Management Science

Publication details, including instructions for authors and subscription information:
http://pubsonline.informs.org

Is Price Commitment a Better Solution to Control Carbon Emissions and Promote Technology Investment?

Xiaoshuai Fan, Kanglin Chen, Ying-Ju Chen

Published in Management Science on March 25, 2022 as DOI: 10.1287/mnsc.2022.4365.
This article has not been copyedited or formatted. The final version may differ from this version.

http://pubsonline.informs.org/journal/mnsc

MANAGEMENT SCIENCE
Articles in Advance, pp. 1–17
ISSN 0025-1909 (print), ISSN 1526-5501 (online)

Is Price Commitment a Better Solution to Control Carbon Emissions and Promote Technology Investment?

Xiaoshuai Fan,[a] Kanglin Chen,[a,*] Ying-Ju Chen[b]

[a] Department of Information Systems and Management Engineering, College of Business, Southern University of Science and Technology, Shenzhen 518055, China; [b] School of Business and Management, The Hong Kong University of Science and Technology, Hong Kong
*Corresponding author

Contact: fanxs@sustech.edu.cn, https://orcid.org/0000-0002-0461-6713 (XF); chenkl@sustech.edu.cn (KC); imchen@ust.hk, https://orcid.org/0000-0002-5712-1829 (Y-JC)

Received: November 28, 2020
Revised: November 15, 2021
Accepted: January 14, 2022
Published Online in Articles in Advance: March 25, 2022

https://doi.org/10.1287/mnsc.2022.4365

Abstract. Recent years have seen considerable debate about the practicability of a global quantity/price commitment to control carbon emissions and tackle environmental issues. In this paper, we study the impact of the cap-and-trade policy (quantity commitment) and the carbon tax policy (price commitment) on a firm's technology investment and production decisions. The main feature captured in our model is that there exist correlated uncertainties between the sales market (demand uncertainty) and the permit trading market (permit price volatility) under the cap-and-trade policy. The correlation relationship stands on the following intuition. The demands for final products affect firms' production output, which generates the needs of emission permits and influences the permit price. We show that under the cap-and-trade policy, with the uncertainty of the future emission price, the firm could flexibly adjust its production quantity to enhance its profit, resulting in low incentives to invest in clean technology. However, as the (positive) correlation between the sales market and the permit trading market increases, the production flexibility is constrained so that the firm has to increase its technology investment to hedge against the future risk of a high emission price. Making a comparison between the cap-and-trade and carbon tax policies, we find that when the correlation coefficient is moderate, the carbon tax policy generates a multiwin situation (i.e., more technology investment, higher expected profit and consumer surplus, and fewer carbon emissions). Case studies are provided to illustrate the implications and model variants are examined to check the robustness of the main results. Overall, our analysis sheds light on recent debate over carbon pricing and identifies the important role of correlated uncertainties in carbon policy design.

History: Accepted by Charles Corbett, operations management.
Funding: This work was supported by the stable support plan program of Shenzhen Natural Science Fund [Program Contract 20200925160533002] and the National Natural Science Foundation of China [Grant 72101105].
Supplemental Material: The data files and online appendix are available at https://doi.org/10.1287/mnsc.2022.4365.

Keywords: carbon tax • cap-and-trade • correlated uncertainties • pollution abatement • sustainable operations

1. Introduction

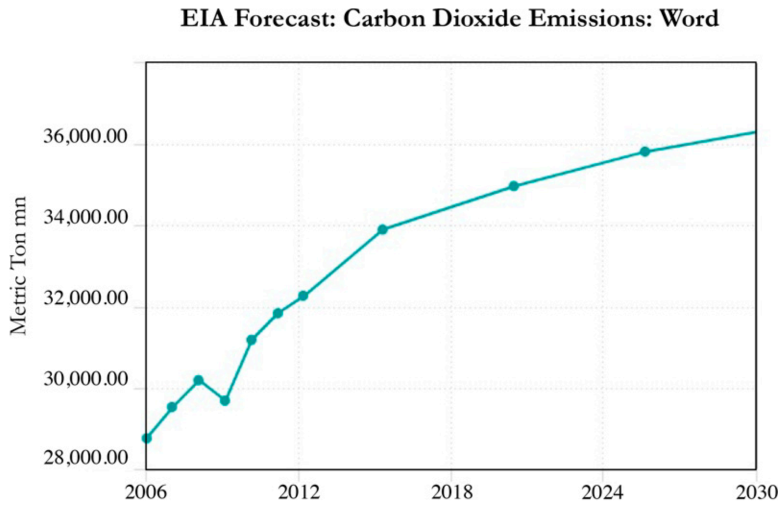
Greenhouse gas (GHG) has been widely recognized as the critical cause of extreme climate events, such as heat waves, heavy downpours, major hurricanes, and so on. As stated by World Meteorological Organization (WMO), "climate change is accelerating as greenhouse gas concentrations drive global temperatures to increasingly dangerous levels."[1] This increasing carbon emission, as well as the global warming trend, is expected to continue by both WMO and CEIC Data. Based on CEIC Data's estimation (presented in Figure 1), the total amount of carbon dioxide (CO_2) will increase by around 6% in the next two decades.

