Optimal Licensing Strategy of Green Technology With Corporate Social Responsibility (CSR)

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Optimal licensing strategy of green technology with corporate social responsibility (CSR)
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Abstract: This paper develops a duopoly model to investigate a firm’s green technology licensing strategy with corporate social responsibility (CSR). In our model, licensing is conducted by an inside innovator and the patent holder may take CSR activities under a time-consistent emission tax. The result shows that fixed-fee licensing is always the optimal strategy of the patent holder when there is no CSR. In the CSR case, when the reduction degree of abatement cost coefficient is large, the optimal licensing strategy of the patent holder changes from pure royalty licensing to fixed-fee licensing as the degree of CSR decreases. Furthermore, we find that neither conflict nor consistency always exists between social welfare and firm payoff goals. When the degree of CSR is relatively low, fixed-fee licensing is preferred both by the patent holder and the government. Otherwise, when the degree of CSR is relatively high, the government prefers fixed-fee licensing, while the patent holder prefers royalty licensing. Finally, we analyze the effects of CSR behaviors on environment and social welfare. We show that CSR is beneficial for environment, while it is not always beneficial for social welfare.

Keywords: Green technology licensing; Corporate social responsibility; Fixed-fee licensing; Royalty licensing
JEL Classifications: D42; M14; I13

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1. Introduction

With the increasing prominence of environmental issues, green innovation is becoming an increasingly important approach for firms to improve their market competitiveness (Porter and Vander Linde, 1995). For example, Apple made significant investments in green technologies such as renewable energy projects in 2017. Through these investments, the company reduced its emissions by more than 2 million tons compared to the previous year. Similarly, Gree, a well-known Chinese home appliance company, reduced its carbon emissions by approximately 9,064.4 tons per year through investing in next-generation refrigeration technologies (Zhang et al., 2020). Most green technologies are likely to be patented. Licensing is critical to the transfer and diffusion of green technology. According to the PTC (Patent Cooperation Treaty) database, developed countries invent the majority of environmental management technologies, accounting for more than 60% of all patents in these fields worldwide. At the same time, developing countries are increasingly importing eco-technologies from foreign inventors to reduce GHS (Green House Gases).

Three forms of green technology licensing have been discussed in literature: fixed-fee, royalty, and two-part tariff (fixed-fee plus royalties) (e.g., Kim et al., 2014, 2017; Hattori, 2017; Li, 2021). While the literature on green technology licensing is extensive, it frequently views profit maximization as the primary aim of a private firm, neglecting the possibility that a firm may be concerned with corporate social responsibility (CSR). As we know, CSR has become a mainstream worldwide corporate strategy since Porter and Kramer (2006, 2011) provided a systematic study connecting comparative advantage with CSR. Under the CSR strategy, firms establish corporate self-disciplines that prioritize not just profit, but also ethical considerations, environmental sustainability, and community welfare as critical drivers of business performance. A growing number of companies around the world have issued various CSR statements and carried out various activities. According to KPMG (2016), more than 90% of the world top companies have issued CSR reports since 2011. Many companies practicing CSR pay attention to customer welfare, environmental issues, and green manufacturing. As shown by PricewaterhouseCoopers (PwC) (2010), the environmental activities of companies have become the main focus of CSR reporting. According to KPMG (2015, p. 12; 2017, p. 50), 82% of companies worldwide reported carbon emissions, and the percentage of companies reporting carbon reductions increased from 58% in 2015 to 67% in 2017. It is no exaggeration to say that firms cannot ignore the effect of CSR behaviors when designing green business strategies.

However, to the best of our knowledge, no papers attempt to analyze the relation between the licensing strategy of green technology and CSR. This paper aims to fill this research gap in the literature. Particularly, we focus on the following research questions:

1) Which licensing contract, fixed-fee or royalty, is the optimal one for green technology under no CSR and CSR cases, respectively? Is there a conflict between enterprise and government goals for any given licensing strategy?

2) Is there any difference in the optimal licensing contracts between no CSR and CSR cases?
3) Does CSR result in a cleaner environment and higher social welfare under green technology licensing?

4) What are the effects of exogenous parameters on environment, firm profits, and social welfare under the optimal licensing contract of green technology with CSR?

To investigate the research questions, we consider a duopoly model in which a patent holder may take CSR activities under a time-consistent emission tax. We first explore the optimal licensing strategy under the cases of no CSR and CSR, and then compare the equilibrium results in the two cases. Furthermore, we numerically verify the effectiveness of the model and the sensitivity of key parameters. The main results of this paper are as follows: First, we find that when there is no CSR, fixed-fee licensing is always the optimal contract from the viewpoint of the patent holder. This is not the case when the patent holder engages in CSR activity. In the case of CSR, the optimal licensing strategy shifts from pure royalty licensing to fixed-fee licensing as the degree of CSR decreases when the reduction degree of abatement cost coefficient is large.

Second, in the case of CSR, there is no contradiction or inconsistency between social welfare and firm payoff objectives. Optimal licensing contracts can conflict when there is a high degree of CSR. That is, the government prefers fixed-fee licensing, while the patent holder wants royalty licensing. When CSR degree is low, the optimal licensing contract is consistent. That is, fixed-fee licensing is the best contract from the perspective of both the patent holder and the government. This finding suggests that government intervention may be beneficial when a firm’s choice of licensing contract is inconsistent with social incentive.

Third, we demonstrate that CSR is beneficial to environment, but not necessarily to social welfare. When the degree of CSR is high, social welfare from CSR is lower than that of those who do not engage in CSR. However, when the degree of CSR is low, social welfare is greater with CSR than without CSR. Notably, this finding differs from the study by Fukuda and Ouchida (2020), who show that a higher degree of CSR monotonically increases social welfare in a monopoly model. Social welfare may be improved due to the emission-reducing effect of CSR in a monopoly model. However, in our model, this emission-reducing effect does not occur and thus the level of social welfare depends on the degree of CSR.

The rest of this paper is organized as follows. Section 2 summarizes the relevant literature on green technology licensing and CSR. Section 3 provides an overview of the basic model. Section 4 examines optimal green technology licensing contracts without and with CSR, and then compares the main findings in these two cases. Section 5 discusses the impacts of key parameters on the equilibrium results using numerical examples and sensitivity analysis. Section 6 summarizes the findings and suggests future research directions to address the limitations of the study. All proofs are given in the appendix.

2. Literature review

Our work is closely linked to the following two streams of research: technology licensing and CSR. In this section, we examine each stream and discuss how our research differs from previous
studies.

2.1. Technology licensing

The first stream of research mainly focuses on technology licensing strategy. According to whether a patentee aims to license its innovation outside or inside his own industry, the literature on technology licensing can be roughly divided into two categories (Heywood et al., 2014): that is, licensing by an outside innovator and licensing by an inside innovator. When the patentee licenses his innovation outside his own industry, he will not compete with his potential licenses on product market. Kamien and Tauman (1984, 1986) find that if a patent holder faces multiple downstream licenses, fixed-fee licensing does not increase marginal production cost, thus reducing output needed to obtain additional rents. So fixed-fee licensing is better than royalty licensing. Kamienetal (1992) extends this conclusion to the case of price competition. Many subsequent scholars challenge this conclusion and find that when there is information asymmetry (Gallini and Wright, 1990; Sen, 2005), royalty licensing may be better than fixed-fee licensing. If two licenses compete on price (Muto, 1993), or if the number of licensees is limited to an integer number (Sen, 2007), royalty licensing is found to be superior. When patent-holding firms participate in the market competition, it is found that royalty licensing is often better than fixed-fee.

Under fixed-fee licensing, the output of two firms are the same, and thus marginal cost is the same. Conversely, under royalty licensing, patent-holding firms charge a certain patent fee for unit output, which enjoys a cost advantage over licensee. Hence, royalty licensing is better than fixed-fee licensing (Wang, 1998; Wang and Yang, 1999). Fauli-Oller and Sandonis (2002) study price competition situation and draw the same conclusion. Even in the duopoly model of differentiated products, there are similar conclusions (Wang, 2002). However, previous researches have primarily focused on production technology licensing, while green technology licensing is rarely considered in licensing studies.

