed contracts?

To discuss the above questions, a novel game model is proposed, considering a Stackelberg game between the supply chain members. The game theory approach helps the researchers formulate multi-agent problems with dependent strategic decisions such as those we face here. More precisely, due to the sequential decision-making nature of the problem, a leader–follower structure is discussed under two revenue-cost-sharing contracts between the energy supplier and product manufacturer. These contracts investigated in combination with a TWC scheme, are formulated as a traditional two-stage supply chain model with a novel linear demand function. However, to simplify the formulation process, we suppose no explicit cost recovery, as in similar implemented schemes.

Additionally, a thorough comparative analysis is performed, as well as an investigation of social welfare, which can be considered as the policymakers' utility function. Note that the investigation of rebound effects in this study further focuses on industrial energy savings, in particular indirect rebound effects, because the scheme of TWCs is neutral to the direct rebound effect. Finally, the following items are the research contributions of this work:

- A simultaneous pricing, revenue, and cost-sharing mechanism for energy services and energy-efficient products is discussed, taking into account three objectives for the government.
- The market mechanism of a TWC scheme is formulated for the first time as a multi-agent problem using a game-theoretic model.
- A multi-item social welfare index is investigated, to compare the proposed revenue-cost-sharing contracts from the governance perspective.
- The effect of industrial and household energy rebound on energy conservation and players' profits is discussed in a monopolistic game environment on smart technologies.

The rest of the present study is structured as follows. The two following subsections illustrate research gaps and the motivation for this study in detail. The methodology of the problem is described in Sect. 3 under the two investigated contracts. In Sect. 4, we discuss managerial points, based on the analytical and numerical sensitivity analysis. Section 5 presents important discussions. The last section explains conclusions and future research.

2 Literature review

In the last decade, some new instruments, such as carbon credits or white certificates, have been used to protect the environment and develop energy markets in association with energy-intensive sectors (Abbas et al., 2023a; An et al., 2022; Le Cadre et al., 2020; Mousavian et al., 2020; Stede, 2017). These financial instruments include soft measures, such as voluntary changes, and hard measures such as technological improvements in the behavior of end-users, through a validation process of white certificates (Bertoldi & Rezessy, 2008). Tradable white certificates (TWCs), introduced as "market-based instruments" for encouraging energy efficiency among energy-intensive consumers, have been a popular policy measure (Oikonomou et al., 2009).

The implementation of TWCs led to more energy efficiency and social acceptability and enhanced the environmental incentive marketplace. Their implementation also reduced GHG emissions as a consequence of using high-performance technologies (Ceglia et al., 2023; Chlond et al., 2023; Meng et al. 2023; Micah et al., 2023). Ceglia et al.

(2023) described the analysis of a case study investigating two micro combined-heat-and-power (micro-CHP) units installed in southern Italy under white certificate (WC) schemes. The findings confirm the growth of WCs, considering three different scenarios based on the level of timing accuracy. Chlond et al. (2023) assessed the effectiveness of four different support programs implemented in France to enhance residential energy efficiency. These programs include the income tax credit, a grant initiative, a reduction in value-added tax, and the utilization of WCs. The WCs offer the most cost-effective method for obtaining funding through programs aimed at reducing energy expenses.

In an integration between market mechanism and obligation, these certificates are given to the obligated parties (e.g., energy suppliers and distributors) in energy-saving projects for a specific efficiency target by overall governance.[1] The obligated parties also can benefit from the energy savings in the form of a tradable proof, or they can sell their credits to other parties, bilaterally or on a spot market.[2] Also, there usually is a cost recovery mechanism in the tariffs, which allows the energy supplier to recover the implementation costs of energy efficiency projects (Abbas et al., 2024; Bertoldi et al., 2010; Caragliu, 2021). These mechanisms compensate a portion of the cost incurred by direct investment in the involved energy-intensive sectors (e.g., industrial and residential sectors). Incentive policies such as *cost capitalization*, *performance bonuses*, and *shared savings* can also motivate end-users to take part in the energy efficiency process.

In particular, white certificates could reduce about 2% of primary energy consumption by energy-heavy sectors, including natural gas and electricity production in Italian industrial sectors (Morganti & Garofalo, 2022; Rosenow et al., 2020; Stede, 2017), as well as 1.3 TWh of initial energy consumption in French industrial firms (Bertoldi et al., 2010). A green certificate scheme for large suppliers of gas and electricity in Italy was also discussed in detail (Argun et al., 2021; Stede, 2017). The imperial results denote improvements in the economic environment of energy efficiency policies—improvements such as rising social awareness and the push to cover the costs of technological improvements. Macchiaroli et al. (2021) investigated the TWC schemes, to cut down on energy use. In this study, it has been observed that not many integrated water service-related projects have been submitted for the issuance of TWCs thus far. The findings also demonstrate how TWC schemes affect the long-term financial viability of water sector investments.

Another alternative that can help obligated parties reduce their energy efficiency costs is the coordination contract with other supply chain members. For example, a revenue-cost-sharing contract from an energy supplier or distributor can be proposed, to convince end-users (e.g., product manufacturers) to consume less energy, along the lines of a “top-down” mandate that would be more efficient and effective to implement than a decentralize decision-making would be. This type of contract also may provide suitable conditions, to meet other goals (e.g., increasing the net profit of decision-makers and GDP) following an increase in the production of energy-intensive appliances (Xu & Wang, 2017). In this respect, some scientific works addressed the revenue-cost contract in supply chains (Yu et al., 2020). For example, Li et al. (2021) took into account a supply chain with one

[1] The role of obligated parties in energy-saving projects can be equated with an employer or a contractor doing projects themselves.

[2] There are some components in each TWC scheme, such as obligated parties, target features (e.g., individual targets and their metrics), eligible measures, eligible third parties (e.g., brokers or contractors), incentive policies, and cost recovery and penalty mechanisms that distinguish one program from the another. In this study, the common components of TWC schemes are considered the parameters within which to discuss a general framework of the policy instrument.

supplier and one retailer, investing in item-level RFID while taking their respective stocks and demand into account. The primary goal of the study was to create an efficient method that, by applying item-level RFID, optimizes the revenues of both participants and the whole supply chain, given that the supplier may be reluctant to use RFID. The outcomes demonstrate that for supply chain coordination, the revenue-cost-sharing contract works far better than the wholesale-price contract.

Furthermore, in the past decade, energy-efficient products with the lowest possible energy consumption footprint, called "energy-efficient products" (e.g., energy-efficient home appliances) have been developed for energy-intensive sectors. Therefore, some EEPs support the products mentioned above, using incentive policies, such as energy labeling (Park, 2017) and subsidy programs (Wang et al., 2017). For example, in order to support government decision-making on policy and conformity assessment alternatives for the implementation of proposed energy-efficient lighting standards in the Caribbean Island country of Antigua and Barbuda, Shah (2018) addressed a regulatory effect assessment. Based on primary data collected from an expert panel, the technique included a multi-criteria evaluation approach along with a perceptual cost-effectiveness assessment. The study's conclusions point to a possible course of action that would involve a phased approach to a legal need for energy-efficient lighting products. This would involve a voluntary incentive policy combined with consumer market intervention, such as product subsidies combined with product exchange programs. Kumar et al. (2021) discussed a carbon-cum-energy efficient production method for South Asia's varied agroecosystem. According to the findings, compared to the rice–wheat system, the millet-based system uses 84% less energy and has an 87% smaller carbon footprint. Additionally, the energy ratio in the millet-based system reduces carbon intake by 172% while increasing production by 61%. While the implementation of EEPs may result in energy savings, their implementation also may be offset partially or completely by rebound effects (Zhou et al., 2018).

As implied by its name, "rebound effects" refer to behavioral factors in consumers that offset technological or managerial improvements in energy efficiency. This happens because of a decrease in the breakpoint price of the measures undertaken after they have improved the efficiency of a product or process. Rebound effects can be investigated according to where new energy-efficiency technologies are used, such as in the projects we can see in EEPs, i.e., on the consumer or producer side (Rasti-Barzoki & Moon, 2020; Sorrell, 2007). Regarding this phenomenon, however, industrial rebound effects result in more energy consumption than do energy rebound effects in the residential sphere, but in turn, this may lead to more production capacity, GDP, and social welfare (Zhang & Peng, 2017). On the other hand, there are misguided policies that address rebound effects that should be distinguished from correct policies (Ruzzenenti & Bertoldi, 2017). Therefore, it can be said that there is a significant concern over the impact of rebound effects on energy consumption. Hence, in this study, we consider rebound effects after efficiency improvements have been made on typical energy-efficient products and processes simultaneously.

From the modeling perspective, sustainable supply chain management has been studied using various mathematical methods (Baptista et al., 2019; Ghadimi et al., 2018). For example, Raj et al. (2018) formulated a supply chain regarding corporate social responsibility (CSR) assumption under five various contracts. The results show that establishing a coordination contract between a buyer and a supplier is the most effective way to go, vis-à-vis CSR measures. Furthermore, some works addressed social welfare under different mathematical forms (Hafezalkotob, 2017). Some papers also applied game theory to solve similar problems (Fathi et al., 2023; Oliveira et al., 2019; Zhang et al., 2023). Hafezalkotob (2017) explored the government intervention policy in two sustainable supply chains, comprising a retailer and a manufacturer. The results indicate the advantage of cooperation-based structures to maximize energy savings. In another work, Hafezalkotob (2018) investigated six different policies that can help the government guide members of a supply chain through energy-saving processes. The results denote the advantages of the proposed policies, given their effects on environmental issues. As a result, these studies did not mention a novel pricing mechanism for energy services and energy-efficient products under a TWC scheme, nor did they consider social welfare or rebound effects. In other words, according to the literature reviewed, there is no similar research investigating an EEP in a sustainable supply chain, as we discuss in this study. Also, none of the reviewed studies have designed a TWC scheme from the energy supplier's side, using a multi-agent formulation.

The research gaps recognized in this study can be summerized as follows:

- Lack of intensive mathematical works formulating the supply chain contracts that can facilitate optimizing the mechanisms of energy markets (e.g., revenue-sharing contracts in such mentioned problems).
- Little investigation of the role of TWC schemes on energy savings, GHG emissions reduction, and social welfare obtained from electricity consumption using mathematical models.
- Absence of simultaneous consideration of the supply and demand side in the process of improving efficiency by WC schemes in energy consumption and energy-saving as a strategic multi-agent problem.
- Little discussion of the impact of the proven phenomenon such as rebound effects on equilibrium decisions of the spot market players regarding energy-consumer products.

3 Methodology

3.1 Problem statement

Suppose an appliance supply chain including a producer (denoted by m) and an energy supplier (denoted by s) as the game players. Due to the financial benefits of trading the green certificates in energy markets, the energy supplier offers a cooperation contract to the manufacturer under a TWC scheme including hard measures. Based on the literature, we assume that the scheme implies the enhancement of the efficiency of energy-intensive processes and products (Abbas et al., 2023b; Shah et al., 2023a, 2023b). Note that in this process, the delivery mechanism is determined via partnerships with manufacturers. On this matter, the industry also does not earn a certificate by improving energy-saving in its plants. Figure 1 shows the framework of the basic problem, in which a leader–follower relationship is considered between the supplier and the manufacturer.