To abate the GHG emissions, especially CO_2, the carbon emission regulations have been developed rapidly recently, for example, the United Nations Framework Convention on Climate Change adopted in 1992, the Kyoto Protocol established in 1997 and enforced in 2005, and the Paris Agreement issued in 2015. Currently, the regulations focus more on limiting the total amount of emissions through setting explicit quotas for those contracting parties and allowing emission trading (i.e., carbon cap-and-trade policy) to flexibly balance the supply and demand of emission permits. However, the cap-and-trade policy is criticized for some inevitable drawbacks on its own.

First, it is difficult to reach a global agreement on an international harmonized cap-and-trade policy (Weitzman 2015). Based on the lessons learned from the Kyoto Protocol, one of the major obstacles is to fairly determine the quotas of carbon emissions by disaggregating the

Q:1

Figure 1. (Color online) Global CO_2 Emissions



worldwide quantity cap into individual quantity caps among nations. Disagreements over this cap disaggregation result in reluctance for developing countries to join, leaving the cap-and-trade system operating with a patchwork of regional voluntarism. The absence of uniform (or globally committed) carbon regulation leads to inconsistent enforcement around the world, which causes inefficiency in emission abatement such as free rides and carbon leakage. As it still has a long way to go for reaching a global quantity commitment (i.e., cap-and-trade policy), recent years have witnessed considerable debate over the practicability of price commitment (i.e., carbon tax policy). Some economic analysis (MacKay et al. 2015, Cramton et al. 2017) showed that it is more likely to reach a common international commitment in price than in quantity, because a uniform price facilitates reciprocal "I will if you will" agreements. In this study, we abstract away the issue of the possibility and the difficulty to reach price and quantity commitments. We only want to contrast these two policies from the operations perspective to understand their strategic advantages and disadvantages. If one can show that the price commitment is more effective than the quantity commitment, then taking into account the possibility to reach an international harmonized policy, the dominance of the price commitment will be more outstanding.

Another common concern for the cap-and-trade policy is that permit price volatility in the permit trading market might create hurdles for firms to invest in clean technology for emission abatement. Enhancing energy efficiency through clean technology investment is regarded as the most valuable way to reduce carbon emissions. It could reduce the total amount of CO_2 discharged to the atmosphere in production and after manufacturing without sacrificing the economic benefits. However, price volatility in cap-and-trade systems has been well documented (Metcalf 2009, Schmalensee and Stavins 2017), and the uncertainty about carbon price can result in suboptimal investment in clean technology (Blyth et al. 2007, Gilbert et al. 2014). Practically, regulations have a large impact on firms' incentives on technology innovation, but the incentives under different carbon policies are quite divergent and underdeveloped in the literature. As such, the research questions we explore are as follows. (1) How does the choice of carbon policy (i.e., cap-and-trade policy or carbon tax policy) influence a firm's investment decision on clean technology and production decisions? (2) How does the choice of carbon policy affect the firm's expected profit, the consumer surplus, and the total amount of carbon emissions? (3) Is it possible that one policy mechanism dominates the other, or would a policymaker's preference between the two be conditional? If the latter, on what factors does that preference depend?

To address these questions, we develop a two-stage monopoly model under which a firm faces demand uncertainty and permit price uncertainty (if it is under the cap-and-trade policy). The correlation between the sales market and the permit trading market is captured in our model because a high demand for the final products commonly indicates a high demand for the emission permits when this industry's performance is positively correlated to the macroeconomy and vice versa. This correlation relationship has been empirically verified by Chevallier (2011, p. 1295), who stated that "industrial production is found to impact positively (negatively) the carbon market during periods of economic expansion (recession), thereby confirming the existence of a link between the macroeconomy and the price of carbon." To maximize its expected profit, the firm determines its investment in clean technology in the first stage and then decides its production quantity in the second stage after observing the realized market potential and permit price. The model of the two-stage problem is motivated by the fact that the investment decision is a longer-term strategy compared with the production plan.

The main results we derive are as follows. First, under the carbon tax policy, the technology investment level is not affected by the correlation parameter, because there is no correlation between the market potential and the carbon price that is fixed as a tax rate. Under the cap-and-trade policy, the technology investment level increases with the correlation coefficient. The rationale behind this result lies on the production flexibility. The firm benefits from the ability to flexibly adjust its production quantity in response to the realized market potential and permit price. The value generated from such production flexibility, however, is impaired as the correlation coefficient increases. With diminishing advantage of the production flexibility, the firm must invest in clean technology to lower the emission cost, which will help improve its expected revenue in the sales market.