The literature addressing green technology licensing includes only a few papers: Kim et al. (2014, 2017), Hattori (2017), Xia et al. (2019), and Li (2021). Kim et al. (2014) examine the welfare consequences of an innovator’s green licensing strategy with an emissions tax. Kim et al. (2017) explore the use of strategic fixed-fee license contracts in a mixed duopoly environment in which public and private companies may acquire green technology from overseas innovators. Hattori (2017) examines the optimum trade-off between innovation and environmental policy in the context of technology licensing. Xia et al. (2019) examine the effect of command and control regulation on the licensing and spread of emission abatement technology in an oligopolistic market. Li (2021) studies green technology licensing strategy in a mixed oligopoly with an inside innovator. The results indicate that when a licensor is located in a private market, fixed-fee licensing is the optimal licensing contract. In contrast to these studies, we incorporate CSR into our model with a time-consistent emission tax under the context of technology licensing.

2.2. The effects of CSR behaviors on firms’ decisions
Another relevant stream is the effects of CSR behaviors on firms’ decisions. Recently, CSR has gained increasing attention in a wide range of studies in business and economics, including both theoretical and empirical studies. On the one hand, several theoretical studies, including Lambertini and Tampieri (2015), Liu et al. (2015), Lambertini et al. (2016), and Ee et al. (2018), have examined various oligopoly models in which profit-maximizing private firms compete with other private firms that engage in socially responsible activities. Lambertini and Tampieri (2015) examined how socially responsible behavior affects firm profitability and social welfare in a Cournot oligopoly when manufacturing is involved in environmental externalities. Their findings suggest that when the market is large enough, CSR firms earn more profits and generate greater social benefits than profit-seeking rivals. Liu et al. (2015) studied CSR certification and demonstrated how the competitive environment affects firms’ motivation to implement CSR and how CSR helps firms and customers. Lambertini et al. (2016) show that when the market is sufficiently large, CSR firm sells more goods, accumulates more capital, and earns more profit than its profit-seeking opponent in a linear state differential game. Ee et al. (2018) explore the influence of CSR investment on income distribution in a general equilibrium paradigm. They demonstrate that CSR investment exacerbates pay disparity between skilled and unskilled workers via the factor substitution effect, while the rising capital costs eventually drive businesses out. Fukuda and Ouchida (2020) construct a CSR model for a monopolistic market with a time-consistent emission tax, demonstrating that CSR is always advantageous to societal welfare. On the other hand, a substantial body of empirical research examines the benefits of CSR. The preceding literature has established conclusively that firms can improve their economic performance, stock performance, international expansion, customer loyalty and provide green innovation by implementing CSR (Noci and Verganti, 1999; Brunnermeier and Cohen, 2003; Bos-Brouwers, 2010; Liou and Sharma, 2012; Flammer, 2013; Rashid et al., 2015; Chuang and Huang, 2018; Xu et al., 2018; Singh et al., 2020).

According to the literature survey, although several studies related to green technology licensing and CSR have been reported, respectively, few studies consider how CSR affects the optimal licensing strategy of firms. This paper aims to fill the research gap by proposing a duopoly model in which a patent holder may take CSR activities under a time-consistent emission tax. Such a consideration might generate important insights into the firms’ licensing strategy and enrich the results in the literature of CSR.

3. The model

Consider a Cournot duopoly industry in which firm 1 and firm 2 produce homogeneous products. The inverse demand function is given by: \( p = a - Q \), where \( Q = q_1 + q_2 \). The parameter \( a > 0 \) is reservation price; \( q_i \ (i = 1, 2) \) and \( p \) denote the output and price of products, respectively. We assume that production cost function takes a linear form, \( C(q_i) = c q_i \), where \( c(a > c) \) is the unit cost of production. The production process of firms emit pollutants, and a unit of output produces a unit of pollution. Government levies an emission tax \( \tau \) on firms.
per unit of polluting output. Firms use end-of-pipe technology for pollution abatement. The cost function of firm $i$’s abatement activities is assumed quadratic and denoted by $\frac{\gamma_i z_i^2}{2}$, where $z_i$ is abatement effort; $\gamma_i > 0$ stands for the efficiency of abatement cost. Through pollution abatement, a firm’s emission level can be reduced to $e_i = q_i - z_i$.

If no new green technology is developed, the cost coefficient of abatement will remain $\gamma_1 = \gamma$; however, if firm 1 creates a new green technology and applies it to abatement activities, the cost coefficient of abatement will become $\gamma_1' = \gamma - \varepsilon$, where $\varepsilon (\gamma > \varepsilon)$ is the reduction degree of abatement cost coefficient. Firm 1 should decide whether or not to share its technology with competitor firm 2, and if so, how (fixed-fee licensing or royalty licensing). When firm 2 is licensed, a fixed-fee $F$ should be paid to the patent holder under a fixed-fee licensing, while under a royalty license, a royalty rate $r$ per unit of pollution must be paid to the patent holder. Additionally, similar to previous studies of licensing with an inside inventor (Wang, 1998; Fauli-Oller and Sandonís, 2002), this article reduce two-part tariff licensing to fixed-fee licensing, which may not offer any extra important policy implications to our analysis. Hence, we examine only fixed-fee and royalty licensing contracts to keep model simple and tractable.

Obviously, the profits of the patent holder without licensing and with licensing can be expressed as following, respectively

$$\pi_1^N = (a - c - q_1 - q_2)q_1 - \tau(q_1 - z_1) - \frac{(\gamma - \varepsilon)z_1^2}{2}$$

(1)

$$\pi_1^L = (a - c - q_1 - q_2)q_1 - \tau(q_1 - z_1) - \frac{(\gamma - \varepsilon)z_1^2}{2} + F + rz_2$$

(2)

where $\pi_1^N$ represents firm 1’s profit without licensing, and $\pi_1^L$ denotes the profit gained by firm 1 with licensing. Similarly, firm 2’s profit function can be defined as Eqs. (3) and (4), respectively:

$$\pi_2^N = (a - c - q_1 - q_2)q_2 - \tau(q_2 - z_2) - \frac{\gamma z_2^2}{2}$$

(3)

$$\pi_2^L = (a - c - q_1 - q_2)q_2 - \tau(q_2 - z_2) - \frac{(\gamma - \varepsilon)z_2^2}{2} - F - rz_2$$

(4)

Social welfare function $SW$ can be defined as the sum of consumer surplus and firms’ profits plus tax revenues minus pollution damage:

$$SW = CS + \sum_{i=1}^{2} \pi_i + \tau \sum_{i=1}^{2} e_i - ED$$

(5)

where consumer surplus is $CS = \frac{1}{2} (q_1 + q_2)^2$. Following Petrakis and Xepapadeas (1998), Tsai et al. (2016), Martin-Herran and Rubio (2018), and Xing et al. (2021), we assume pollution damage function to be $ED = dE$, where $E = \sum_{i=1}^{2} e_i$, and $d > 0$ denotes marginal pollution damage.
We assume that firm 1 takes CSR strategy. That is, firm 1 is not only concerned with its own profits, but also with the consumer surplus and pollution damage (Fanti and Buccella, 2017, 2018, 2019; Goering, 2012, 2014; Lamberti and Tampieri, 2015; Ouchida, 2019; and others). Thus, the objective function of firm 1 is defined as:

$$\Omega = \pi_1 + \theta(CS - ED)$$  \hspace{1cm} (6)

where the exogenous parameter $\theta \in [0, 1]$ presents the degree of CSR.