The related timeline of decision-making, showing the sequence of the players' decisions, is presented in Fig. 2.

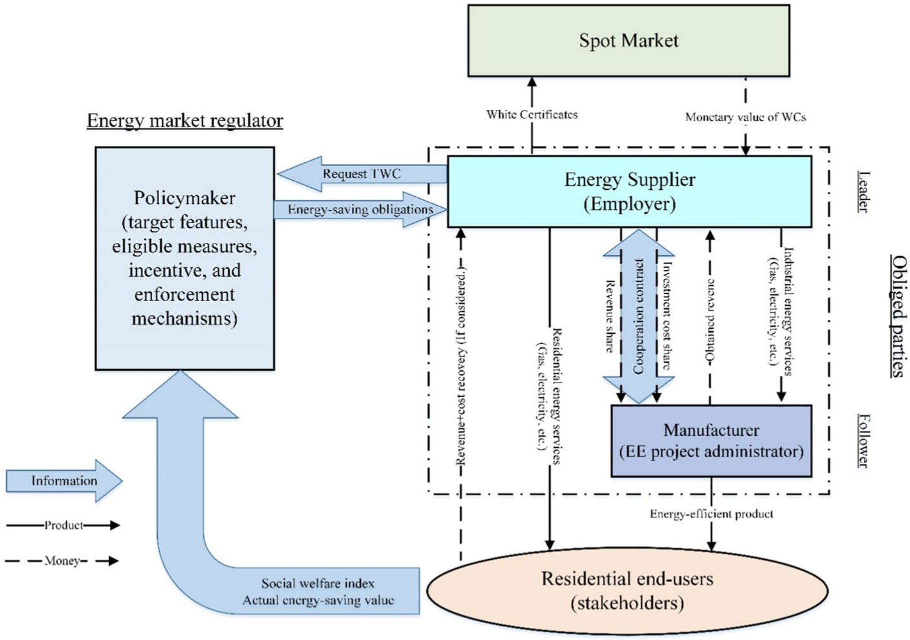


Fig. 1 Structure of basic problem

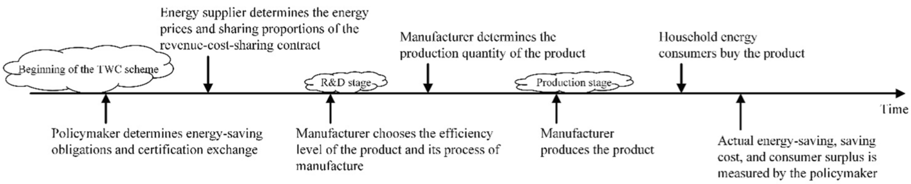


Fig. 2 Timeline of decision sequences

3.2 Prerequisites and assumptions

The assumptions, which are used in this problem, are as follows.

Assumption 1 Due to the investigation of different contracts, monopolistic competition is considered instead of a duopoly between the manufacturers.

Assumption 2 We suppose a possible rate for the efficiency enhancement of the energy-efficient appliance (δ) and the process (δ_p) made by an R&D group using the most cutting-edge technology.

Assumption 3 Non-negative parameters and decision variables, as well as mathematical functions, are discussed for the supply chain players.

As we can see in similar studies (Jafari et al., 2017), the manufacturer and the energy supplier enter the game when they expect a non-negative profit value.

Assumption 4 A quadratic mathematical relation is extended for the energy-saving cost of the manufacturer.

Usually, energy-saving costs cover a broad range of efficiency improvement efforts. In particular, these costs refer to the energy efficiency investments that utilize R&D resources. So, a quadratic mathematical function ($h(\delta^2 + \delta_p^2)$) is considered for energy-saving costs, because measures to enhance efficiency performance are increasingly costly (Dai et al., 2017).

3.3 Problem formulation

We describe two contracts (denoted by *RC I* and *RC II)* for the problem, which can help the energy supplier implement a TWC scheme. In each contract, the energy producer and the manufacturer, as the follower, agree on a revenue-cost-sharing contract that includes a cost share and a revenue share part. Before we explain the formulation of the contracts, some required mathematical functions on retail prices, values of TWC, and energy demand are presented below.

3.3.1 The selling price of the appliance

We define the selling price of the appliance (p), based on a monopolistic game between the energy producer and appliance manufacturer, using a strategic game with perfect information that has been formulated under a leader–follower structure. Therefore, the proposed linear inverse demand function can be mentioned using the Cournot model as follows (Xue et al., 2017).

$$p = \alpha' - q_T - \gamma q_0 \tag{1}$$

where in Eq. (1), the total production (q_T) can reduce the retailer price, considering the related market base (α) and the effect of other manufacturers production (γq_0) on the primary production volume, q.[3] Additionally, due to the indirect rebound effects of industrial energy use (r_p), the following equation calculates as q_T (Eq. (2)).

$$q_T = q\left(1 + \frac{r_p \delta_p e_p}{\left(1 - \delta_p\right) e_p}\right) = q\left(1 + \frac{r_p \delta_p}{1 - \delta_p}\right) \tag{2}$$

where we suppose the partial indirect rebound effect ($r_p \delta_p e_p$) completely assigns to more production of goods or their requirement, based on the energy consumption process (e_p). Note that, because $\frac{r_p \delta_p}{1-\delta_p} > 0$, we have $q_T > q$ in our game model.

[3] We consider $\alpha = \alpha\prime - \gamma q_0$ in our calculations, due to the same effect of these parameters on the results.

3.3.2 Financial value of TWC

Considering the transaction costs of TWC schemes, the energy supplier needs to provide financial resources for the scheme, which can be satisfied with the trade options of the white certificate (Mundaca, 2007). Therefore, in Eq. (3), we propose a mathematical relationship for the financial estimation of a TWC in the energy efficiency market, (v_t), for the first time, according to the white certificate literature (Sorrell et al., 2009).

$$v_t = v_0 \delta e \tag{3}$$

where an efficiency-dependent linear function is considered for the estimated financial value of a TWC in an energy efficiency market i.e., v_t, considering the efficiency level of the product, (δ), and the initial consumption of the industrial energy services, (e), multiplied in the basic financial value of TWC per energy unit (v_0).

3.3.3 Energy demand functions of industrial and household sectors

According to the literature (Ghosh & Shah, 2012), we consider two novel demand functions for industrial and residential energy consumption in Eqs. (4) and (5), respectively.

$$e_{Tm} = (1 - \delta_p) e_p q_T \tag{4}$$

$$e_{Tc} = \left[(1 - (1 - r)\delta) e q_T + e_0 \right] - \beta p_c \tag{5}$$

where industrial energy demand (e_{Tm}) is calculated according to the product quantity of the manufacturer, after the implementation of a TWC. Furthermore, we calculate residential energy demand as (e_{Tc}), using the market base and the impact of the retail price of residential energy consumption, (p_c) and its energy cross-price elasticity (β), on energy demand.

3.3.4 Revenue-cost-sharing contract I (RC I)

Similar to the coordination contracts used in energy markets (Fan et al., 2019), suppose a cooperation contract between the members of a supply chain with the producing cost of the appliance and energy services as c_p and c_s, respectively. In this contract, the energy producer offers a revenue-sharing proportion to the appliance producer (t_r) regarding the financial value of the certificate (v_t), to promote energy efficiency efforts and gain more profit from this process. The energy supplier also considers a deduction rate (denoted by d) for the energy expenditure of the product producer, given by the retail price of industrial energy (p_m), multiplied by the industrial energy demand. Therefore, the following equations show the appliance manufacturer's and the supplier's profits, respectively.

$$\pi_m = \left(p - c_p\right) q_T + \left[\underbrace{t_r v_t}_{\text{Revenue-share}} - \overbrace{(1 - d) p_m e_{Tm}}^{\text{Cost-share}} \right] - h\left(\delta^2 + \delta_p^2\right) \tag{6}$$

$$\pi_s = \left(p_m - c_s\right)e_{Tm} + \left(p_c - c_s\right)e_{Tc} + \left[\underbrace{\left(1 - t_r\right)v_t}_{\text{Revenue-share}} - \overbrace{dp_m e_{Tm}}^{\text{Cost-share}}\right] \tag{7}$$

where the manufacturer sells its energy-efficient products and gives revenue-cost-shares regarding production costs, energy efficiency investments, and energy costs (Eq. 6). The profit function of the energy supplier (Eq. 7) also includes energy sales and revenue-cost-shares.

The energy supplier and manufacturer want to maximize their profits. So, considering the leader–follower structure of the mentioned problem, the mathematical model of the game is mentioned in (Eq. 8):

$$\begin{cases} \left(\underset{p_m,t_r}{max}\pi_s \rightarrow \underset{\delta,q_T}{max}\pi_m\right) \\ \pi_m, \pi_s > 0, \delta, q_T, p_m, t_r > 0 \end{cases} \tag{8}$$

Now, using the functions mentioned above and standard backward induction, the equilibrium decisions of the game problem are presented in Theorem 1. Meanwhile, all the proposition proofs are shown in the appendix.

Theorem 1 *The equilibrium efficiency level, production volume, retail price, and sharing proportion under the first contract are shown as follows in (Eqs. 9–12[4]):*

$$\delta^S = \frac{et_r v_0}{2h} \tag{9}$$

$$q_T^S = \frac{ep_c\left(4h + v_0 H_1\right) - 4c_p h + 4h\alpha - c_s(4eh + ev_0 H_1 + 4e_p h(1 - \delta_p))}{16h - H_1^2} \tag{10}$$

$$p_m^S = \frac{H_3\left(\alpha - c_p\right) - 2ep_c\left(4h + v_0 H_1\right) + 2c_s(4eh + eH_1 v_0 + p_c H_1^2 \alpha - p_c + 4e_p h(1 + \delta_p))}{(8h + H_3)(1 - \delta_p)(1 - d)e_p} \tag{11}$$

$$t_r^S = \frac{8hv_0 e - 2h\left(p_c - c_s\right)H_1\left(c_p - \alpha - H_5\right)}{(8h + H_3)ev_0} \tag{12}$$

3.3.5 Revenue-cost-sharing contract II (RC II)

We address another contract with the same assumptions as the first one but with a different revenue-cost-sharing structure. In this contract, the energy supplier contracts with the manufacturer on the scheme's revenue and related investment costs. Therefore, Eqs.

[4] H_1-H_5 values are given in Appendix.

(13) and (14) show the profit functions of the appliance producer and the energy producer, respectively, under the second scenario.

$$\pi_m = (p - c_p)q_T + \left[\underbrace{t_r v_t}_{\text{Revenue-share}} - \overbrace{(1 - t_c)\left(h\left(\delta^2 + \delta_p^2\right) + p_m e_{Tm}\right)}^{\text{Cost-share}} \right] \tag{13}$$

$$\pi_s = (p_m - c_s)e_{Tm} + (p_c - c_s)e_{Tc} + \left[\underbrace{(1 - t_r)v_t}_{\text{Revenue-share}} - \overbrace{t_c\left(h\left(\delta^2 + \delta_p^2\right) + p_m e_{Tm}\right)}^{\text{Cost-share}} \right] \tag{14}$$

where there is a revenue share on the scheme's benefits and a cost share on energy efficiency investment and the industrial energy consumption for each player. Similar to the first contract, the energy supplier and manufacturer want to maximize their profits. In this regard, the equilibria of the decision variables are calculated according to the pre-described model in Eq. (8).