Second, the carbon tax policy might generate a multiwin situation (i.e., a higher level of technology investment, a higher expected profit, a higher consumer surplus, and a lower amount of carbon emissions) relative to the cap-and-trade policy when the correlation relationship between the sales market and the permit trading market is moderate. This result demonstrates that, although the original intention for researchers to propose the carbon tax policy is a higher probability of reaching a price commitment than a quantity commitment (Cramton et al. 2017), the carbon tax policy may have an outstanding strategic advantage over the cap-and-trade policy.

Third, we find that the strategic advantage of the carbon tax policy continues to hold even when market competition is incorporated. An interesting result derived from the competition case is that the technology investment first decreases and then increases as the degree of competition grows. The driving force behind this result is the tradeoff between the firm's desire to gain a competitive edge over the rival on the emission cost side by investing more and the firm's desire to mitigate competition and maintain its "monopolistic" power by investing less.

The rest of this paper is organized as follows. We first begin with a review of the related literature in Section 2 and then describe the model in Section 3. In Sections 4 and 5, we analyze the monopoly case and contrast the cap-and-trade policy with the carbon tax policy in terms of various performance measurements. In Section 6, we run a case study to estimate correlations in different industries; through theoretical results and estimated data, we predict/identify the impact of carbon policies on technology investment, firm profit, and consumer surplus for various industries. In Section 7, we discuss several extensions that study the impact of market competition, the firm's positive production cost, and constrained production flexibility. Finally, we conclude our results in Section 8. All the proof and the detailed analysis of the case study and model extensions are presented in the online appendix.

2. Literature Review

As we consider a setting with demand uncertainty, permit price uncertainty, technology investment, and the comparison of carbon policies, our work is connected with both the economic literature on pollution regulation/policy and the operations literature.

Pollution policy has been well developed by energy and environmental economists. A large body of research focuses on the optimal policy design (e.g., the optimal permits allocation and carbon tax) and the impact of pollution policies (Seade 1985, Requate 1993, von der Fehr 1993, Shaffer 1995, Lee 1999, Smale et al. 2006, Bushnell and Chen 2012). Within this stream, the possibility of technology improvement is ignored, and hence, the only way to combat carbon emissions is to adjust the production quantity, whereas in our work, we allow firms to make strategic investment decisions. In addition to our research, Laffont and Tirole (1996), Requate (1998), Montero (2002), Requate (2006), and Demailly and Quirion (2006) characterize firms' optimal pollution abatement decisions. The difference is that we incorporate the market uncertainty and the correlation relationship between the permit market and the sales market. These factors are important to determine the value of production flexibility and hence influence the firm's incentive on technology investment.

There is a recent growth of research proposing mechanisms to mitigate the permit price volatility in the cap-and-trade systems, such as setting price ceilings and price floors (Burtraw et al. 2006, Metcalf 2009, Schmalensee and Stavins 2017). Differently, our point of departure is not designing mechanisms to alleviate price volatility. Instead, we incorporate an important but underexplored feature of the cap-and-trade policy (i.e., correlated uncertainties) and aim to assess how this feature affects the comparison of the two prevalent carbon policies. Furthermore, motivated by the difficulty of reaching an international harmonized cap-and-trade policy (Cramton et al. 2017), as well as the resulting deficiency such as carbon leakage induced by no uniform regulation (Islegen et al. 2015, Drake 2018, Huang et al. 2021), we intend to evaluate the effectiveness of the proposed carbon tax policy (Nordhaus 2013, Weitzman 2015, Cramton et al. 2017). Our analysis provides additional theoretical support for government to make better carbon policies.

Because our work compares the quantity commitment policy with the price commitment policy, it is also closely related to the literature on price versus quantity regulation (Weitzman 1974, Mendelsohn 1984, Pizer 2002, Hepburn 2006, Krysiak 2008, Mansur 2013). The seminal work Weitzman (1974) evaluates the impact of the quantity policy and the price policy under both the profit uncertainty (i.e., demand-side uncertainty) and the cost uncertainty (e.g., the permit price uncertainty) on the firm's expected profit. Weitzman (1974) demonstrates that the difference in the firm's expected profit between the quantity policy and the price policy is independent of the uncertainty on the demand side, and it is shrunk to zero as the variance on the cost side goes to zero. Our analysis reveals the same results as in Weitzman (1974) when setting the correlation coefficient to zero. However, by considering the correlation between the product market and the permit trading market, our study generates more implications for the choice of carbon policy. We find that without any impact on the price policy, the correlation affects the quantity policy in the following fashion: As the correlation coefficient increases, the benefit from the production flexibility is reduced, inducing the firm to increase its technology investment. By comparing the firm's expected profit, we derive that with the increase of the correlation coefficient, the dominant role of the price policy is more and more outstanding.

Following Weitzman (1974), Mendelsohn (1984) and Krysiak (2008) analyze a firm's different research and development (R&D) incentives under price and quantity regulation. Mendelsohn (1984) states that the quantity policy tends to encourage more efficient levels of technical change. Krysiak (2008) derives that the firm will make a socially optimal R&D decision under the quantity policy. Departing from this stream, our work shows that the R&D incentive highly depends on the value of the firm's production flexibility that is determined by the correlation between the sales market and the permit trading market and the firm's ex ante capability in flexible production.