As in Puller (2006), Poyago-Theotoky (2007), Ouchida and Goto (2016), and Fukuda and Ouchida (2020), we consider that the government has no pre-commitment ability for an emission tax rate $\tau$. Consequently, the tax rate is set to maximize social welfare after firms’ emission reduction activities. The timing of licensing games consists of five stages. In the first stage, the inside innovator are responsible for announcing how patents will be licensed, as well as determining the most advantageous fixed-fee or royalty to charge for the patent. In the second stage, the licensee can decide whether or not to acquire a license. The third stage involves the two firms determining their respective levels of emission reduction in order to optimize profit. In the fifth stage, each firm independently decides on the output and competes in the market. We solve this game by backward induction and equilibrium concept is the subgame perfect Nash equilibrium.

4. Equilibrium analysis and results

In this section, we investigate the optimal licensing contract of green technology without CSR and with CSR, respectively, and then compare the main results of the two cases.

4.1. Green technology licensing without CSR

In this section, we present the scenario without any CSR as a benchmark, that is, $\theta = 0$. We denote the superscripts $N$, $LF$ and $LR$ to indicate the no licensing, fixed-fee licensing, and royalty licensing regimes, respectively.

4.1.1. No licensing

Now, let us first discuss the no licensing case. At this point, the five-stage game degenerates into a three-stage game. In the third stage, each firm independently decides on the output. The following objective functions in the quantity game is obtained when there is no licensing:

$$\pi_1^N = (a - c - q_1 - q_2)q_1 - \tau(q_1 - z_1) - \frac{(\gamma - \delta)z_1^2}{2}$$  \hspace{1cm} (7)

$$\pi_2^N = (a - c - q_1 - q_2)q_2 - \tau(q_2 - z_2) - \frac{\gamma z_2^2}{2}$$  \hspace{1cm} (8)

The resulting equilibrium is as follows:

$$q_1^N = q_2^N = \frac{a - c - \tau}{3}$$  \hspace{1cm} (9)

In the second stage, government chooses an emission tax in order to maximize the social welfare. Then, by directly solving $\frac{\partial SW^N}{\partial \tau} = 0$, we have
\[ \tau^N = \frac{3d + c - a}{2} \] 

In the first stage, firms choose their pollution abatement levels to maximize profits, respectively. Solving the first-order conditions, the pollution abatement efforts of firms are derived as:

\[ z_1^N = \frac{3d + c - a}{2(\gamma - \varepsilon)} \]  
\[ z_2^N = \frac{3d + c - a}{2\gamma} \]

We assume \( d < a - c < 3d \) to ensure positive output and green innovation investment. This condition also implies green innovation is non-drastic (i.e., \( q_2^N \) is always larger than zero). Noting that this result is different from cost-reducing innovation case. Under cost-reducing innovation, when the innovator could operate as a monopolist (i.e., \( q_2^N \leq 0 \)), innovation is drastic. Because the output of the two firms are the same in this section, green innovation should be non-drastic.

The equilibrium firm profits, consumer surplus, and societal welfare are simplified as follows using Eqs (9)-(12):

\[ \pi_1^N = \frac{(c + \tau^N - a)^2}{9} - \frac{(\gamma - \varepsilon)(z_1^N)^2}{2} + \tau^N z_1^N \]  
\[ \pi_2^N = \frac{(c + \tau^N - a)^2}{9} - \frac{\gamma(z_2^N)^2}{2} + \tau^N z_2^N \]

\[ CS^N = \frac{2(a - c - \tau^N)^2}{9} \]  
\[ SW^N = \frac{4(a - c - \tau^N)^2}{9} + \frac{2(d - \tau^N)(c + \tau^N - a)}{3} + d(z_1^N + z_2^N) - \frac{(\gamma - \varepsilon)[(z_1^N)^2 + (z_2^N)^2]}{2} \]

4.1.2. Fixed-fee licensing

In a fixed-fee licensing contract, firm 1 transfers the patent to firm 2 with a fixed-fee \( F \). The profits of two firms are added to and subtracted from \( F \) based on non-licensed profit, respectively. Therefore, \( F \) has no influence on the first-order conditions of firm 1. After licensing, the emission reduction cost of firm 2 becomes \( \frac{(\gamma - \varepsilon)z_2^2}{2} \). Correspondingly, by solving stages 3-5 of the game, the equilibrium outcomes are given as:

\[ q_1^{LF} = q_2^{LF} = \frac{a - c - d}{2} \]  
\[ \tau^{LF} = \frac{3d + c - a}{2} \]  
\[ z_1^{LF} = z_2^{LF} = \frac{3d + c - a}{2(\gamma - \varepsilon)} \]
In the second stage, firm 2 consider whether to accept licensing. The necessary condition for firm 2 to accept licensing is that the profit after accepting licensing is at least no less than before licensing, \( \pi_2^{LF} \geq \pi_2^N \). In the stage 1, firm 1 transfers its innovation to firm 2 via a fixed-fee contract and charges the optimal fee \( F \) to maximize the profit. Thus, the constrained maximization problem is described as follows

\[
\max_F \pi_1^{LF} = \left[ \frac{(c + \tau^{LF} - a)^2}{9} - \frac{(\gamma - \varepsilon)(z_1^{LF})^2}{2} + \tau^{LF}z_1^{LF} + F \right]
\]

s.t. \( \pi_2^{LF} \geq \pi_2^N \)

The maximum fee that can be charged by firm 1 is just the increment of firm 2’s profit after it accepts the licensing offer. This means the maximum licensing fee \( F \) is determined by \( \pi_2^{LF} = \pi_2^N \), as follows

\[
F = \frac{\varepsilon(a - c - 3d)^2}{8\gamma(\gamma - \varepsilon)} \tag{20}
\]

The optimal firms’ profits, consumer surplus, and social welfare are, respectively,

\[
\pi_1^{LF} = \frac{(c + \tau^{LF} - a)^2}{9} - \frac{(\gamma - \varepsilon)(z_1^{LF})^2}{2} + \tau^{LF}z_1^{LF} + \frac{\varepsilon(a - c - 3d)^2}{8\gamma(\gamma - \varepsilon)} \tag{21}
\]

\[
\pi_2^{LF} = \frac{(c + \tau^{LF} - a)^2}{9} - \frac{(\gamma - \varepsilon)(z_2^{LF})^2}{2} + \tau^{LF}z_2^{LF} - \frac{\varepsilon(a - c - 3d)^2}{8\gamma(\gamma - \varepsilon)} \tag{22}
\]

\[
CS^{LF} = \frac{2(a - c - \tau)^2}{9} \tag{23}
\]

\[
SW^{LF} = \frac{4(a - c - \tau^{LF})^2}{9} + \frac{2(d - \tau^{LF})(c + \tau^{LF} - a)}{3} + d(z_1^{LF} + z_2^{LF}) - \frac{(\gamma - \varepsilon)[(z_1^{LF})^2 + (z_2^{LF})^2]}{2} \tag{24}
\]

Now, it is necessary to investigate whether firm 1 has an incentive to license green inventions for a fixed fee. We can see the following Lemma 1 by comparing the profit before and after licensing.

**Lemma 1.** Under fixed-fee licensing, firm 1 will always license its new green technology to firm 2.

Lemma 1 shows that transferring green technology under a fixed-fee contract is beneficial to the innovating firm. The underlying logic of Lemma 1 is that licensing costs determine the difference in profits between licensing and non-licensing. Since the licensing fee is positive, the firm that owns patent will choose to license its new technology.