Theorem 2 *The equilibrium efficiency level, production volume, retail price, and sharing proportion under the second contract are shown as follows in (Eqs. 15–18):*

$$\delta^S = \frac{e t_r v_0}{2h(1 - t_c)} \tag{15}$$

$$q_T^S = \frac{e p_c (H_2 - v_0 H_1) + (H_2 + 2h)(\alpha - c_p) + c_s(e v_0 H_1 - e_p H_2 (1 - \delta_p) - e H_2)}{(8h - H_3) + 4(H_2 + 2h)} \tag{16}$$

$$p_m^S = \frac{c_p(8h - H_3) + 2(H_2 + 2h)(c_p + e(p_c - c_s) - \alpha) + H_4 - 2c_s e_p H_2 (1 - \delta_p)}{e_p((H_3 - 8h) - 4(H_2 + 2h))(1 - \delta_p)(2 - t_c)} \tag{17}$$

$$t_r^S = \frac{(\alpha p_c + c_p(c_s - p_c))(1 - r)(1 - t_c) + H_8 - p_c^2 H_1 (2 + t_c)}{(4v_0(H_2 + 2h) - (H_3 - 8h))(2 - t_c)} \tag{18}$$

The following corollaries are provided to reveal the relationships between the obtained results:

Proposition 1 *The equilibrium energy efficiency rate in both contracts can be ordered as follows:* $\delta_{II}^S > \delta_I^S$, *where* $c_p \geq \frac{4H_2}{(p_c - c_s)(1 - r)H_1} + \alpha$.

As we can see, due to including a cost share on energy efficiency investments, there are more efforts to improve the efficiency level in the second contract than in the first contract. However, this result could be valid for manufacturers, who have a relatively energy-efficient process with a high production cost.

Proposition 2 *Considering the production level of the appliances in both contracts, we have* $q_T^I > q_T^{II}$ *where* $e_p > \frac{16he(p_c-c_s)+\left(8h-H_3\right)(e\left(p_c-c_s\right)t_c+(1+t_c)\alpha)}{c_s(16h+\left(8h-H_3\right)t_c)(1-\delta_p)}$.

Proposition 2 shows that, if the manufacturer uses an energy-intensive process (e.g., with obsolete production facilities) to produce goods, industrial rebound effects increase the quantity of the produced efficient appliances after the TWC scheme is applied. The lower bound of the energy consumption level is calculated in this proposition.

Proposition 3 *Considering the revenue-sharing parameter in both contracts, we have* $t_r^I < t_r^{II}$, *where* $e_p < \frac{16he(p_c-c_s)+\left(8h-H_3\right)(e\left(p_c-c_s\right)t_c+(1+t_c)\alpha)}{c_s(16h+\left(8h-H_3\right)t_c)(1-\delta_p)}$.

Proposition 3 shows that considering the obtained upper bound for the input energy of the production process, the supplier should spend more share of certificate revenue to motivate the manufacturer to engage in the energy efficiency scheme.

3.3.6 Social welfare index

In our study, we explored social welfare and how it improved after the successful implementation of a TWC scheme. However, we considered this factor as being related to the policymaker's utility function in environmental schemes. We explain the different items of that function as follows.

The consumer surplus (CS)

Similar to related studies (Hafezalkotob, 2017; Sheu, 2011), we assume the total production amount of energy-efficient products and energy demand as consumer surplus described in Eq. (19).

$$CS = \sum_i \frac{1}{2} D_i^2 = \frac{1}{2}\left[q_T^2 + \eta(e_{Tc}^2 + e_{Tm}^2)\right] \tag{19}$$

The energy-saving value (ES)

We consider total energy savings as an environmental advantage that results in greater social welfare, according to similar studies (Sheu, 2011; Sheu & Chen, 2012). Equation (20) shows the energy-saving formulation as a novel function obtained by the technology upgrades of the manufacturing process and resulting energy-efficient appliances, respectively.

$$ES = \left[\left((1-\delta_p)e_p q_T - e_p q\right) + [(1-r)\delta e]q_T\right]u \tag{20}$$

The supply chain revenue (SCR)

The members of a supply chain earn income from selling their products and services. Therefore, similar to findings in existing literature [for example, (Sheu & Chen, 2012)], Eq. (21) shows the mathematical relation of supply chain revenue as follows.

$$SCR = \pi_s + \pi_m \tag{21}$$

Finally, considering Eqs. (19–21), the following equation presents the social welfare index (SW) (Eq. 22):

$$SW = CS + ES + SCR \tag{22}$$

4 Results

Here, we examine the results of parametric and numerical analysis of the two considered contracts.

4.1 Parametric analysis

We discuss some important parameters according to the analysis of the equilibrium decisions as follows.

Proposition 4 *Regarding the feasibility conditions, if* $c_p > \alpha + \frac{32eh(p_c-c_s)}{8h+H_3}$ *and* $c_p > \frac{(8h-H_3)\alpha-8e(p_c-c_s)H_2+8h(1-t_c)\alpha}{8h(2-t_c)-H_3}$, *then* $\frac{\partial t_r^I}{\partial p_c} > 0$ *and* $\frac{\partial t_r^{II}}{\partial p_c} > 0$ *respectively, under the investigated contracts.*

According to Proposition 4, it can be deduced that the energy supplier only can compensate the paid revenue share (to a manufacturer with a higher production cost than the established thresholds) by increasing the selling price of household energy. Proposition 5 presents the mathematical relation between the manufacturer's cost share and energy price in *RC I,* as follows.

Proposition 5 *If* $\alpha < \frac{8eh(p_c-c_s)}{H_3}$, $v_0 < \frac{H_3(c_p-\alpha)-8eh(p_c-c_s)}{2(p_c-c_s)eH_1}$, $c_p > \frac{(8h-p_c^2H_1^2)\alpha-H_6}{H_3}$, *and* $h > \frac{1}{8}(p_c-c_s)^2H_1^2$ *we have* $\frac{\partial p_m^I}{\partial d} < 0$ *under the first proposed contract (RC I).*

Considering a costly manufacturing process (at least $\frac{(8h-p_c^2H_1^2)\alpha-H_6}{H_3}$) and required energy-efficiency investment (at least $\frac{1}{8}(p_c-c_s)^2H_1^2$), the supplier does not increase d along with p_m^I, if the market base and the estimated financial value of TWC are lower than $\frac{8eh(p_c-c_s)}{H_3}$ and $\frac{H_3(c_p-\alpha)-8eh(p_c-c_s)}{2(p_c-c_s)eH_1}$, respectively. These thresholds establish the financial conditions that the supplier does not provide additional support for the manufacturer.

Proposition 6 *We have* $\frac{\partial q_T^{II}}{\partial t_c} < 0$, *if* $e_p > \frac{8he(p_c-c_s)+(8h-H_3)(\alpha+e(p_c-c_s))}{c_s(16h-H_3)(1-\delta_p)}$ *under the second proposed contract (RC II).*

According to this proposition, if the manufacturer has an energy-intensive process before implementing a TWC scheme (i.e., $e_p > \frac{8he(p_c-c_s)+(8h-H_3)(\alpha+e(p_c-c_s))}{c_s(16h-H_3)(1-\delta_p)}$), the increase in t_c does not lead to more production. From a business point of view, this may be interesting for the energy supplier, because we can see a trade-off between a cost-sharing proportion and future household energy use made by energy-consuming products.

Table 1 Item-specific parameters (EU, 2010; Amazon.com, 2018; Ansuategi et al., 2014)

Item 1	Parameter	Amount	Item 2	Parameter	Amount
Washing machine	α	1,200	Refrigerator	α	4,900
	c_p	798 ($)		c_p	4,200 ($)
	e	0.023 (MWh/month)		e	0.063 (MWh/month)
	e_p	1.1 (MWh)		e_p	1.9 (MWh)
	h	90.0 ($)		h	198 ($)

Table 2 Common values of parameters (Blázquez et al., 2013; González, 2010; IRENA, 2018)

Parameter	Amount	Parameter	Amount	Parameter	Amount
β	0.25	η	0.30	e_0	60 (MWh/month)
r	49%	u	200 ($/MWh)	p_c	190 ($/MWh)
r_p	10%	δ_p	0.04	t_c	0.10
v_0	6,000 ($/MWh)	c_s	118 ($/MWh)	d	0.05

Proposition 7 *Considering* $\delta_{II}^S > \delta_I^S$, $q_T^I > q_T^{II}$, *then* $e_{Tm}^I > e_{Tm}^{II}$, *if* $e_p > \frac{16he(p_c-c_s)+(8h-H_3)(e(p_c-c_s)t_c+(1+t_c)\alpha)}{c_s(16h+(8h-H_3)t_c)(1-\delta_p)}$.

Based on Proposition 7, the manufacturer with energy-intensive processes produces more products, leading to more industrial energy use under *RC I.* Additionally, considering this proposition and Proposition 3 together, we can say that increasing revenue share in a product's supply chain with an energy-intensive process can enhance energy saving in the household sector more than in the industrial sector.

Due to the high mathematical complexity of each solution's comparison, we examine other energy policies using a comprehensive numerical analysis of a real case study.

4.2 Experimental analysis under a case study

A thorough numerical analysis of the sensitive parameters is conducted here under a real case study. Due to the plethora of electrical home appliances, we focus in this study the two most common appliances found in homes—the refrigerator and the washing machine—with energy consumption data obtained from Spain as a pioneer country on EEPs. We also suppose that the energy supplier generates electrical energy by solar photovoltaic technology. Table 1 presents the mentioned data for the special parameters of each appliance, as follows.

Furthermore, Table 2 represents the value of the common parameters between both case studies.

Figure 3 demonstrates the feasible regions for the concavity of the product producer's and supplier's profit functions, based on a data pre-analysis, with changes to the manufacturing process (e and h in Fig. 3a) and energy generation parameters (p_c and c_s in Fig. 3b). Note that, outside the specified region, each selected point should be examined carefully.