Within the operations literature, some researchers focus on the optimal allocation of emission allowance (Zhao et al. 2010, Caro et al. 2013), whereas others concentrate on the strategic operational decisions under carbon regulation. Gong and Zhou (2013), for example, investigate the optimal production plan under the cap-and-trade policy. Wang et al. (2021) focus on the process of green technology and regulation development. Yuan et al. (2018) dynamically design the joint plan of emissions permit trading and production. Subramanian et al. (2007) and Anand and Giraud-Carrier (2020) examine both the emission abatement decision and the production decision under permits for emissions. Zhao (2003), Yalabik and Fairchild (2011), Krass et al. (2013), Drake et al. (2016) and Nguyen et al. (2018) focus on the technology innovation under the pressure of regulations. Our work is distinguished from the previous literature as we incorporate demand uncertainty and the correlation between the sales market and the permit trading market. Also, we focus on the contrast between the cap-and-trade policy and the carbon tax policy. A related study (Drake et al. 2016) demonstrates that firms benefit from the emission price uncertainty under the cap-and-trade policy and could obtain a higher expected revenue relative to the carbon tax. Our analysis reveals that the production flexibility is not only determined by the volatility of the market demand and the permit price but is also influenced by the correlation relationship between the sales market and the permit trading market. Hence, the firm may not always benefit from the permit price uncertainty under the cap-and-trade policy. In a nutshell, relative to Drake et al. (2016), our analysis provides more general results and implications.

3. Model

To compare the performance of the carbon tax policy and the cap-and-trade policy in terms of the technology investment (which determines the emission intensity), the firm's expected profit, the consumer surplus, and the total amount of CO_2 emissions, we investigate the setting of a monopoly firm (he hereafter) with the power to control his R&D and production decisions. In Section 7.1, we extend our model to the case with market competition and show that our main results continue to hold qualitatively. We first introduce the characteristics of the sales market and the two carbon policies, following which we present the firm's optimization problem.

3.1. Sales Market

The firm produces and sells his product in the market. We assume that the market price p of the product is captured by an inverse demand function $p(q) = a - bq$, where a is the market potential, q is the firm's production quantity, and b represents the demand sensitivity. The market potential a is a random variable with mean $\bar{a}$ and variance σ_D^2, capturing the demand uncertainty in the sales market.

3.2. Cap-and-Trade

Under the cap-and-trade policy, a quota (denoted by w) of carbon emissions is assigned to the firm by the government. If overemitting, the firm has to purchase extra emission permits from a permit trading market at a carbon price that exhibits price volatility. If underemitting, the firm can sell the redundant permits. Denote k as the trading price of the emission permit, which is a random variable with mean $\bar{k}$ and variance σ^2. As there exists uncertainty in both the sales market and the permit trading market (captured by the randomness in a and k), we assume that the correlation coefficient between the permit price k and the market potential a is $\rho \in [-1,1]$. The positive ρ is validated by the situation where the global economy is becoming stronger, and all industries are revived and are willing to produce more. In this scenario, the demand for emission permits is increasing, which results in a large permit price premium. However, when the global economy is weak but a particular industry performs well in the market, the total demand and the price for emission permits are decreased, but the demand for products in this particular industry is enhanced. Considering $\rho \in [-1,1]$, our model will capture all the possible scenarios mentioned previously.

3.3. Carbon Tax

Under the carbon tax policy, the carbon price is predefined by a fixed tax rate on carbon emissions. We let the tax rate per emission equal to the average trading price in the cap-and-trade market, that is, $\bar{k}$. This is because we desire to focus on investigating the strategic benefit of the carbon tax policy (or the cap-and-trade policy) on the firm's technology investment decision and production decision without involving the price advantages (or disadvantages) of the implemented policy. Because the carbon price is fixed as a tax rate, there is no correlation between the market potential and the carbon price under this policy.

3.4. Firm's Optimization Problem

The firm engages in a two-stage optimization problem; he determines technology investment in the first stage and then production in the second stage. We focus on the case where the firm could produce by quickly responding to the realized market size a and permit price k (if it is under the cap-and-trade policy). That is to say, the market potential a and permit price k (if it is under the cap-and-trade policy) are uncertain to the firm in the investment stage, but they are realized and publicly observed in the production stage. Under such a case, we say that the firm has *ex ante full production flexibility*. Quick response manufacturing, which is increasingly prevalent among manufacturers because of the advanced technical supports, enables firms to achieve flexible production. We consider the case where the firm's production flexibility is ex ante constrained in Section 7.3, under which the firm has to predetermine the production quantity or the market price before uncertainty is resolved.