**Proof:** See Appendix.

4.1.3. Royalty licensing

In this section, we consider only licensing through a royalty. Under this licensing arrangement, firm 1 licenses its technology to firm 2 at a stated royalty rate \( r \). The equilibrium results are given as:
During the royalty licensing stage, firm 1 as the leader selects $r$ to maximize its profit, subject to the following participation constraint, i.e.,

$$\max_r \pi_1^{LR} = \left[ \frac{(c + \tau^{LF} - a)^2}{9} - \frac{(\gamma - \epsilon)(z_1^{LF})^2}{2} + \tau^{LF} z_1^{LF} + rz_2^{LR} \right]$$

s.t. $\pi_2^{LR} \geq \pi_2^N$

Thus, firm 1 will choose the following royalty rate to extract firm 2’s increased profit

$$r = \begin{cases} 
\frac{(3d + c - a)(1 - \sqrt{1 - \frac{\epsilon}{\gamma}})}{2}, & 0 < \frac{\epsilon}{\gamma} < \frac{3}{4} \\
\frac{3d + c - a}{4}, & \frac{3}{4} \leq \frac{\epsilon}{\gamma} < 1
\end{cases}$$

The optimal firms’ profits, consumer surplus, and social welfare are, respectively,

$$\pi_1^{LR} = \frac{(c + \tau^{LF} - a)^2}{9} - \frac{(\gamma - \epsilon)(z_1^{LF})^2}{2} + \tau^{LF} z_1^{LF} + rz_2^{LR}$$

$$\pi_2^{LR} = \frac{(c + \tau^{LF} - a)^2}{9} - \frac{(\gamma - \epsilon)(z_2^{LF})^2}{2} + \tau^{LF} z_2^{LF} - rz_2^{LR}$$

$$CS^{LR} = \frac{2(c + \tau - a)^2}{9}$$

$$SW^{LR} = \frac{4(a - c - \tau^{LR})^2}{9} + \frac{2(\tau^{LR} - d)(a - c - \tau^{LR})}{3} + d(z_1^{LR} + z_2^{LR}) - \frac{(\gamma - \epsilon)(z_1^{LR})^2 + (z_2^{LR})^2}{2}$$

**Lemma 2.** Under royalty licensing, firm 1 will license its new green technology to firm 2.

**Proof:** See Appendix.

The intuition is similar to that of Lemma 1.

4.1.4. The optimal licensing strategy without CSR

By comparing the equilibrium outcomes of fixed-fee and royalty contracts, the subsequent Proposition 1 can be obtained.

**Proposition 1.** Fixed-fee licensing is the optimal strategy for both the patent holder and the government in the case of no CSR.

**Proof:** See Appendix.

Since the type of licensing has no impact on output and abatement levels, the profit differential
between fixed-fee and royalty licensing contracts is entirely dependent on the license fee. It is straightforward to verify that the license fee under fixed-fee licensing is greater than royalty licensing (see the proof of Proposition 1 in the Appendix). Therefore, fixed-fee licensing is the optimal choice for the patent holder. Likewise, it has the same result for government. The economic intuition is clear. Fixed-fee licensing increases profits and decreases pollution damage, thus enhancing social welfare. In the light of Proposition 1, we may infer that there is no contradiction between social welfare and firm payoff goals. That is, all licensing schemes contribute to the enhancement of social welfare.

Notably, Proposition 1 deviates from the past work on the optimal patent licensing (Wang, 1998, 2002; Fauli-Oller and Sandonis, 2002; Kamien and Tauman, 2002). According to the above studies, when innovators compete in product markets, royalty licensing is preferable to fixed-fee licensing for the patent holder. The economic reasoning for this result is as follows. In the earlier literature, marginal cost is the same for both firms when licensing on a fixed-fee basis. By contrast, under royalty licensing, the patent holder gets a cost advantage by collecting a royalty rate on each unit of production. Hence, royalty licensing is preferable to fixed-fee licensing. The main difference between us and them is that we take into account green technology that can reduce abatement costs, rather than production costs. In our model, the levels of firms’ output is the same under different licensing contracts, and the patent holder’s revenue is only affected by the value of the licensing fee. Under either licensing contract, the increase in profits from reduced abatement cost is taken away by the licensor. Thus, the higher the abatement cost, the higher the licensing fee; conversely, the lower the abatement cost, the lower the licensing fee. It can be easily demonstrated that the abatement cost under a fixed-fee licensing contract minus the abatement cost under a royalty licensing contract is equal to \( \frac{r^2}{2(\gamma - \varepsilon)} \), which is greater than zero. Therefore, from the perspective of the patent holder, fixed-fee licensing is the most favorable choice.

**Proposition 2.** From consumers’ perspective, both fixed-fee and royalty licensing are the optimal licensing strategies in the case of no CSR.

**Proof:** See Appendix.

The reasoning behind Proposition 2 is the following: since licensing type has no impact on output level, consumer surplus is equal across all licensing types. That is, any type of licensing contract is optimal and feasible for consumers.

### 4.2 Green technology licensing with CSR

In this section, we continue our analysis with CSR, that is, \( 0 < \theta \leq 1 \). We use subscript “\( C \)” to denote the case of CSR.

**4.2.1. No licensing**

The following results can be easily obtained by mirroring the analysis in the previous sections:

\[
q_{1c}^* = \frac{(a-c-d) + \theta(a-c-2d)}{2}, \quad q_{2c}^* = \frac{(a-c-d) - \theta(a-c-2d)}{2}
\]  
(33)
\[ z_{1c}^N = \frac{3d + c - a + \theta(a - c)}{2(\gamma - \epsilon)}, \quad z_{2c}^N = \frac{3d + c - a + \theta(a - c - 2d)}{2\gamma} \] (34)

\[ \tau_c^N = \frac{3d + c - a + \theta(a - c - 2d)}{2} \] (35)

\[ \Omega_c^N = \frac{(a - c)^2 + 2(\theta - \theta^2) + d^2(1 + 6\theta - 4\theta^2) + 2d(c - a)(1 + 4\theta - 2\theta^2)}{4} + \frac{d\theta(z_{1c}^N + z_{2c}^N)}{4} + \tau_c^N z_{1c}^N - \frac{(\gamma - \epsilon)(z_{1c}^N)^2}{2} \] (36)

\[ \pi_{1c}^N = \frac{(a - c - d)^2 - [(a - c - 2d)(\theta)]^2}{4} - \frac{(\gamma - \epsilon)(z_{2c}^N)^2}{2} + \tau_c^N z_{2c}^N \] (37)

\[ \pi_{2c}^N = \frac{[c + d - a + \theta(a - c - 2d)]^2}{4} - \frac{\gamma(z_{2c}^N)^2}{2} + \tau_c^N z_{2c}^N \] (38)

\[ CS_c^N = (a - c - d)^2 \] (39)

\[ SW_c^N = \frac{1}{2}(c + d - a)^2 + d(z_{1c}^N + z_{2c}^N) - \frac{(\gamma - \epsilon)(z_{1c}^N)^2}{2} - \frac{\gamma(z_{2c}^N)^2}{2} \] (40)

Similarly, we assume \( 2d < a - c < 3d \) to ensure positive output and green innovation investment, which also implies green innovation is non-drastic (i.e., \( q_2^N \) is always larger than zero). Some comparative-static effects with respect to \( \theta \) are:

Lemma 3. \( \frac{\partial z_{1c}^N}{\partial \theta} > 0, \quad \frac{\partial q_{1c}^N}{\partial \theta} < 0, \quad \frac{\partial z_{1c}^N}{\partial \theta} > 0, \) and \( \frac{\partial z_{2c}^N}{\partial \theta} \) > 0.

Proof: See Appendix.

Lemma 3 illustrates how the degree of CSR affects firms’ production and abatement effort. These comparative-static findings indicate that a rise in CSR leads the CSR firm (i.e., firm 1) to increase output, while the non-CSR firm (i.e., firm 2) decreases output. Meanwhile, a rise in CSR degree encourages firms to reduce their emissions more. The economic intuition is as follows. The marginal expansion of \( \theta \) increases marginal social concern, thus boosting the CSR firm’s production and emission reduction levels. In contrast, the output of the non-CSR firm would decrease as a result of output substitution effect. To compensate for the loss of earnings in the product market, the non-CSR firm will increase the level of emission reduction.