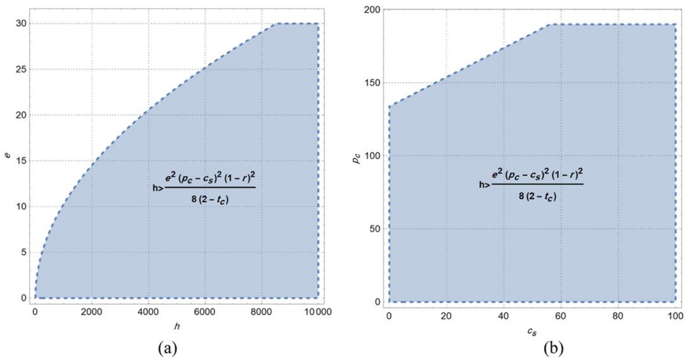


Fig. 3 Feasible region of the problem for the manufacturing process (**a**) and energy generation (**b**) parameters

Table 3 Equilibria of decision variables by setting parameters on default values

Case 1	Var	*CR I*	*CR II*	Case 2	Var	*CR I*	*CR II*
Washing machine	δ	0.22	0.23	Refrigerator	δ	0.12	0.13
	q_T	70.0	70.4		q_T	122.3	122.2
	p_m(\$/MWh)	263.0	278.5		p_m(\$/MWh)	262.8	277.5
	t_r	0.28	0.27		t_r	0.13	0.11
	p(\$)	1,130	1,129		p(\$)	4,776	4,778
	v_t(\$/MWh)	30.0	31.8		v_t(\$/MWh)	45.4	47.8
	e_{Tm}(MWh/month)	73.2	73.1		e_{Tm}(MWh/month)	223.0	222.9
	e_{Tc}(MWh/month)	13.9	13.9		e_{Tc}(MWh/month)	19.7	19.6
	π_s(\$)	10,733	10,732		π_s(\$)	30,833	30,833
	π_m(\$)	4,910	4,909		π_m(\$)	14,949	14,948
	π_T(\$)	15,643	15,642		π_T(\$)	45,782	45,781
	SW	18,274	18,276		SW	59,202	59,205

Regarding the default values of the parameters, the equilibria decisions of each contract are calculated using Theorem 1 and Theorem 2 and are presented in Table 3 as follows.

According to Table 3, the industrial energy cost and energy consumption in the first contract are more than what we can see in the second one. Also, more revenue share is obtained under *RC I* than under *RC II*. However, a similarity between the other equilibria solutions of each case can be seen here.

As an important result, the two proposed contracts can be used by the obligated parties to increase their profits, considering the effective exogenous variables such as energy market risks, regional limitations, and regulations. Nevertheless, the second contract follows an efficient production approach while the first one focuses on more production which leads to more energy consumption and less efficiency level.

Figure 4 represents the equilibria profits, in conjunction with the calculated social welfare benefits for the two home appliances being considered in this case study.

Based on Fig. 4, refrigerator production leads to more social welfare than washing machine production in both contracts. In contrast, the production of washing machines

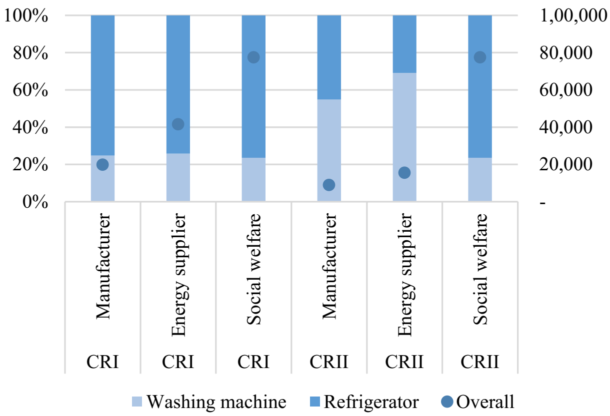


Fig. 4 Players' profits under numerical example

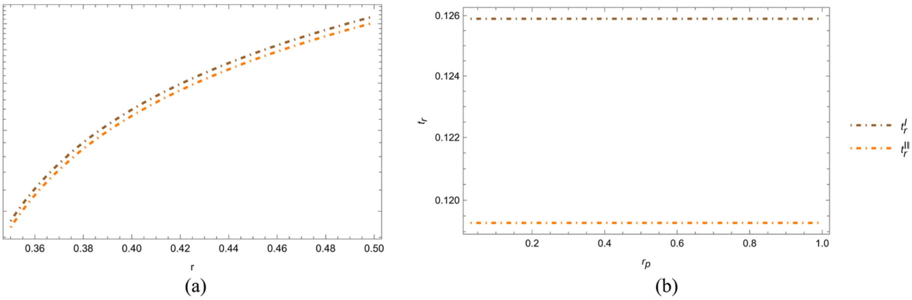


Fig. 5 Effect of energy rebound, i.e., $\boldsymbol{r}$ (**a**) and $\boldsymbol{r_p}$ (**b**) parameter, on revenue share proportion

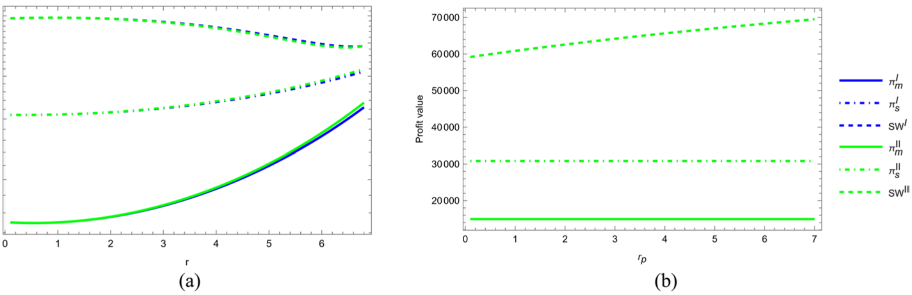


Fig. 6 Effect of energy rebound, i.e., $\boldsymbol{r}$ (**a**) and $\boldsymbol{r_p}$ (**b**) parameter, on players' profits

results in more revenue for the supply chain, regardless of the product quantity produced by the manufacturer. Furthermore, refrigerator production offers less profit for the manufacturer than washing machine production under the second scenario, while we can see the opposite situation under the first scenario. Finally, the overall production level in *CRI* is more than what the supply-chain players produced in *CRII*. Then, we explore the impact of change in the parameter values under a reasonable range of uncertainty in a primary estimation.

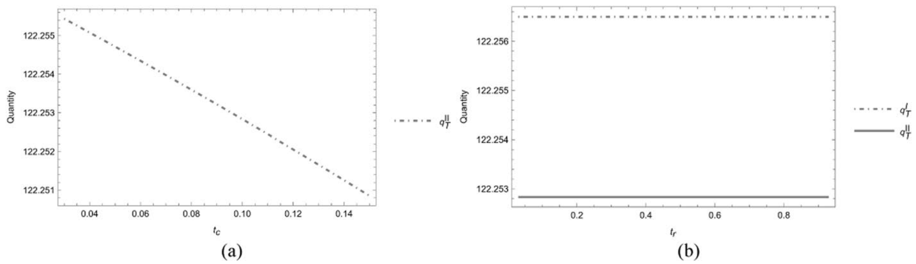


Fig. 7 Effect of cost-share (**a**) and revenue-share (**b**) proportion of the second contract on production

4.2.1 The energy rebound parameters

We investigate the industrial rebound effects in Figs. 5 and 6 as follows. Figure 5a and b show the impact of rebound effects on the revenue-sharing in *RC I* and *RC II*. This figure reveals that increases in the rebound effects of household energy use led to more revenue share of the manufacturer, in particular, under the first contract (Fig. 5a). However, there is no significant change in energy consumption when industrial rebound effects continually increase (Fig. 5b).

As a result, we can say that the potential household rebound effects provide more flexibility for the supplier to share more proportion of a TWC scheme's benefits with the manufacturer, while the industrial rebound effects do not impact the revenue-sharing part of the investigated contracts.

The effect of energy rebound on players' profits and social welfare is represented in Fig. 6. Based on Fig. 6 (a), we can see a gradual increase in a manufacturer's and supplier's profit and a decrease in welfare, respectively, when the energy rebound of household consumption rises. Furthermore, we see a smooth decrease in social welfare by increasing the energy rebound of industrial consumption (Fig. 6b).

Corollary 1 *The proposed contracts can stimulate the manufacturer to follow the efficiency mandates without a reduction in profits. Therefore, total energy consumption does not increase under the described conditions.*

Corollary 2 *The potential household rebound effects are more effective than the industrial ones in the setting of contract parameter values under the proposed scenarios. This result can be meaningful in the investigation of economic parameters established in direct energy rebound in the residential sector.*

4.2.2 The sharing parameters

We describe the numerical analysis of the sharing parameters (the t_r, t_c, and d parameters) in the following subsection. Figure 7 describes the impact of the sharing proportions on production volume. Based on Fig. 7a and b, there is less production when the cost-sharing proportion of *RC II* increases (Fig. 7a). Also, we can see no significant change in production volume about the revenue-sharing proportion.

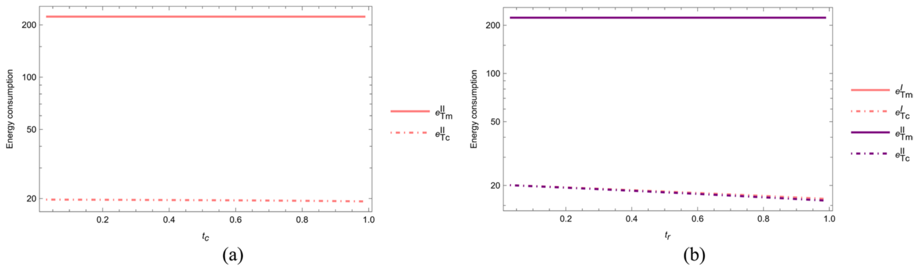


Fig. 8 Effect of cost-share (**a**) and revenue-share (**b**) proportion of the second contract on energy consumption

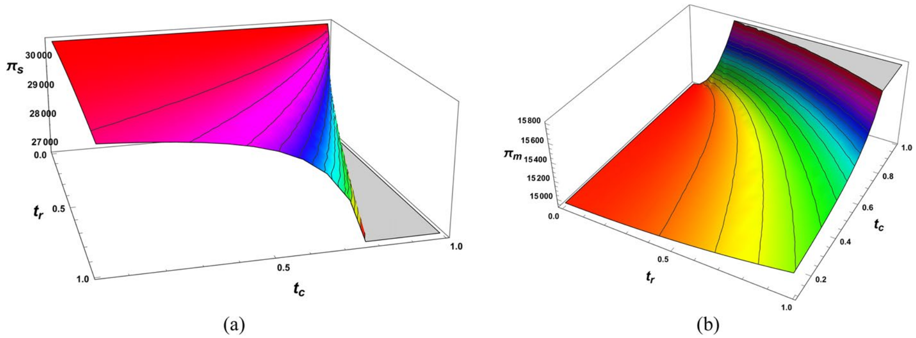


Fig. 9 Effect of share proportions of the second contract on supplier's (**a**) and manufacturer's (**b**) profit

As a result, the cost-sharing part of the investigated contract has a greater impact on production than it does on the revenue-sharing part of this problem. However, related literature confirms the obtained result under an appropriate level of energy efficiency potential (Bertoldi et al., 2010).

Figure 8 shows more energy use when sharing parameters continually increase. According to Fig. 8a, we can see a linear relationship between the t_c changes and energy consumption. Also, there is more energy consumed in the first contract than there is in the second contract (Fig. 8b). From an analytical perspective, the increase in sharing parameters results in less energy use, due to the reduced production of efficient appliances by the manufacturer. However, these decrease in energy consumption are linear regarding the revenue share proportion, unlike the way they are regarding the cost share proportion in *RC II*.