The details of each stage are specified as follows. In the first stage, facing the uncertainty of the market potential a and the permit price k (if it is under the cap-and-trade policy), the firm decides his technology investment which lowers the emission intensity (i.e., the amount of emissions per unit product) of the production process to a level γ ($\in [0,\gamma^+]$).[2]

The parameter γ^+ represents the initial emission intensity of the firm. This continuous measure of investment (i.e., $\gamma \in [0,\gamma^+]$) is widely adopted in both theoretical research (Anand and Giraud-Carrier 2020) and empirical studies (Hartman et al. 1997). To abate the emission intensity to the level γ, the firm incurs an investment cost of $\beta(\gamma^+ - \gamma)^2$, where β is the investment cost coefficient. The investment cost in an increasing and quadratic form is commonly adopted in the literature (Subramanian et al. 2007, Anand and Giraud-Carrier 2020) and is also validated in empirical studies. For example, using data from the U.S. manufacturing industries, Hartman et al. (1997) estimated firms' pollution abatement costs by industry sector and found evidence for quadratic investment costs in various industries such as power generation (e.g., coal), paper and pulp, iron and steel, and cement.

In the second stage, observing the realized market potential a and the permit price k, the firm determines his production quantity q. Without loss of generality, we normalize the production cost to zero. In Section 7.2, we extend our analysis to positive production cost that is dependent on the emission intensity (or technology level) γ. Our main results still qualitatively hold. The total amount of emission S is determined by the production quantity q and the emission intensity γ, that is, $S = q\gamma$. That is to say, the higher the production quantity or the higher the emission intensity is, the higher the amount of CO_2 that is released. Once the production quantity q is determined, the corresponding trading amount of the emission permits is also confirmed under the cap-and-trade policy. If the quota preassigned by the government cannot cover the carbon emissions in the production stage (i.e., $\gamma q > w$), then the firm has to purchase emission permits from the trading market at cost $(\gamma q - w)k$. Otherwise (i.e., $\gamma q \le w$), the firm has redundant emission permits to sell and gains $(w - \gamma q)k$. To fairly compare with the cap-and-trade policy, we assume that under the carbon tax policy, the firm has been provided with a green fund or subsidy that is certainty monetary equivalent of the quota assigned under the cap-and-trade policy (i.e., $w\bar{k} = \mathbb{E}[wk]$). That is to say, with the subsidy, the effective tax paid by the firm is $(\gamma q - w)\bar{k}$ for overemitting, and the effective green subsidy received by the firm is $(w - \gamma q)\bar{k}$ without overemitting.

To avoid the trivial case where the firm is willing to invest to fully eliminate CO_2 emissions, we make the following assumption.

Assumption 1. *The investment cost β is not negligible, that is, $4b\beta > \bar{k}^2 + \sigma^2$ and $4b\beta\gamma^+ > \max\{\bar{a}\bar{k}, \bar{a}\bar{k} + \rho\sigma_D\sigma\}$, which ensure a nonnegative inner solution of the emission intensity γ. Furthermore, the market potential is large enough to ensure nonnegativity of the production (i.e., $a > \gamma^+ k$ for any realized a and k).*

Assumption 1 is not restrictive. To be more specific, the first condition can be rewritten as $4b\beta > \mathbb{E}[k^2]$, which states that the investment cost coefficient is not negligible. The condition is imposed to guarantee the concavity of the expected profit with respect to γ.

The second condition can be rewritten as $4b\beta\gamma^+ > \mathbb{E}[ak]$ with $k = \bar{k}$ under the carbon tax policy, which indicates that the firm's initial emission intensity γ^+ is high. This condition is imposed to rule out the trivial case where the firm's initial emission intensity is low, and the firm invests to fully abate carbon emissions. We focus on high-polluting firms/industries in this study. In practice, high-polluting firms/industries are the leading source of the greenhouse gas emissions, and hence, they should be paid as much attention as possible. For instance, according to the report by McKinsey (2013), GHG emissions from the power industry were estimated to be 10.9 gigatonnes of CO_2 equivalents ($GtCO_2e$) per year in 2005, accounting for 24% of global GHG emissions. The iron and steel industry generated emissions of 2.6 $GtCO_2e$ per year and represented around 16% of worldwide industrial emissions. Global emissions from this industry were projected to grow by 3.2% annually through 2030. As another example, the cement industry was assessed to occupy 11% of worldwide industrial emissions.

These two conditions jointly ensure an inner solution of the optimal emission intensity. Also, to avoid the case where the fluctuations in the permit price k and in the market potential a lead to no production, we focus on the scenario where a is large enough (i.e., $a > \gamma^+ k$ for any realized a and k) even with uncertainty to make sure $q > 0$.

Table 1 summarizes our notation for convenience of reference.

4. Analysis of Investment and Production Decisions

Using backward induction, we first solve the firm's production decision in the second stage under both policies.