4.2.2. Fixed-fee licensing

Under fixed-fee licensing, the equilibrium results are given as:

\[ q_{1c}^{LF} = \frac{(a - c - d) + \theta(a - c - 2d)}{2}, \quad q_{2c}^{LF} = \frac{(a - c - d) - \theta(a - c - 2d)}{2} \] (41)

\[ z_{1c}^{LF} = \frac{3d + c - a + \theta(a - c)}{2(\gamma - \epsilon)}, \quad z_{2c}^{LF} = \frac{3d + c - a + \theta(a - c - 2d)}{2(\gamma - \epsilon)} \] (42)

\[ \tau_c^{LF} = \frac{3d + c - a + \theta(a - c - 2d)}{2} \] (43)
Using Eqs (36) and (45), the following Lemma 4 can be obtained.

**Lemma 4.** Under fixed-fee licensing, firm 1 that engages in CSR activities will license its technology to firm 2.

**Proof:** See Appendix.

This lemma states that under a fixed-fee licensing contract, it is always superior to license new innovation from the viewpoint of the patent-hold er. The rationale behind this is as follows. The patent holder’s payoff differences under licensing and no licensing depends on firm 2’s emission reduction level and the licensing fee (i.e., $\Omega^F_C - \Omega^N_C = d(z^F_{2c} - z^N_{2c}) + F_C$). Because the difference of firm 2’s emission reduction level and the licensing fee are greater than zero, it is profitable for the patent-holder to transfer the new green technology. Interestingly, the solution in the CSR case is the same as that in the no CSR case. Thus, Lemma 4 implies that irrespective of the degree of CSR, the patent-holding firm will always license new innovation to its competitor.

### 4.2.3. Royalty licensing

Under the royalty licensing, the equilibrium results are given as:

$$d^{LR}_{1c} = \frac{(a - c - d) + \theta(a - c - 2d)}{2}, \quad d^{LR}_{2c} = \frac{(a - c - d) - \theta(a - c - 2d)}{2}$$

$$z^{LR}_{1c} = \frac{3d + c - a + \theta(a - c)}{2(y - \epsilon)}, \quad z^{LR}_{2c} = \frac{3d + c - a + \theta(a - c - 2d) - 2r_c}{2(y - \epsilon)}$$

$$z^{LR}_c = \frac{3d + c - a + \theta(a - c - 2d)}{2}$$
Lemma 5. Under royalty licensing, firm 1 that engages in CSR activities will license its new technology to firm 2.

Proof: See Appendix.

The intuition is similar to that of Lemma 4.

4.2.4. The optimal licensing strategy with CSR

Now, we compare consumer surplus, patent holder payoff, and social welfare under the different licensing strategies and summarize the following Propositions 3-5.

Proposition 3. (i) if $0 < \frac{\varepsilon}{\gamma} < \frac{3}{4}$, from the perspective of patent holder, fixed-fee licensing contract is optimal; (ii) if $\frac{3}{4} < \frac{\varepsilon}{\gamma} < 1$, royalty licensing contract is optimal when the degree of CSR is relatively high; fixed-fee licensing contract is dominant when the degree of CSR is relatively low.

Proof: See Appendix.

Proposition 3 discusses how the patent holder’s level of CSR affects the optimal licensing strategy. Proposition 3 shows that firm 1 will always choose a fixed-fee licensing contract when the reduction degree of abatement cost coefficient is small. However, if the reduction degree of abatement cost coefficient is large, the ideal licensing contract shifts from pure royalty licensing to fixed-fee licensing as the level of CSR decreases. The intuition behind Proposition 3 is as follows.

If $0 < \frac{\varepsilon}{\gamma} < \frac{3}{4}$, the difference in patent holder’s profits under the two licensing contracts depends on the licensing fee and the emission reduction level of firm 2. Using Eqs.(42) and (51), we obtain that the emission reduction level of firm 2 under fixed-fee licensing is larger than that under royalty
licensing (i.e., $z_{2c}^{LF} > z_{2c}^{LR}$). Accordingly, the patent holder’s profit under fixed-fee licensing is larger than that under royalty licensing, which means fixed-fee licensing is the optimal contract. If $\frac{3}{4} < \varepsilon < 1$, the optimal licensing contract is solely determined by licensing fee. Under either licensing contract, the licensor retains the profit increase associated with the reduced abatement cost, implying that the licensing fee’s value is contingent on abatement cost. As Lemma 3 shows, the marginal increase of $\theta$ expands the output level of patent holder (i.e., $\frac{\partial q_{1c}^{LF}}{\partial \theta} > 0$) but decreases the output level of firm 2 (i.e., $\frac{\partial q_{2c}^{LF}}{\partial \theta} < 0$). When the patent holding firm gives more priority to CSR, the cost of abatement under fixed-fee licensing is lower than that under royalty licensing. Therefore, the value of license fee under fixed-fee licensing contract is smaller than that under royalty licensing contracts, which indicates that royalty licensing is the best contract from the patent holder’s perspective. When the patent holder is less concerned about CSR, the abatement cost under fixed-fee licensing is greater than that under royalty licensing. Therefore, the value of license fee is greater under fixed-fee licensing than under royalty licensing. This implies that fixed-fee licensing is the optimal arrangement. Noting that this conclusion deviates from the scenario where no CSR exists. Due to the identical output level, the licensing fee in the absence of CSR is only determined by emission abatement effort. However, when there is CSR, both output and emission abatement influence the licensing fee. Therefore, the optimal green technology licensing strategy relies on the degree of CSR.

**Proposition 4.** From consumers’ perspective, both fixed-fee and royalty licensing are optimal licensing strategies in the case of CSR.

**Proof:** See Appendix.

The analysis of Proposition 4 is similar to that of Proposition 2.

**Proposition 5.** From the perspective of government, fixed-fee licensing is the optimal strategy.

**Proof:** See Appendix.

Propositions 3 and 5 imply that there is never a conflict or inconsistency between social welfare and firm payoff goals. Conflicts between optimal licensing contracts arise when the degree of CSR is relatively high. That is, the government wants a fixed-fee licensing arrangement, but the patent holder would prefer a royalty-based arrangement. On the other hand, consistency between optimal licensing contracts occurs when the degree of CSR is relatively low. In other words, from the perspective of both the patent holder and the government, fixed-fee licensing is the best arrangement. Note that Propositions 3 and 5 are not in line with Proposition 1, where the patent holder does not take CSR activities.

4.3. Comparison of results

We are now able to compare the equilibrium results in two cases, i.e. without and with CSR.
After performing some simple calculations, we obtain the following Lemma 6.

**Lemma 6.** Comparing the equilibrium results under the different cases, we have the following relations: (i) \( q_{1c}^{LF} > q_{1}^{LF} \), \( q_{1c}^{LR} > q_{1}^{LR} \), \( z_{1c}^{LF} > z_{1}^{LF} \), \( z_{1c}^{LR} > z_{1}^{LR} \), and \( \pi_{1c}^{LF(R)} > (<) \pi_{1}^{LF(R)} \) for \( \theta < (>) \theta^{LF(R)} \), where \( \theta^{LF(R)} \) satisfies \( \pi_{1c}^{LF(R)} = \pi_{1}^{LF(R)} \) and \( 0 < \theta^{LF(R)} \leq 1 \); (ii) \( q_{2c}^{LF} < q_{2}^{LF} \), \( q_{2c}^{LR} < q_{2}^{LR} \), \( z_{2c}^{LF} > z_{2}^{LF} \), \( z_{2c}^{LR} > z_{2}^{LR} \), and \( \pi_{2c}^{LF(R)} > (<) \pi_{2}^{LF(R)} \) for \( \theta < (>) \theta^{LF(R)} \), where \( \theta^{LF(R)} \) satisfies \( \pi_{2c}^{LF(R)} = \pi_{2}^{LF(R)} \) and \( 0 < \theta^{LF(R)} \leq 1 \).