In Fig. 9a and b, where the maximum or minimum areas are shown by hot colors, the effect of the sharing proportions of *RC II* on the supply chain players is presented. According to Fig. 9, the optimal values of t_c and t_r parameters, which can maximize the supplier's and manufacturer's profit, can be achieved under the considered contract as a Pareto solution.

According to the above figures, we can see that the proposed model helps the supplier determine the sharing proportions of the revenue-cost-sharing contracts regarding the most profitable position. Hence, given the benefits of participating in the proposed contracts, manufacturers should be amenable to adopting them.

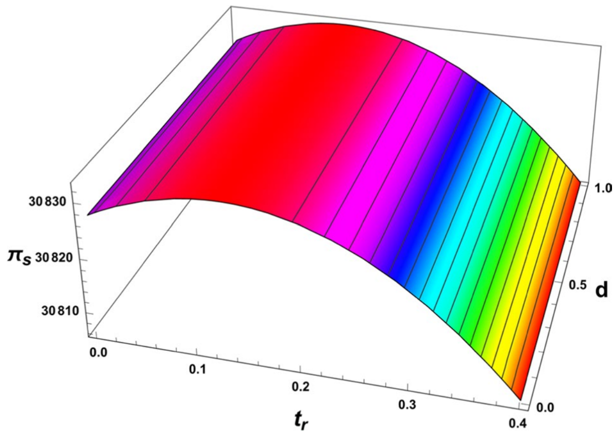


Fig. 10 Simultaneous effect of share proportions of the first contract on the supplier's profit

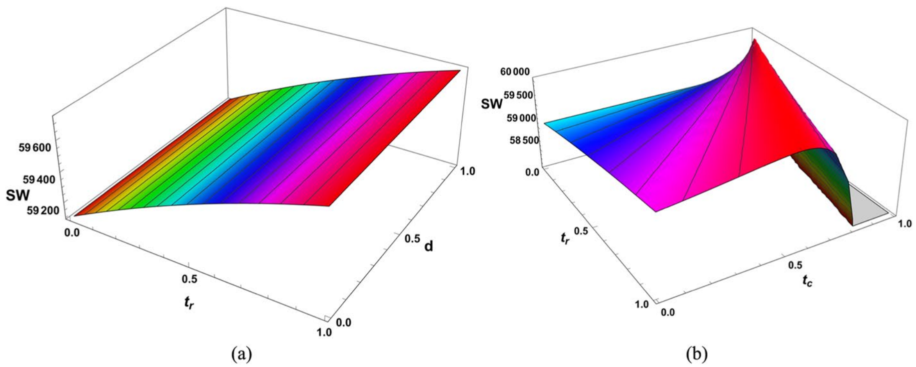


Fig. 11 Simultaneous effect of sharing proportions of the first (**a**) and second contract (**b**) on social welfare index

Figure 10 indicates the relationship between the revenue- and cost-sharing proportions in *RC I* and the profit of the energy producer. Based on this figure, the optimal level of the revenue share to maximize the producer's profit can be seen clearly. Hence, an appropriate parameter setting is needed to maximize the supplier's profits. However, after the optimum point (in this case, $t_r^I = 0.29$, $d = [0, 1]$), the profit value decreases, due to an increase in revenue and cost share of the manufacturer.

As a managerial point, the cost-sharing parameter in *RC I* has a negligible impact on the members. Finally, Fig. 11 demonstrates the effect of sharing-related parameters on the proposed social welfare index. Based on Fig. 11a, the optimal level of the revenue share parameter can be seen (in this case, $t_r^I = 1.0$, $d^I \in [0, 1]$) under the first contract. However, the effect of the cost share of the energy price is negligible. Also, according to Fig. 11b, the optimal level of t_c and t_r parameters can be set according to the maximum value of the social welfare in *RC II* as a pareto solution.

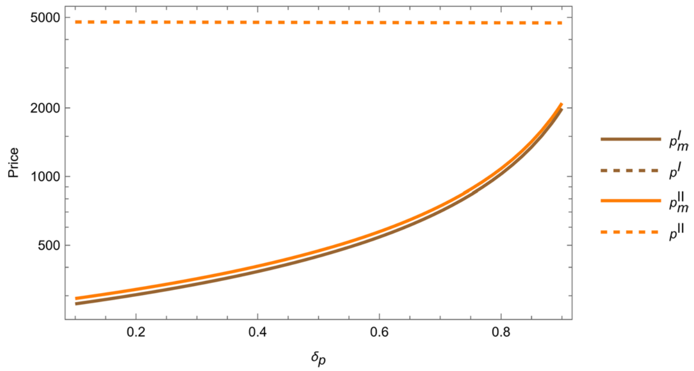


Fig. 12 Impact of production efficiency level on retail prices

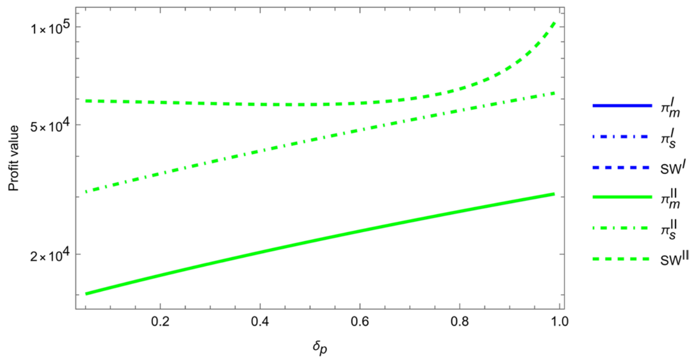


Fig. 13 Impact of production efficiency level on players' profits and social welfare

Corollary 3 *Considering the obtained results, it is clear that revenue share and cost share have an advantage in welfare improvement in RC I and RC II contracts under consideration.*

Corollary 4 *The manufacturers with an efficient production process are less significantly motivated by the revenue share of a TWC scheme than the low-efficient manufacturers concerning both contracts are.*

Figure 12 presents the growth of sales prices of energy-efficient appliances and energy services for the industrial firm, when the energy efficiency of the production process increases. So, according to this figure, energy-intensive manufacturers with low-efficient processes benefit from low-price services concerning other manufacturers. However, there is no significant difference between the proposed contracts on the addressed prices.

In Fig. 13, we show the impact of production efficiency level on players' profits and social welfare. Social welfare increases when the efficiency rate of manufacturing processes results in higher profits for the supplier and manufacturer.

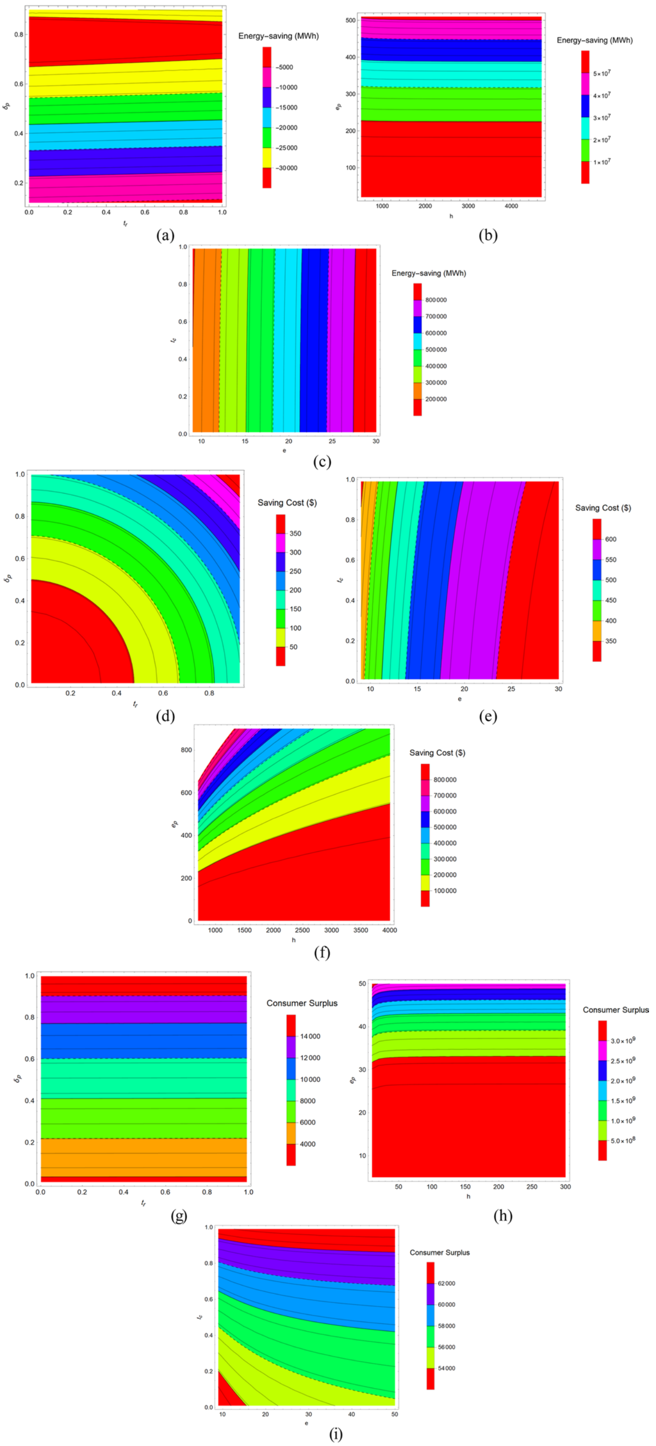


Fig. 14 Impact of manufacturer's parameters on social welfare (**a**-**i**)

4.2.3 Cost-effectiveness analysis

In this subsection, we perform a comprehensive exploration on the cost-effectiveness of the investigated contracts' options, to propose some useful insights, based on the assessment of instrument performance. Figure 14 demonstrates the relation between the manufacturer's parameters and related contract parameters. We apply these contour plots to explain the insights and policy suggestions.

Figure 14a–c demonstrates the impact that a manufacturer's energy-efficient process has on revenue share and cost share proportions, the energy consumption of the product, and efficiency investment costs

Corollary 5 *According to the contracts' analysis, both the revenue share and the energy efficiency of the manufacturing process have a direct effect on energy savings. Nevertheless, the energy efficiency rate is more effective than the revenue share of the manufacturer, in which energy saving is at a maximum level in both contracts. In contrast, the cost-sharing proportion can reduce energy saving in an energy-intensive process (in RC II).*

Corollary 6 *In our problem, the most effective parameter on the obtained energy saving is the product's energy use before energy efficiency enhancement.*

The impact of contract-related parameters (t_r and t_c) and production-related parameters (e and δ_p) on the saving costs of the energy efficiency project is provided in Fig. 14d–f. By comparing the mentioned figures, the following can be concluded.

Corollary 7 *If the policy-maker selects a saving-cost goal, a cost-sharing contract on energy efficiency investment can be proposed as the most appropriate instrument for energy-intensive products. In contrast, a revenue-sharing contract may be more useful for the product manufacturers who have the most energy-efficient processes.*

Finally, Fig. 14g–i describes the impact of contracts' parameters and manufacturing-related parameters on consumer surplus as an important section of the social welfare index. The comparisons of these charts reveal the following.