Table 1. Summary of Notation

Symbol	Definition
a	The market potential, with mean $\bar{a}$ and variance σ_D^2
k	The carbon price, with mean $\bar{k}$ and variance σ^2 under the cap-and-trade policy; while fixed at $\bar{k}$ under the carbon tax policy
ρ	The correlation coefficient between a and k under the cap-and-trade policy
w	The quota of carbon emissions preassigned to the firm by the government
β	The investment cost coefficient of upgrading technology
γ^+	The firm's initial emission intensity
γ	The firm's emission intensity after upgrading technology
p	The market price of the product
b	The parameter measuring demand sensitivity
q	The firm's production quantity

We use T to denote the carbon tax policy and use C to denote the cap-and-trade policy. Given the implemented policy (carbon tax policy or cap-and-trade policy) and the technology investment decision (i.e., γ) and after observing the realization of the permit price k and the potential market a in the second stage, the firm determines the production quantity to maximize the second-stage profit as follows:

$$\max_q \pi(q;\gamma,a,k) = (a-bq)q - (\gamma q - w)k,$$

where $k = \bar{k}$ under the carbon tax policy. It follows that the optimal production quantity is

$$q^*(\gamma,a,k) = \frac{a-\gamma k}{2b}. \tag{1}$$

In the first stage, the firm's decision is to determine the investment in clean technology to maximize his expected profit. The optimization problems under the carbon tax policy and the cap-and-trade policy are as follows, respectively:

$$\max_\gamma \Pi_T(\gamma) = \mathbb{E}_a[\pi(q^*(\gamma,a,\bar{k});\gamma,a,\bar{k}) - \beta(\gamma^+ - \gamma)^2]; \tag{2}$$

$$\max_\gamma \Pi_C(\gamma) = \mathbb{E}_{\{a,k\}}[\pi(q^*(\gamma,a,k);\gamma,a,k) - \beta(\gamma^+ - \gamma)^2]. \tag{3}$$

Lemmas 1 and 2 characterize the firm's optimal investment decisions under the carbon tax policy and the cap-and-trade policy, respectively.

Lemma 1. *The optimal emission intensity under the carbon tax policy is as follows:*

$$\gamma_T^* = \frac{4b\beta\gamma^+ - \bar{a}\bar{k}}{4b\beta - \bar{k}^2}. \tag{4}$$

Several important results could be derived from Lemma 1. From the expression of γ_T^*, we find that the demand uncertainty σ_D has no influence on the firm's investment decision under the carbon tax policy. This is because the firm could flexibly adjust his production quantity (i.e., $q_T^* = (a - \gamma_T^*\bar{k})/2b$) to preclude the negative effect generated from the demand volatility. Second, investment motivation is enhanced as the expected market potential level $\bar{a}$ increases. When the expected market potential $\bar{a}$ is high, the firm anticipates that the expected production quantity will also be high. To lower the marginal emission cost (i.e., $\gamma_T\bar{k}$) and to increase the profit margin, the firm has stronger incentives to invest in clean technology.

Lemma 2. *The optimal emission intensity under the cap-and-trade policy is as follows:*

$$\gamma_C^* = \begin{cases} \dfrac{4b\beta\gamma^+ - \bar{a}\bar{k} - \rho\sigma_D\sigma}{4b\beta - \bar{k}^2 - \sigma^2} & \text{if } \bar{a}\bar{k} + \rho\sigma_D\sigma > (\bar{k}^2 + \sigma^2)\gamma^+ \\ \gamma^+ & \text{if } \bar{a}\bar{k} + \rho\sigma_D\sigma \le (\bar{k}^2 + \sigma^2)\gamma^+. \end{cases} \tag{5}$$

Consider a special case first where there is no correlation between the market potential a and the permit price k (i.e., $\rho = 0$). First, we get the same result as that derived from the carbon tax policy: Demand uncertainty σ_D does not affect the firm's investment decision, whereas a larger expected market potential $\bar{a}$ motivates the firm to invest more. Second, from the expression of γ_C^* in (5) with $\rho = 0$, the optimal emission intensity is increasing with the uncertainty of the permit price σ. That is to say, the firm's incentive to invest in clean technology is diluted when the permit price significantly fluctuates. The underlying reason is as follows. (To better serve our explanations, we use Figure 2 to illustrate the dynamics between the permit price uncertainty σ and the technology investment level.)

With the increase of the permit price volatility, the firm's benefit from production flexibility is also enhanced. When the permit price is realized to be low, the firm could take advantage of the realized low emission cost to expand his production for extracting a high profit from the market. However, when the permit price is realized to be high, the firm could cut down his total production and take advantage of supply shortage to raise the market price and to grab a satisfactory profit. Hence, under a fluctuated permit trading market, the firm could flexibly adjust his production to control his emission cost and the profit margin from selling the product. As a result, the firm could benefit from the uncertainty in the permit trading market. However, a high investment will impair such production flexibility. This is because investment in clean technology could be partially regarded as a commitment to the future production quantity. A higher investment will induce more production in the future. When the permit price greatly fluctuates, it is risky for the firm to largely invest in clean technology (i.e., commit a high production quantity). Accordingly, the firm will lower his investment as the volatility in the permit price increases.