**Proof:** See Appendix.

Lemma 6-(i) shows that CSR yields two effects for firm 1: an emission abatement-enhancing effect and an output enhancing-effect. This result is in line with Lemma 3. Lemma 6-(i) also states that firm 1 can increase its profit from taking CSR activity only when the degree of CSR is relatively low. The rationale behind this is as follows: emission abatement-enhancing effect can be decomposed into a negative abatement cost effect and an indeterminate tax payment effect. When the degree of CSR is relatively low, tax payment effect is positive. Hence, the output enhancing-effect dominates the emission abatement-enhancing effect.

Lemma 6-(ii) shows that an increase in \( \theta \) induces production substitution from the non-CSR firm to the CSR firm and increases the non-CSR firm’s abatement effort. The reason is that when firm 1 engages in CSR and firm 2 is profit-seeking, firm 1 can attract more customers from its competitors, thus increasing its own output but decreasing the output of firm 2. Moreover, Lemma 6-(ii) shows that CSR has an ambiguous effect on the non-CSR firm’s profit. The reason is similar to that in Lemma 6-(i).

**Proposition 6.** \( E_{c}^{LF(R)} < E^{LF(R)} \); \( SW_{c}^{LF(R)} > (<) SW^{LF(R)} \) for \( \theta < (>) \theta^{LF(R)} \), where \( \theta^{LF(R)} \) satisfies \( SW_{c}^{LF(R)} = SW^{LF(R)} \) and \( 0 < \theta^{LF(R)} \leq 1 \).

**Proof:** See Appendix.

Proposition 6 states that the total emissions with CSR is smaller than that without CSR, regardless of the degree of CSR. The rationale behind this is as follows: as shown in Lemma 6, CSR yields an emission abatement-enhancing effect for both firms, while CSR does not affect the output levels of whole industry (i.e., \( q_{1c}^{LF} + q_{2c}^{LF} = q_{1}^{LF} + q_{2}^{LF} \) and \( q_{1c}^{LR} + q_{2c}^{LR} = q_{1}^{LR} + q_{2}^{LR} \)). Therefore, firms total emissions decrease with the degree of CSR. After analyzing the impact of CSR on the environment, one might further ask, will the social welfare enhance when firm 1 takes CSR activities into account? Proposition 6 shows that when the degree of CSR is high (i.e., \( \theta > \theta^{LF(R)} \)), the social welfare with CSR is lower than that without CSR. However, when the degree of CSR is low (i.e., \( \theta < \theta^{LF(R)} \)), the social welfare with CSR is higher than that without CSR. This can be explained as follows. The difference in the social welfare between CSR and non-CSR cases is dependent on the cost of abatement and total emissions. It is evident that the marginal increase of \( \theta \) increases abatement cost but decreases total emissions. When the degree of CSR is low and the declining effect of abatement costs on the social welfare is outweighed by the increasing effect of total emissions.
emissions on the social welfare, the social welfare will increase. By contrast, when the degree of CSR is high, the increasing effect of total emissions on the social welfare is outweighed by the declining effect of abatement cost on the social welfare, thus resulting in increased social welfare.

Proposition 6 suggests that CSR is not necessarily beneficial to social welfare in a duopoly market. This is contrary to the findings of Fukuda and Ouchida (2020), who show that in a monopoly model, the higher the degree of CSR, the greater the social welfare. In their framework, there are two distortions. The first distortion is caused by external diseconomies resulting from the monopolist’s emissions, while the second distortion is caused by the monopolist’s market power. A single emissions tax only addresses the external diseconomies, but it does not address the market power of monopolist. Because the distortions of market forces cannot be corrected in their framework, CSR reduces total market output and therefore produces fewer emissions. Since CSR has a reducing effect on emissions in a monopoly model, social welfare may be improved. However, in our model, this emission-reducing effect does not occur, and social welfare depends on the degree of CSR. That is, when CSR is low, it contributes to social welfare; when CSR is high, it detracts from social welfare.

5. Numerical analysis

In this section, we discuss the implications of our model by means of numerical studies. First, we use a numerical example to illustrate the optimal licensing strategy of green technology under no CSR and CSR cases. Then, we numerically analyze the sensitivities of equilibrium solutions to the key parameters \( \varepsilon, \gamma, \) and \( d \). Referring to the previous studies such as Fukuda and Ouchida (2020) and Wang (2021), the benchmark parameters used in the numerical analysis are set as follows: \( a = 1, c = 0.6, d = 0.15, \gamma = 10, \theta = 0.5, \varepsilon = 7 \).

5.1. The optimal licensing strategy from the perspectives of patent holder and government

Figs. 1-2 show the optimal licensing strategy of green technology under no CSR and CSR cases, respectively. Note that we set \( \varepsilon = 7 \) and \( \varepsilon = 9 \) in Fig. 2 to show the effects of different royalty rates on the choice of licensing strategy. The main results are as follows.

In Figs. 1, we find that firm 1’s profit and the social welfare under fixed-fee licensing are always larger than that under royalty licensing regardless of the value of \( \varepsilon \). As a result, from the standpoint of both the patent holder and the government, fixed-fee licensing is the most advantageous option in the absence of CSR. The observations are consistent with our proposition 1.

In Fig. 2, if \( 0 < \frac{\varepsilon}{\gamma} < \frac{3}{4} \), the payoff of firm 1 under fixed-fee licensing is larger than that under royalty licensing, and thus firm 1 will always choose the fixed-fee licensing contract. If \( \frac{3}{4} < \frac{\varepsilon}{\gamma} < 1 \), we can observe that firm 1’s payoff is larger under fixed-fee licensing than under royalty licensing when \( 0 < \theta < 0.03 \), and thus firm 1 will choose a fixed-fee licensing arrangement. Otherwise, firm 1 would choose a royalty-based strategy when \( 0.03 < \theta < 1 \). Additionally, we find that social
welfare is always larger under fixed-fee licensing than under royalty licensing. That is, government always prefers fixed-fee licensing in the case of CSR, which verifies the result of proposition 5.

Fig. 1. The green technology licensing strategy in the case of no CSR

Fig. 2. The green technology licensing strategy in the case of CSR

5.2. Sensitivity analysis of the equilibrium solutions

In this section, we respectively examine the reduction degree of abatement cost coefficient $\varepsilon$, the efficiency of abatement cost $\gamma$, and the marginal damage of pollution $d$ on total emissions, firms’ profits, and social welfare under different green technology licensing contracts. To that end, we change one of the parameters and leave the others unchanged under different CSR degree. Figs. 3-6 summarize the corresponding results.

5.2.1. Impacts of key parameters on total emissions

Now, we investigate the impacts of the reduction degree of abatement cost coefficient $\varepsilon$, the efficiency of abatement cost $\gamma$, and the marginal damage of pollution $d$ on total emissions, which are described in Fig. 3.
Fig. 3. Impacts of key parameters on total emissions with different CSR degree
The specific observations in Fig. 3 are listed as the following. When the CSR degree $\theta$ remains unchanged, total emissions decrease with the reduction degree of abatement cost $\varepsilon$ under two licensing contracts. A possible explanation lies in the following aspects. A higher $\varepsilon$ indicates a more advanced green technology, which can reduce more emissions. Similarly, marginal pollution damage $d$ exerts the same impacts on total emissions. However, total emissions are declining with an increase in the efficiency of abatement cost $\gamma$. The underline reason is that the firm may invest more abatement efforts to reduce emissions with a lower abatement cost efficiency, thus decreasing total emissions. We also find that when other parameters keep unchanged, as the CSR degree $\theta$ increase, total emissions experience downward trend. In other words, the higher the CSR degree, the lower the total emissions.