Corollary 8 *Regarding the assumptions used, the input energy of the production process, before the implementation of the scheme, can provide more surplus for energy and product consumers. The cost-share parameter can be introduced as the second most effective parameter on consumer surplus.*

5 Discussions and implications

5.1 The proposed contracts' comparison

The obtained results and findings of the present work are summarized in this section. Thus, we compare the two considered contracts on TWC schemes to suggest applicable managerial implications and useful energy policies regarding the implementation of

Table 4 Summary of supply chain contracts compared

Contract	Advantages	Disadvantages
RC I	Controlling energy rebound of industrial energy use Ability to stimulate the manufacturer to follow energy efficiency projects More relative profit for the supply-chain members than *RC II* More social utility than *RC II* More economic stability for the players than *RC II*	Less energy efficiency of energy-efficient products than *RC II* Less sensitive to the financial value of the TWC than *RC II* More energy consumption than *RC II*
RC II	Ability to stimulate the manufacturer to follow energy efficiency projects and GHG emission reduction obligations More energy efficiency of energy-efficient products than *RC I* Controlling energy rebound of industrial energy use More suitable for energy efficiency investment than *RC I*	Less social utility than *RC I*

efficiency measures. Table 4 demonstrates the comparisons between the two proposed supply chain contracts.

The manufacturers should only benefit, as they have a higher margin for energy-efficient products and processes and other incentives. This is because a price deduction on industrial energy costs may not lead to more energy-saving for them. In this regard, according to Table 4, the advantages of the second proposed contract (*RC II*) can be expressed for the relatively efficient manufacturer as follows: (i) using the second proposed contract, the manufacturer with a relatively efficient production process has the potential power to improve efficiency of its facilities and control industrial rebound effects; (ii) from a financial perspective, the energy-intensive manufacturers, who need a costly energy efficiency upgrade for their production line experience better circumstances under the second proposed contract; (iii) this contract leads to a higher level of welfare under the same conditions offered by the other contract; so, as a result, the second cooperation contract is recommended for societies where social welfare takes priority over energy saving; (iv) the *RC II* contract can create a more favorable situation for low-income manufacturers, to enhance their economic level, from a business point of view; (v) the *RC II* contract provides the possibility of a trade-off between cost-sharing and future household energy use reduction caused by using energy-efficient products made in a costly production process.

Based on the findings of existing literature, *RC II* could also increase the total factor productivity in the long term (Peng et al., 2019; Shah et al., 2023c; Wang et al., 2024). It is interesting to compare this finding with the finding of Marques et al. (2019) about the incentive investment in energy efficiency projects. This type of contract is recommended for energy-intensive processes, such as the processes used in construction sectors, as an appropriate energy scheme (Kalantzis & Revoltella, 2019). Nevertheless, if the manufacturer has a relatively efficient process with an acceptable production cost, the energy supplier only can compensate the revenue share by increasing the retail price of household energy services under *RC II*. So, if producing energy-efficient products (e.g., electrical home appliances) takes priority over industrial energy consumption, it is better for a manufacturer to choose *RC I*.

Table 5 Comparison of proposed financial instruments

Policy	Advantages	Disadvantages
Revenue-sharing side	Maintain the production ratio and social welfare An intensive instrument for the manufacturers Decrease in energy consumption and carbon emission	
Cost-sharing side	More profit for the supply-chain members than revenue-sharing A light instrument for the manufacturers	No significant change in energy consumption and GHG emission reduction

5.2 Financial instruments comparison

Table 5 shows the individual impact of the revenue- and cost-sharing sections, as two parts of the presented contracts. These findings can help energy policymakers make more appropriate decisions.

Based on Table 5, a revenue-sharing contract proves to be a more effective means of boosting the adoption rate of tradable white certificates (TWC) amongst parties that are required to do so than does a cost-sharing contract. Revenue-sharing encourages stakeholders, to prioritize and maximize energy-saving initiatives by tying incentives to results. According to previous works, this promotes innovation and ongoing development (Alipour-Vaezi et al., 2022; Li et al., 2019; Yenipazarli, 2017; Yu et al., 2020). The policy instrument analysis highlights the superiority of revenue-sharing as a stimulus for sustainable development, as it drives energy reductions at a reduced cost to society. Its adaptability transcends industries, allowing significant gains in energy efficiency regardless of technological knowledge and bridging the gap between high-tech and low-tech sectors. Revenue-sharing arrangements also provide a workable solution by encouraging ongoing energy-saving measures, which always entail worries about consumer-side rebound effects. In contrast, the cost-sharing strategy excels in promoting the use of inexpensive, highly efficient technology in energy-intensive processes like the production of plastics and petroleum refinement. Cost-sharing ensures cost-effectiveness in companies with high energy consumption while promoting accessibility to new technology by evenly dispersing financial responsibilities. To put it simply, the careful choice of policy tools based on industry-specific circumstances emphasizes how important revenue-sharing and cost-sharing contracts are to promoting sustainability and energy efficiency in a variety of industries.

This result is confirmed by previous findings that approve the effectiveness of a revenue-sharing contract against regular contracts, such as wholesale price contracts (Niederhoff & Kouvelis, 2019; Zhuang et al., 2022). As a result, the non-contract-related efficiency efforts of manufacturers may not be counted as industrial energy-saving measures. So, considering the energy savings target metric of the TWC scheme, both investigated policies can work as well as individual incentive instruments in supply chains (Iorember et al., 2022; Li et al., 2019).

6 Conclusions

We addressed an appliance supply chain that included an energy producer and a product manufacturer, who produces efficient appliances in a monopoly. The energy producer provides energy services simultaneously for the industrial and residential end-users. Also, the energy producer, due to social pressures, financial benefits, and environmental concerns follows a tradable white certificate (TWC) scheme and proposes two types of revenue-cost-sharing contracts to the manufacturer, to encourage greater energy efficiency. This is brought about by using cutting-edge technological and managerial methods. On this point, we studied for the first time the impact of the rebound effect caused by improvements made on three objectives—energy saving, saving cost, and consumer surplus. Furthermore, a novel index for the assessment of social welfare was introduced to measure the outcome of a social welfare level vis-à-vis the proposed contracts.

To solve the proposed problem, the authors presented a two-stage game model with perfect information, based on a leader–follower structure, so that the energy supplier, in the upper level, determined the energy price, and the manufacturer determined the energy-efficiency rates, the production volume, and the selling price of the appliances. After solving the problem, a thorough analysis of the equilibria and players' profits was performed. The results reveal that the second contract has more advantages. Nevertheless, social welfare in the second contract is less than it is in the other contract. Furthermore, the findings suggest that sharing the revenue and energy use costs is better in the second proposed contract than sharing in the first one for the obligated parties to improve the quality of white certificate implementation.

6.1 Policy recommendations

Based on the investigation, we can present some recommendations as follows:

Insight 1 Based on the obtained results (Figs. 5, 6, and Corollary 2), investing in parameters affecting the potential household rebound effects of energy-intensive products can be considered a serious recommendation for policymakers in the energy field. On this matter, instrumental policies such as raising awareness about the existence of rebound effects can be useful in controlling energy consumption on the demand side and encouraging the players of the energy supply chain to use revenue-sharing contracts, taking into account the assumptions of the problem.

Insight 2 From an energy-saving perspective, RC II has an advantage, due to its inclusion of a cost-sharing contract on energy-efficiency investments (Fig. 14a–c and Corollary 6). In this regard, RC II proposes an appropriate option to decrease industrial energy use. So, if policymakers seek to enhance energy-saving value on the supply side, the contract that provides efficient low-cost technologies for manufacturers of energy-efficient products can be considered an effective policy. In addition, revenue-sharing can be introduced as the most important policy instrument that can complete this goal in both proposed contracts.

Insight 3 Considering the energy-saving costs, the results of a cost-effectiveness analysis show that cost-sharing on efficiency investment in RC II and revenue-sharing in RC I, respectively, can motivate the manufacturers of energy-efficient products to use more energy-efficient methods in their production processes (Fig. 14d–f and Corollary 7). In addition, a TWC scheme with energy efficiency improvement options for energy-efficient products that reduces energy-saving costs is recommended for energy-intensive industries instead of a revenue-sharing contract. On this matter, a public authority can use supportive policy instruments, e.g., grant and loan programs, to facilitate expensive energy-saving projects. Additionally, using similar trading mechanisms such as what is applied in the carbon market can be useful to enhance the flexibility of these projects.

Insight 4 From the social welfare perspective, the findings suggest that there is no remarkable difference between the EEPs with middle- or high-efficiency targets on the production process under the proposed contracts. Also, energy-efficiency improvement options for energy-efficient processes embedded in TWC schemes can provide more surplus for end-users than revenue- or cost-sharing in similar contracts (Fig. 14g–i and Corollary 8). However, there is a long-standing conflict between the production of more efficient equipment obtained from processes that conserve energy and the energy consumption of end-users—two important parts of the social welfare equation.

Insight 5 Considering the substantial influence of the manufacturer's cost-share parameter within the cost-sharing contract relative to other factors, there is a compelling argument to prioritize policies aimed at reducing the investment costs associated with energy consumption efficiency for manufacturers over alternative financial support mechanisms such as taxation, particularly under similar conditions (Figs. 7, 9, and 11). Such a strategic emphasis can effectively heighten manufacturers' motivation, to engage in energy-efficiency projects. By alleviating the financial burden on manufacturers through targeted incentives and subsidies aimed specifically at enhancing energy efficiency, policymakers can catalyze greater participation in sustainability initiatives. This approach not only fosters environmental stewardship but also yields tangible economic benefits for manufacturers through reduced operational costs and enhanced competitiveness. Moreover, by aligning incentives with desired outcomes, governments can encourage ongoing investment in energy-saving technologies and practices, thereby facilitating a transition towards a more sustainable and resilient industrial landscape.

Insight 6 Given the substantial influence of input energy within the production process and energy-consumer products before any energy efficiency enhancements, the implementation of regulatory policies such as "restriction" and "target setting" schemes emerge as a viable strategy, to address energy storage and consumption costs at the supply side (Fig. 14b–i). These policies serve to optimize energy utilization, leading to enhanced energy efficiency and improved returns on energy investment. By imposing restrictions on energy usage and setting specific targets for energy consumption, regulatory frameworks can effectively steer industries toward more sustainable practices. This not only reduces energy waste but also promotes the adoption of innovative technologies and processes geared toward maximizing energy efficiency. Moreover, by incentivizing energy conservation and efficiency improvements, these policies contribute to mitigating environmental impact and fostering long-term sustainability. Consequently, the integration of regulatory measures aimed at enhancing energy storage and consumption practices holds significant potential, to drive positive outcomes for both businesses and the environment, paving the way for a more resilient and resource-efficient future.