Now consider the case where the market potential is correlated with the permit price (i.e., $\rho \neq 0$). We find that the optimal emission intensity γ_C^* is decreasing in ρ. Specifically, when the market potential is positively (negatively) correlated with the permit price, the firm will enlarge (reduce) his investment in clean technology relative to the case where $\rho = 0$. The previous result is driven by the fact that the positive correlation between the market potential and the permit price will weaken the value of production flexibility, whereas the negative correlation will reinforce the value of production flexibility. Next, we elaborate the underlying mechanisms in the scenario of a positive correlation between a and k (see Figure 3 for an illustration), which can be easily applied to the analysis for the case with negative correlation.

When the realized permit price k is low, the firm intends to produce more because of a low emission cost; however, the positive correlation between a and k indicates a low market potential that suppresses production and results in a low output eventually. On the contrary, when the realized permit price is high, the firm should produce less to inflate the market price; however, a large market potential signified by the high permit price conveys that it is beneficial to produce more. From this, we observe that the positive correlation between the permit price and the market potential prevents the firm from expanding production when the realized k is small. Also, it provides excessive impetuses for the firm to produce more when the realized k is high, relative to the case where $\rho = 0$. In a word, the value of production flexibility is constrained in the presence of the positive correlation between a and k, and hence, to resist the uncertainty from the permit trading and the sales markets, the firm has to invest more to lower down his emission cost in advance. A similar analysis is applied to the case where the correlation is negative. Under such a case, the value of production flexibility is enhanced so that it is unnecessary for the firm to combat the emission intensity to a low level (because the firm could use the production flexibility to largely improve his profit).

With a clear understanding of the mechanism about ρ, we are ready to discuss how it alters the dynamics between the permit price uncertainty σ and the firm's incentive on technology investment when $\rho \neq 0$. As identified earlier in the case of $\rho = 0$, a higher σ has a direct effect that enhances the value of production flexibility. When $\rho \neq 0$, a higher σ induces an additional indirect effect on the production flexibility through amplifying the impact of ρ. We take the positive correlation scenario (i.e., $\rho > 0$) for elaboration (Figure 4).

Recall that the value of production flexibility is constrained in the presence of a positive correlation between a and k, because a large (small) realization of a is associated with a high (low) realization of k. With other market characteristics fixed, a more fluctuated permit price implies that when the realized a is large (small), the realized k can even be much higher (lower).

Figure 2. Dynamics Between the Permit Price Uncertainty and Technology Investment

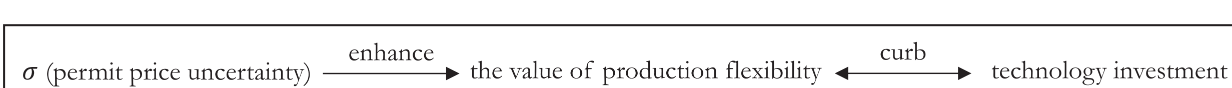


Figure 3. Dynamics Between the Correlation Coefficient and Technology Investment

This further constrains the firm's production flexibility; that is, the impact of ρ is amplified. We find that if the correlation is weak, the amplifying effect is limited and offset by the enhancing effect, so the result remains the same as obtained in the case with $\rho = 0$. If the correlation is sufficiently strong, however, the result is reversed. As σ increases, the amplifying effect can be dominant, resulting in less production flexibility and incentivizing the firm to invest more. A similar analysis applies to the case with a negative correlation, which enhances the value of production flexibility. A larger σ further adds value on this through both direct and indirect effects, reducing the firm's incentive on technology investment.

Comparing the optimal emission intensities under the carbon tax policy and the cap-and-trade policy, we derive the following result.

Proposition 1. *There exists a threshold $R_0 = \gamma_T^* \sigma / \sigma_D$ such that the following results hold:*

(a) *The firm invests more under the carbon tax policy than under the cap-and-trade policy (i.e., $\gamma_T^* < \gamma_C^*$) if and only if the correlation coefficient is smaller than a threshold (i.e., $\rho < R_0$).*

(b) *The threshold R_0 has the following properties: (i) it is decreasing in $\bar{a}$; (ii) there exists at most a positive threshold of $\bar{k}$ such that R_0 is increasing in $\bar{k}$ if $\bar{k}$ is larger than this threshold; (iii) it is decreasing in σ_D; and (iv) it is increasing in σ.*