5.2.2. Impacts of key parameters on profits

We next focus on the impacts of the reduction degree of abatement cost coefficient $\varepsilon$, the efficiency of abatement cost $\gamma$, and the marginal damage of pollution $d$ on the profits of firms 1 and 2 with different CSR degree. The results are summarized in Figs. 4-5.
Fig. 4. Impacts of key parameters on $\pi_1$ with different CSR degree

(a) Fixed-fee licensing

(b) Royalty licensing
Fig. 5. Impacts of key parameters on $\pi_1$ with different CSR degree

From Figs. 4 we find that the relationship between the reduction degree of abatement cost coefficient and the profit of firm 1 depends on CSR degree under the two licensing contracts. When CSR degree is sufficiently larger, the profit of firm 1 increases as the reduction degree of abatement cost coefficient increases; however, when CSR degree is sufficiently small, the profit of firm 1 decreases as the reduction degree of abatement cost coefficient increases. In contrast to the reduction degree of abatement cost coefficient, we find the opposite phenomenon existing between abatement cost efficiency and firm 1’s profit. That is, when CSR degree is sufficiently larger, the profit of firm 1 decreases as the efficiency of abatement cost increases but increases as the efficiency of abatement cost increases. In addition, Fig. 4 shows the profit of firm 1 decreases as marginal pollution damage decreases. Finally, Figs. 4 demonstrates that when other parameters remain unchanged, as the CSR degree $\theta$ increases, the profits of firms under different CSR strategies increase. This result indicates that CSR is beneficial to profits of firms due to the abatement-enhancing effect of CSR.

Fig. 5 shows that the reduction degree of abatement cost coefficient $\varepsilon$ has no effect on the profit of firm 2, while the profit of firm 2 decreases as the efficiency of abatement cost $\gamma$ rises under the two licensing contracts. Additionally, we find that the relationship between marginal pollution damage and firm 2’s profit is non-linear. When CSR degree is relatively low, the profit of firm 2 decreases as marginal pollution damage increases; conversely, when CSR degree is relatively high, the profit of firm 2 increases as marginal pollution damage increases. Finally, Fig. 5 illustrates
that when other parameters keep unchanged, the profit of firm 1 increases with the increase of CSR degree $\theta$.

5.2.3. Impacts of key parameters on social welfare

In this subsection, we turn our attention to the impacts of the reduction degree of abatement cost coefficient $\varepsilon$, the efficiency of abatement cost $\gamma$, and the marginal damage of pollution $d$ on social welfare, which is illustrated in Fig. 6.

(a) Fixed-fee licensing
The specific observations in Fig. 6 are listed as the following. For a given CSR degree, an increasing $\varepsilon$ leads to a higher social welfare under the two licensing contracts. The underlying reason is that, the higher abatement cost efficiency directly increases pollution abatement, which leads to a higher social welfare. However, the efficiency of abatement cost $\gamma$ and the marginal damage of pollution $d$ exert the different impacts on social welfare relative to abatement cost efficiency. The reasonable behind this result is that for a given CSR degree, higher abatement cost efficiency $\gamma$ and marginal pollution damage $d$ give a higher incentive for firms to reduce emissions, thus increasing social welfare. Furthermore, Fig. 6 shows that when other parameters keep unchanged, social welfare is up then down with an increase in the CSR degree $\theta$, which is predicted by Proposition 6.

6. Concluding remarks

In this paper, we consider a duopoly model in which a patent holder may take CSR activities under a time-consistent emission tax. We investigate the firm’s green technology licensing strategy with CSR and analyze the effects of CSR behaviors on environment and social welfare. The main results can be summarized as follows:

First, our findings suggest that in the absence of CSR, the best option for a patent holder is always a fixed-fee licensing contract. However, this is not the case when the patent holder engages in CSR. As the level of CSR decreases, the ideal licensing arrangement transitions from a pure royalty license to a fixed-fee license. That is, when CSR is high, royalty licensing contract is ideal; when CSR is low, fixed-fee licensing contract is predominant. Second, we demonstrate that in the case of CSR, there is no contradiction or inconsistency between social welfare and firm payoff goals. When the degree of CSR is high, there is a conflict between social welfare and corporate incentive goals because the government prefers fixed-fee licensing while the patent holder prefers royalty licensing. When the degree of CSR is low, the ideal licensing contract is consistent. In other words, fixed fee licensing is the best contract from the perspective of the patent holder and the government. Finally, we demonstrate that CSR benefits the environment, but not necessarily social welfare, compared to the lack of CSR.
Our findings provide several important practical implications for both managers and government. When the degree of CSR is high, the profit of patent-holding firm declines. Therefore, managers should choose a suitable degree of CSR, which is conducive to the double improvements of emission reduction levels and profit. In other words, managers should implement CSR operations if doing so is not expensive; otherwise, traditional non-CSR operations are preferred. Furthermore, the implementation of CSR strategy will lead to a decline in the level of social welfare when the degree of CSR is high. At this time, the government should actively implement a green R&D subsidy policy, thus reducing the cost of emission reduction and improving firms’ profits and the social welfare. Finally, when the independent choice of licensing strategy is not in line with the social incentive, a government intervention may be desirable.

Our model can be extended in several directions. First, future research may examine firms’ green technology licensing with CSR in a mixed market. Second, as examined by Wang et al. (2014) and Li (2021), we believe that the analysis of mixed duopoly would greatly enrich the literature on CSR. Further studies can be made on the case in which both firms adopt the CSR strategy. Additionally, the optimal licensing strategy for green technology in a duopoly market with demand-side network effects would be interesting to investigate. Lastly, it would be worthwhile to consider either endogenous CSR activities or free entry into our framework. In each case, an additional stage will be added, which we believe will generate additional insights.
Author Declarations

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Appendix

Proof of Lemma 1. The difference between firm 1’s profits under fixed-fee licensing and that under no licensing is given by \( \pi_{LF}^1 - \pi_{FN}^1 = F > 0 \).

Proof of Lemma 2. The difference between firm 1’s profits under royalty licensing and that under no licensing is given by \( \pi_{LR}^1 - \pi_{RN}^1 = r_{z_2}^{LR} > 0 \).

Proof of Proposition 1. Straightforward comparison of the expressions in (21)-(29) and (24)-(32) yields:

\[
\pi_{LF}^1 - \pi_{LR}^1 = \begin{cases} 
\frac{(a-c-3d)^2}{8(g-\epsilon)} \left(1 - \sqrt{1 - \frac{1}{\gamma}}\right)^2 > 0, & 0 < \frac{\epsilon}{\gamma} < \frac{3}{4} \\
\frac{a-c+2d}{2(y-\epsilon)} - \frac{r_{LR}}{2(y-\epsilon)} \sqrt{1 - \frac{1}{\gamma}} > 0, & 0 < \frac{\epsilon}{\gamma} < \frac{3}{4} \\
\frac{r(a-c-d)}{8(y-\epsilon)} > 0, & \frac{3}{4} < \frac{\epsilon}{\gamma} < 1
\end{cases}
\]

Proof of Proposition 2. Simple calculations yield that \( CS_{LF}^1 = CS_{LR}^1 \).

Proof of Lemma 3. Differentiating the Eqs. (33)-(34) with respect to \( \theta \) gives

\[
\frac{\partial q_{1C}^N}{\partial \theta} = \frac{a-c-2d}{2} > 0, \quad \frac{\partial q_{2C}^N}{\partial \theta} = -\frac{a-c-2d}{2} < 0, \quad \frac{\partial z_{2C}^N}{\partial \theta} = \frac{a-c}{2(y-\epsilon)} > 0,
\]

\[
\frac{\partial z_{2C}^N}{\partial \theta} = \frac{a-c-2d}{2\gamma} > 0.
\]

Proof of Lemma 4. With \( z_{2C}^{LF} > z_{2C}^{LR} \) and \( F_c > 0 \), one can immediately derive the following result:

\( \Omega_{LF}^c - \Omega_{LR}^c = d(z_{2C}^{LF} - z_{2C}^{LR}) + F_c > 0 \).