Insight 7 Based on our investigations, the advantages of RC II for relatively efficient manufacturers include improved facility efficiency, better financial circumstances for energy-intensive manufacturers, higher societal welfare, economic uplift for low-income manufacturers, and a trade-off between cost-sharing and future household energy savings.

Insight 8 In the investigated problem, revenue-sharing contracts are more effective than cost-sharing contracts in boosting tradable white certificate (TWC) adoption among obligated parties. They prioritize energy-saving initiatives, foster innovation, and drive sustainability at lower societal costs. Revenue-sharing benefits diverse industries and addresses rebound effects, while cost-sharing promotes cost-efficient technology adoption in energy-intensive sectors, ensuring accessibility. Overall, strategic policy tool selection emphasizes revenue-sharing and cost-sharing contracts' importance in promoting sustainability and energy efficiency.

Some of the benefits that emerged from this finding relate specifically to the application of such energy efficiency instruments. The private sector's willingness to engage in energy efficiency and renewable energy generation projects can be greatly increased by the emergence of a free, non-governmental energy market that is competitive. This change promotes innovation and technological growth in the energy sector while also being in line with global sustainability goals. Furthermore, public authorities can accomplish predefined goals in an organized manner by putting in place a multi-level framework that is customized to certain industries and their patterns of energy usage.

Regulations can successfully guide the shift toward environmentally friendly practices while maintaining economic viability and competitiveness by establishing targets that are specific to the industry. Particularly in industries with significant energy use, like the food industry, these strategic actions can bring about revolutionary change. Businesses are under increasing pressure to implement energy-efficient procedures and to incorporate renewable energy sources into their operations as they become more aware of the financial advantages of sustainability projects. This improves resilience and long-term profitability in addition to reducing the impact on the environment. The results highlight how crucial it is to provide reliable energy efficiency tools that are adapted to the changing dynamics of the green energy markets for spurring sustainable development across all industries.

6.2 Research limitations

While our study provides valuable insights into the implementation of TWC schemes in energy efficiency markets, several notable limitations warrant consideration. Firstly, the simplified mathematical representation of certain parameters, such as the financial estimation of TWCs, may constrain the generalizability of our findings to nonlinear contexts. The intricacies of real-world dynamics may necessitate more nuanced modeling approaches, to capture complex relationships accurately. Secondly, addressing the multi-agent problem-solving aspect, particularly in the context of duopolistic competition, posed significant challenges due to the inherent complexity of interactions between parameters and decision variables.

Our study focused on prioritizing key factors, but the exclusion of certain variables may have implications for the comprehensiveness of our analysis. Additionally, data gathering presented obstacles, potentially impacting the depth and breadth of our research insights. Furthermore, the absence of an explicit cost recovery mechanism in our model represents a notable gap, as it could influence the dynamics of energy-saving processes. Although not explicitly explored in this study, future research should investigate the implications of cost recovery mechanisms on energy efficiency initiatives, drawing parallels to their impact on household energy prices. Recognizing these limitations underscores the need for continued research efforts to refine modeling approaches, address data challenges, and explore additional factors that shape the effectiveness of TWC schemes in fostering energy efficiency and sustainability.

6.3 Future research

For future research, the related financial function of white certificate (WC) applications in the energy efficiency marketplace can be applied more practically than it has been applied in the current formulation. Also, in future research, a novel penalty function for energy suppliers, who violate the efficiency target, could be proposed under the given problem. Finally, future scientific studies could be conducted by extending the model explored in this study.

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Declarations

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References

Abbas, J., Balsalobre-Lorente, D., Amjid, M. A., Al-Sulaiti, K., Al-Sulaiti, I., & Aldereai, O. (2024). Financial innovation and digitalization promote business growth: The interplay of green technology innovation, product market competition, and firm performance. *Innovation and Green Development, 3*, 100111.

Abbas, J., Rehman, S., Aldereai, O., Al-Sulaiti, K. I., & Shah, S. A. R. (2023a). Tourism management in financial crisis and industry 4.0 effects: Managers traits for technology adoption in reshaping, and reinventing human management systems. *Human Systems Management*. https://doi.org/10.3233/HSM-230067

Abbas, J., Wang, L., Ben Belgacem, S., Pawar, P. S., Najam, H., & Abbas, J. (2023b). Investment in renewable energy and electricity output: Role of green finance, environmental tax, and geopolitical risk: Empirical evidence from China. *Energy, 269*, 126683.

Alipour-Vaezi, M., Aghsami, A., & Rabbani, M. (2022). Introducing a novel revenue-sharing contract in media supply chain management using data mining and multi-criteria decision-making methods. *SOFT COMPUTING, 26*, 2883–2900.

Amazon.com, (2018). LG LPXS30886D 30.0 Cu. Ft. Black Diamond French Door Refrigerator. Amazon.com.

An, Y., Zhou, D., Wang, Q., Shi, X., & Taghizadeh-Hesary, F. (2022). Mitigating size bias for carbon pricing in small Asia-Pacific countries: Increasing block carbon tax. *Energy Policy, 161*, 112771.

Ansuategi, A., Delgado, J., & Galarraga, I. (2014). *Green energy and efficiency: An economic perspective*. Springer.

Argun, I. D., Kayakutlu, G., Ozgozen, N. Y., & Daim, T. U. (2021). Models for energy efficiency obligation systems through different perspectives. *Technology in Society, 64*, 101436.

Balsalobre-Lorente, D., Abbas, J., He, C., Pilař, L., & Shah, S. A. R. (2023). Tourism, urbanization, and natural resources rents matter for environmental sustainability: The leading role of AI and ICT on sustainable development goals in the digital era. *Resources Pol., 82*, 103445.

Baptista, S., Barbosa-Póvoa, A. P., Escudero, L. F., Gomes, M. I., & Pizarro, C. (2019). On risk management of a two-stage stochastic mixed 0–1 model for the closed-loop supply chain design problem. *European Journal of Operational Research, 274*, 91–107.

Bertoldi, P. (2010). Assessment of white certificates in improving residential energy efficiency. *Light and Engineering, 18*, 8–11.

Bertoldi, P., & Rezessy, S. (2008). Tradable white certificate schemes: Fundamental concepts. *Energy Effic., 1*, 237–255.

Bertoldi, P., Rezessy, S., Lees, E., Baudry, P., Jeandel, A., & Labanca, N. (2010). Energy supplier obligations and white certificate schemes: Comparative analysis of experiences in the European Union. *Energy Policy, 38*, 1455–1469.

Blázquez, L., Boogen, N., & Filippini, M. (2013). Residential electricity demand in Spain: New empirical evidence using aggregate data. *Energy Economics, 36*, 648–657.

Carabalí, D. M., Forero, C. R., & Cadavid, Y. (2018). Energy diagnosis and structuring an energy saving proposal for the metal casting industry: An experience in Colombia. *Applied Thermal Engineering, 137*, 767–773.

Caragliu, A. (2021). Energy efficiency-enhancing policies and firm performance: Evidence from the paper and glass industries in Italy. *Energy Policy, 156*, 112415.

Ceglia, F., Marrasso, E., Pallotta, G., Roselli, C., & Sasso, M. (2023). Assessing the influence of time-dependent power grid efficiency indicators on primary energy savings and economic incentives for high-efficiency cogeneration. *Energy, 278*, 127969.

Chen, Q., Gu, Y., Tang, Z., Wei, W., & Sun, Y. (2018). Assessment of low-carbon iron and steel production with CO_2 recycling and utilization technologies: A case study in China. *Applied Energy, 220*, 192–207.

Chlond, B., Gavard, C., & Jeuck, L. (2023). How to support residential energy conservation cost-effectively? An analysis of public financial schemes in France. *Environmental & Resource Economics, 85*, 29–63.

Choi, C., Choi, J., Kim, C., & Lee, D. (2020). The smart city evolution in South Korea: Findings from big data analytics. *The Journal of Asian Finance, Economics and Business, 7*, 301–311.

Dai, R., Zhang, J., & Tang, W. (2017). Cartelization or Cost-sharing? Comparison of cooperation modes in a green supply chain. *J. Cleaner Prod., 156*, 159–173.

Ejaz, W., Naeem, M., Shahid, A., Anpalagan, A., & Jo, M. (2017). Efficient energy management for the internet of things in smart cities. *IEEE Communications Magazine, 55*, 84–91.

(EU), C.D.R., (2010). Supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of household refrigerating appliances, pp. 17–46.

Ezbakhe, F., & Pérez-Foguet, A. (2021). Decision analysis for sustainable development: The case of renewable energy planning under uncertainty. *European Journal of Operational Research, 291*(2), 601–613. https://doi.org/10.1016/j.ejor.2020.02.037

Fan, K., Li, X., Wang, L., & Wang, M. (2019). Two-stage supply chain contract coordination of solid biomass fuel involving multiple suppliers. *Computers & Industrial Engineering, 135*, 1167–1174.

Fathi, B., Ashena, M., & Anisi, M. (2023). Efficiency evaluation of sustainability indicators in a two-stage network structure: A Nash bargaining game approach. *Environ. Dev. Sustainability, 25*, 1832–1851.

Fawcett, T., Rosenow, J., & Bertoldi, P. (2019). Energy efficiency obligation schemes: Their future in the EU. *Energy Effic., 12*, 57–71.

Ghadimi, P., Ghassemi Toosi, F., & Heavey, C. (2018). A multi-agent systems approach for sustainable supplier selection and order allocation in a partnership supply chain. *European Journal of Operational Research, 269*, 286–301.

Ghosh, D., & Shah, J. (2012). A comparative analysis of greening policies across supply chain structures. *Int. J. Product. Econ., 135*, 568–583.

Gill, C., & Lang, C. (2018). Learn to conserve: The effects of in-school energy education on at-home electricity consumption. *Energy Policy, 118*, 88–96.

González, J. F. (2010). Empirical evidence of direct rebound effect in Catalonia. *Energy Policy, 38*, 2309–2314.

Gunnarsdottir, I., Davidsdottir, B., Worrell, E., & Sigurgeirsdottir, S. (2022). Indicators for sustainable energy development: An Icelandic case study. *Energy Policy, 164*, 112926.

Hafezalkotob, A. (2017). Competition, cooperation, and coopetition of green supply chains under regulations on energy saving levels. *Transportation Research Part e: Logistics and Transportation Review, 97*, 228–250.

Hafezalkotob, A. (2018). Modelling intervention policies of government in price-energy saving competition of green supply chains. *Computers & Industrial Engineering, 119*, 247–261.

Iorember, P.T., Iormom, B., Jato, T.P., Abbas, J., 2022. Understanding the bearable link between ecology and health outcomes: the criticality of human capital development and energy use. Heliyon 8.

Irena, I. (2018). *Renewable power generation costs in 2017*. Abu Dhabi: Report, International Renewable Energy Agency.

Jafari, H., Hejazi, S. R., & Rasti-Barzoki, M. (2017). Pricing decisions in dual-channel supply chain with one manufacturer and multiple retailers: A game-theoretic approach. *RAIRO-Operations Research, 51*, 1269–1287.

Jiakui, C., Abbas, J., Najam, H., Liu, J., & Abbas, J. (2023). Green technological innovation, green finance, and financial development and their role in green total factor productivity: Empirical insights from China. *J. Cleaner Prod., 382*, 135131.