Proof of Lemma 5. Straightforward calculations lead to that

\[
\Omega_{LR}^c - \Omega_{LR}^c = \begin{cases} 
\frac{A}{4(y-\epsilon)} > 0, & 0 < \frac{\epsilon}{\gamma} < \frac{3}{4} \\
\frac{[3d-a+c + \theta(a-c-2d)]^2}{16(y-\epsilon)} > 0, & \frac{3}{4} < \frac{\epsilon}{\gamma} < 1
\end{cases}
\]

where

\[
A = [a-c-3d-\theta(a-c-2d)][a-c-5d-\theta(a-c-2d)] \left(\frac{\epsilon}{\gamma} + \sqrt{1 - \frac{1}{\gamma}} - 1\right) > 0.
\]

Proof of Proposition 3. We compare the patent holder’s payoff under the different licensing strategies and get the following results:
\[
\Omega_{c}^{LF} - \Omega_{c}^{LR} = \begin{cases} 
\frac{B}{8(\gamma - \varepsilon)}, & 0 < \frac{\varepsilon}{\gamma} < \frac{3}{4} \\
\frac{D[3d + c - a + \theta(a - c - 2d)]}{16(\gamma - \varepsilon)}, & \frac{3}{4} < \frac{\varepsilon}{\gamma} < 1
\end{cases}
\]

Simple calculations yield that if \(0 < \frac{\varepsilon}{\gamma} < \frac{3}{4}\), then \(\Omega_{c}^{LF} > \Omega_{c}^{LR}\); if \(\frac{3}{4} < \frac{\varepsilon}{\gamma} < 1\), then \(\begin{cases} 
\Omega_{c}^{LF} < \Omega_{c}^{LR}, & 0 < \theta < \theta^* \\
\Omega_{c}^{LF} > \Omega_{c}^{LR}, & \theta^* < \theta \leq 1
\end{cases}\).

where \(\theta^* = \frac{(2\varepsilon - \gamma)(3d + c - a)}{(2\varepsilon - \gamma)(a - c - 2d) + 4d\gamma}\),

\[B = [(3d + c - a)(2\gamma - \varepsilon) + [(a - c - 2d)(2\gamma - \varepsilon) + 4d(\gamma - \varepsilon)]\theta - 2\sqrt{(\gamma - \varepsilon)(3d + c - a) + (a - c)\theta)] [3d + c - a - (a - c - 2d)\theta] > 0,\]

\[D = \frac{(\gamma - 2\varepsilon)(a - c - 3d + (2d + c - a)\theta) + 4d\gamma\theta}{\gamma} > 0.\]

Proof of Proposition 4. Simple calculations yield that \(CS_{c}^{LF} = CS_{c}^{LR}\).

Proof of Proposition 5. Simple calculations yield that

\[SW_{c}^{LF} - SW_{c}^{LR} = \begin{cases} 
\frac{G[3d + c - a + \theta(a - c - 2d)]}{8(\gamma - \varepsilon)}, & 0 < \frac{\varepsilon}{\gamma} < \frac{3}{4} \\
\frac{H[3d + c - a + \theta(a - c - 2d)]}{32(\gamma - \varepsilon)}, & \frac{3}{4} < \frac{\varepsilon}{\gamma} < 1
\end{cases}
\]

where \(G = d(4 - \frac{\varepsilon}{\gamma} - 4\sqrt{1 - \frac{\varepsilon}{\gamma}} + \varepsilon(a - c - 2d)(1 - \theta)) > 0,\)

\(H = 3a - 3c - d - 3\theta(a - c - 2d) > 0.\)

Proof of Lemma 6. The output and emission reduction levels between different cases are compared as follows:

(i) \(q_{1c}^{LF} - q_{1c}^{LR} = q_{1c}^{LR} - q_{1c}^{LR} = \frac{\theta(a - c - 2d)}{2} > 0,\)

\(z_{1c}^{LF} - z_{1c}^{LR} = z_{1c}^{LR} - z_{1c}^{LR} = \frac{\theta(a - c)}{2} > 0,\)

\(\begin{cases} 
\pi_{1c}^{LF(R)} > \pi_{1c}^{LF(R)}, & 0 < \theta < \theta^{LF(R)} \\
\pi_{1c}^{LF(R)} < \pi_{1c}^{LF(R)}, & \theta^{LF(R)} < \theta \leq 1
\end{cases}\)

where \(\theta^{LF} = \frac{2(3d - a + c)(a - c - 2d)(\gamma + \varepsilon)}{\gamma(a - c)(4d - a + c) + (a - c - 2d)^2[2\gamma^2 - (1 + 2\gamma)\varepsilon]},\)

\(\theta^{LR} = \begin{cases} 
\frac{2(3d - a + c)(a - c - 2d)}{(a - c - 2d)^2} \left[2\varepsilon + \gamma \left(2\sqrt{\frac{\varepsilon}{\gamma} - 1}\right)\right], & 0 < \varepsilon < \frac{3}{4} \\
\frac{6(3d - a + c)(a - c - 2d)}{(a - c - 2d)^2} \left[(4\gamma - 4\varepsilon - 3) + 8d^2\gamma\right], & \frac{3}{4} < \varepsilon < 1
\end{cases}\)
(ii) \( q_{2c}^{LF} - q_2^{LF} = q_{2c}^{LR} - q_2^{LR} = -\frac{\theta(a-c-2d)}{2} < 0 \), \( z_{2c}^{LF} - z_2^{LF} = \frac{\theta(a-c)}{2} > 0 \),

\[
\begin{aligned}
\frac{\theta(a-c-2d)}{2(\gamma - \varepsilon)} &> 0, \quad 0 < \varepsilon < \frac{3\gamma}{4}, \quad \left\{ \begin{array}{l}
\pi_{2c}^{LF(R)} > \pi_{2c}^{LF(R)}, \quad 0 < \theta < \theta_{2c}^{LF(R)}\pi_{2c}^{LF(R)}, \quad 0 < \theta \leq 1.
\end{array} \right.
\end{aligned}
\]

where \( \theta_{2c}^{LF} = \frac{2(3d + c-a)(3\gamma - 4\varepsilon)}{(a-c-2d)(8\gamma^2 - 8\gamma \varepsilon - 3\gamma + 4\varepsilon)} \),

\[
\theta_{2c}^{LR} = \begin{cases}
\frac{2(3d-a+c)}{(a-c-2d)(2\gamma-1)}, & 0 < \varepsilon < \frac{3}{\gamma} \\
\frac{2(3d-a+c)}{(a-c-2d)(8\gamma - 8\varepsilon - 1)}, & \frac{3}{4} < \varepsilon < 1.
\end{cases}
\]

**Proof of Proposition 6.** The output and emission reduction levels between different cases are compared as follows:

\[
E_C^{LF} - E_C^{LR} = -\frac{\theta(a-c-d)}{(\gamma - \varepsilon)} < 0 \quad \text{and} \quad E_C^{LR} - E_C^{LF} = -\frac{\theta(a-c-d)+(r-r_e)}{(\gamma - \varepsilon)} < 0,
\]

\[
\left\{ \begin{array}{l}
\text{SW}^{LF(R)} > \text{SW}^{LF(R)}, \quad 0 < \theta < \theta_{2c}^{LF(R)}\pi_{2c}^{LF(R)}, \quad 0 < \theta \leq 1.
\end{array} \right.
\]

where \( \theta_{2c}^{LF} = \frac{4(a-c-d)^2}{(a-c)^2+(a-c-d)^2} \),

\[
\theta_{2c}^{LR} = \begin{cases}
\frac{4\gamma[(a-c)(a-c-3d)+3d^2]+I}{2\gamma[(a-c)^2 - 2d(a-c-d)]-\varepsilon(a-c-2d)^2}, & 0 < \varepsilon < \frac{3}{\gamma} \\
\frac{2[5(a-c)^2+d(5c-5a-2d)]}{5(a-c)^2-4d(a-c-d)}, & \frac{3}{4} < \varepsilon < 1.
\end{cases}
\]

\[I = 2(a-c-2d)[2d\gamma\sqrt{1-\frac{\varepsilon}{\gamma}-\varepsilon(a-c-3d)}].\]