Kalantzis, F., & Revoltella, D. (2019). Do energy audits help SMEs to realize energy-efficiency opportunities? *Energy Economics, 83*, 229–239.

Kumar, R., Mishra, J. S., Mondal, S., Meena, R. S., Sundaram, P. K., Bhatt, B. P., Pan, R. S., Lal, R., Saurabh, K., Chandra, N., Samal, S. K., Hans, H., & Raman, R. K. (2021). Designing an ecofriendly and carbon-cum-energy efficient production system for the diverse agroecosystem of South Asia. *Energy, 214*, 118860.

Lauri, C. (2021). Expert knowledge and smart city administration. *European Review of Digital Administration & Law (ERDAL), 2*, 57–76.

Le Cadre, H., Jacquot, P., Wan, C., & Alasseur, C. (2020). Peer-to-peer electricity market analysis: From variational to Generalized Nash Equilibrium. *European Journal of Operational Research, 282*, 753–771.

Li, T., Zhang, R., Zhao, S., & Liu, B. (2019). Low carbon strategy analysis under revenue-sharing and cost-sharing contracts. *J. Cleaner Prod., 212*, 1462–1477.

Li, Y., Deng, S., Zhang, Y., & Liu, B. (2021). Coordinating the retail supply chain with item-level RFID and excess inventory under a revenue-cost-sharing contract. *International Transactions in Operational Research, 28*, 1505–1525.

Macchiaroli, M., Dolores, L., Nicodemo, L., & De Mare, G. (2021). Energy Efficiency in the Management of the Integrated Water Service. A Case Study on the White Certificates Incentive System. In O. Gervasi, B. Murgante, S. Misra, C. Garau, I. Blečić, D. Taniar, B. O. Apduhan, A. M. A. C. Rocha, E. Tarantino, & C. M. Torre (Eds.), *Computational Science and Its Applications – ICCSA 2021* (pp. 202–217). Springer International Publishing.

Manrique, R., Vásquez, D., Vallejo, G., Chejne, F., Amell, A. A., & Herrera, B. (2018). Analysis of barriers to the implementation of energy efficiency actions in the production of ceramics in Colombia. *Energy, 143*, 575–584.

Marques, A. C., Fuinhas, J. A., & Tomás, C. (2019). Energy efficiency and sustainable growth in industrial sectors in European Union countries: A nonlinear ARDL approach. *J. Cleaner Prod., 239*, 118045.

Mattoni, B., Nardecchia, F., Benelli, A., Buscaglione, S., Pagliaro, F., Burattini, C. (2017). A quantitative evaluation of the mutual influences among Smart strategies applied at district level. In *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, (pp. 1–5).

Meng, Q., Yan, Z., Abbas, J., Shankar, A., & Subramanian, M. (2023). Human-computer interaction and digital literacy promote educational learning in pre-school children: Mediating role of psychological resilience for kids' mental well-being and school readiness. *International Journal of Human-Computer Interaction*. https://doi.org/10.1080/10447318.2023.2248432

Micah, A. E., Bhangdia, K., Cogswell, I. E., Lasher, D., Lidral-Porter, B., Maddison, E. R., Nguyen, T. N. N., Patel, N., Pedroza, P., & Solorio, J. (2023). Global investments in pandemic preparedness and COVID-19: Development assistance and domestic spending on health between 1990 and 2026. *The Lancet Global Health, 11*, e385–e413.

Monstvilas, E., Borg, S. P., Norvaišienė, R., Banionis, K., & Bliūdžius, R. (2023). A review of the 1–2 apartment residential building stock in lithuania based on an analysis of energy performance certificates. *Journal of Physics: Conference Series, 2654*, 012061.

Morganti, P., & Garofalo, G. (2022). Interactions between market forces and regulatory interventions in the Italian market of white certificates. *Energy Effic., 15*, 18.

Mousavian, S., Conejo, A. J., & Sioshansi, R. (2020). Equilibria in investment and spot electricity markets: A conjectural-variations approach. *European Journal of Operational Research, 281*, 129–140.

Mundaca, L. (2007). Transaction costs of Tradable White Certificate schemes: The energy efficiency commitment as case study. *Energy Policy, 35*, 4340–4354.

Niederhoff, J. A., & Kouvelis, P. (2019). Effective and necessary: Individual supplier behavior in revenue sharing and wholesale contracts. *European Journal of Operational Research, 277*, 1060–1071.

Oikonomou, V., Patel, M. K., van der Gaast, W., & Rietbergen, M. (2009). Voluntary agreements with white certificates for energy efficiency improvement as a hybrid policy instrument. *Energy Policy, 37*, 1970–1982.

Oliveira, B. B., Carravilla, M. A., Oliveira, J. F., & Costa, A. M. (2019). A co-evolutionary metaheuristic for the car rental capacity-pricing stochastic problem. *European Journal of Operational Research, 276*, 637–655.

Park, J. Y. (2017). Is there a price premium for energy efficiency labels? Evidence from the Introduction of a Label in Korea. *Energy Economics, 62*, 240–247.

Peng, J., Xiao, J., Wen, L., & Zhang, L. (2019). Energy industry investment influences total factor productivity of energy exploitation: A biased technical change analysis. *J. Cleaner Prod., 237*, 117847.

Raj, A., Biswas, I., & Srivastava, S. K. (2018). Designing supply contracts for the sustainable supply chain using game theory. *Journal of Cleaner Production, 185*, 275–284.

Rasti-Barzoki, M., & Moon, I. (2020). A game theoretic approach for car pricing and its energy efficiency level versus governmental sustainability goals by considering rebound effect: A case study of South Korea. *Applied Energy, 271*, 115196.

Rosenow, J., Skoczkowski, T., Thomas, S., Węglarz, A., Stańczyk, W., & Jędra, M. (2020). Evaluating the Polish White Certificate scheme. *Energy Policy, 144*, 111689.

Ruzzenenti, F., & Bertoldi, P. (2017). Energy Conservation Policies in the Light of the Energetics of Evolution. In N. Labanca (Ed.), *Complex Systems and Social Practices in Energy Transitions: Framing Energy Sustainability in the Time of Renewables* (pp. 147–167). Springer International Publishing.

Shah, K. U. (2018). Regulatory impact assessment for implementing energy-efficient lighting standards in the small island developing state of Antigua & Barbuda. *Energy Strategy Reviews, 22*, 216–229.

Shah, S. H. A., Fahlevi, M., Rahman, E. Z., Akram, M., Jamshed, K., Aljuaid, M., & Abbas, J. (2023c). Impact of green servant leadership in pakistani small and medium enterprises: Bridging pro-environmental behaviour through environmental passion and climate for green creativity. *Sustainability, 15*, 14747.

Shah, S. A. R., Zhang, Q., Abbas, J., Balsalobre-Lorente, D., & Pilař, L. (2023a). Technology, urbanization and natural gas supply matter for carbon neutrality: A new evidence of environmental sustainability under the prism of COP26. *Resources Pol., 82*, 103465.

Shah, S. A. R., Zhang, Q., Abbas, J., Tang, H., & Al-Sulaiti, K. I. (2023b). Waste management, quality of life and natural resources utilization matter for renewable electricity generation: The main and moderate role of environmental policy. *Utilities Policy, 82*, 101584.

Sheu, J.-B. (2011). Bargaining framework for competitive green supply chains under governmental financial intervention. *Transportation Research Part e: Logistics and Transportation Review, 47*, 573–592.

Sheu, J. B., & Chen, Y. J. (2012). Impact of government financial intervention on competition among green supply chains. *International Journal of Production Economics, 138*, 201–213.

Sorrell, S. (2007). *The Rebound Effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency* (pp. 4–8). UK Energy Research Centre London.

Sorrell, S., Harrison, D., Radov, D., Klevnas, P., & Foss, A. (2009). White certificate schemes: Economic analysis and interactions with the EU ETS. *Energy Policy, 37*, 29–42.

Stede, J. (2017). Bridging the industrial energy efficiency gap–Assessing the evidence from the Italian white certificate scheme. *Energy Policy, 104*, 112–123.

Sueyoshi, T., Li, A., & Liu, X. (2019). Exploring sources of China's CO_2 emission: Decomposition analysis under different technology changes. *European Journal of Operational Research, 279*, 984–995.

Ünal, B. B., Onaygil, S., Acuner, E., & Cin, R. (2022). Application of energy efficiency obligation scheme for electricity distribution companies in Turkey. *Energy Policy, 163*, 112851.

Wang, S., Abbas, J., Al-Sulati, K. I., & Shah, S. A. R. (2024). The impact of economic corridor and tourism on local community's quality of life under one belt one road context. *Evaluation Review, 48*, 312–345.

Wang, Z., Wang, X., & Guo, D. (2017). Policy implications of the purchasing intentions towards energy-efficient appliances among China's urban residents: Do subsidies work? *Energy Policy, 102*, 430–439.
Xu, J., Yang, G., Wang, F., & Shu, K. (2022). A provincial renewable portfolio standards-based distribution strategy for both power plant and user: A case study from Guangdong. *China. Energy Policy, 165*, 112935.
Xu, L., & Wang, C. (2017). Contracting pricing and emission reduction for supply chain considering vertical technological spillovers. *The International Journal of Advanced Manufacturing Technology, 93*, 481–492.
Xue, W., Zuo, J., & Xu, X. (2017). Analysis of market competition and information asymmetry on selling strategies. *Annals of Operations Research, 257*, 395–421.
Yenipazarli, A. (2017). To collaborate or not to collaborate: Prompting upstream eco-efficient innovation in a supply chain. *European Journal of Operational Research, 260*, 571–587.
Yu, B., Wang, J., Lu, X., & Yang, H. (2020). Collaboration in a low-carbon supply chain with reference emission and cost learning effects: Cost sharing versus revenue sharing strategies. *J. Cleaner Prod., 250*, 119460.
Zhang, X., Yang, F., Wei, F., & Wang, Y. (2023). Provincial CO_2 emission efficiency analysis in China based on a game cross-efficiency approach with a fixed-sum undesirable output. *Environment Development and Sustainability*. https://doi.org/10.1007/s10668-023-03205-0
Zhang, Y.-J., & Peng, H.-R. (2017). Exploring the direct rebound effect of residential electricity consumption: An empirical study in China. *Applied Energy, 196*, 132–141.
Zhou, M., Liu, Y., Feng, S., Liu, Y., & Lu, Y. (2018). Decomposition of rebound effect: An energy-specific, general equilibrium analysis in the context of China. *Applied Energy, 221*, 280–298.
Zhou, W., & Huang, W. (2016). Contract designs for energy-saving product development in a monopoly. *European Journal of Operational Research, 250*, 902–913.
Zhuang, D., Abbas, J., Al-Sulaiti, K., Fahlevi, M., Aljuaid, M., & Saniuk, S. (2022). Land-use and food security in energy transition: Role of food supply. *Frontiers in Sustainable Food Systems*. https://doi.org/10.3389/fsufs.2022.1053031

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