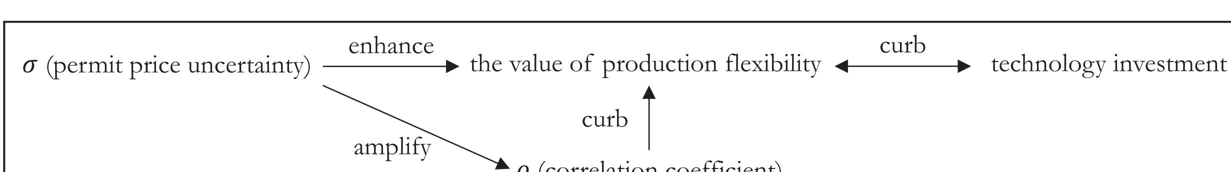
Proposition 1(a) shows that when $\rho < R_0$, the technology investment under the carbon tax policy is more than that under the cap-and-trade policy (i.e., $\gamma_T^* < \gamma_C^*$). However, a striking result we derive is that when $\rho \geq R_0$, the firm is willing to invest more under the cap-and-trade policy even though the firm clearly anticipates a high uncertainty in the future market regarding both the permit price and the market potential. To dissect this result, when ρ is high, we know that the value of production flexibility under the cap-and-trade policy is impaired heavily based on the previous analysis. Consequently, the benefit from production flexibility under this policy is less than that under the carbon tax policy, even though the carbon tax policy eliminates the uncertainty of the permit price and the value of production flexibility generated from such uncertainty. Hence, the firm under the cap-and-trade policy should invest more in emission abatement to reduce the emission cost, which could enhance the ex ante expected profit.

Proposition 1(b) further analyzes how the comparison of investment decisions under the two policies is affected by market characteristics. The threshold R_0 is decreasing in $\bar{a}$, which indicates an expanding region for the cap-and-trade policy to induce more investment. Although a larger expected market potential $\bar{a}$ encourages investment under both policies, the investment under the cap-and-trade policy increases with $\bar{a}$ at a faster rate. This is because the cap-and-trade policy exhibits uncertainty in both the sales market and the permit trading market and the firm's investment decision is thus more sensitive to the change of the expected market potential under this policy.

The impact of $\bar{k}$ is similar to that of $\bar{a}$ in most of the cases (i.e., R_0 decreases with $\bar{k}$ when $\bar{k}$ is smaller than a threshold and such threshold may not exist as shown in Proposition 1(bii): As the emission cost increases, the firm has incentives to invest more for emission abatement under both policies, and the investment is more sensitive to the change of $\bar{k}$ under the cap-and-trade policy than under the carbon tax policy. Contrary to what one may expect, however, a sufficiently high $\bar{k}$ might discourage investment (i.e., R_0 increases with $\bar{k}$ upon the conditions of a threshold existing and $\bar{k}$ being larger than this threshold). This is driven by the firm's leverage against emission abatement through investment or production. When the emission cost is sufficiently high, the firm cuts down his output to reduce the emissions substantially in the production stage, making it not necessary to invest too much for abatement in the investment stage.

Regarding the impact of σ, as stated in Lemma 2, the fluctuation of the permit price under the cap-and-trade policy reduces the firm's incentive to invest when the correlation coefficient is small. Our analysis reveals that this is indeed the case when $\rho \leq R_0$. Therefore, the region that favors the cap-and-trade policy shrinks (R_0 increases). However, the impact of σ_D is opposite (R_0

Figure 4. Dynamics Between the Permit Price Uncertainty and Technology Investment When $\rho \neq 0$



decreases in σ_D). Note that $R_0 = \gamma_T^* \sigma / \sigma_D$, and it is positive. Hence, we can focus on the positive correlation scenario (i.e., $\rho > 0$) to explain the dynamics between R_0 and σ_D. Recall that the production flexibility is constrained in the presence of positive correlation between a and k. This impact of ρ is further amplified in a more fluctuated sales market. Thus, as σ_D increases, the firm is more willing to invest under the cap-and-trade policy (than that under the carbon tax policy) to compensate for the reduced value of production flexibility.

Proposition 1 shows the discrepancy between the investment decisions under different policies. Next, we compare the firm's expected profits under different policies. Define

$$\Pi(\gamma) = \frac{(\bar{a} - \gamma \bar{k})^2}{4b} + w\bar{k} - \beta(\gamma^+ - \gamma)^2. \tag{6}$$

Plugging the optimal emission intensities shown in (4) and (5) into the profit functions in (2) and (3), respectively, we can get that

$$\Pi_T^* = \Pi(\gamma_T^*) + \frac{\sigma_D^2}{4b},$$
$$\Pi_C^* = \Pi(\gamma_C^*) + \frac{\sigma_D^2 + \gamma_C^*(\gamma_C^* - 2\tilde{\rho})\sigma^2}{4b},$$

where $\tilde{\rho} = \rho\sigma_D/\sigma$. The expected profit under each policy is consisting of two terms. The first term $\Pi(\cdot)$ is the firm's expected profit with the value of production flexibility excluded, which can be interpreted as a measure of the firm's *investment effectiveness*.[3] The second term is the firm's additional expected gains from making production decision after observing the realization of a or k. It measures the firm's *value of production flexibility*, which is increasing with the volatility of market potential/carbon price when $\rho = 0$. In general, the more volatile the market potential/carbon price is, the more value the firm can obtain from the quick-response production. This relationship is empirically verified by International Energy Agency (IEA), which based its study on oil plants that could produce electricity in response to the changes in carbon price and found that the value of such operational flexibility increases with the degree of uncertainty (IEA 2007).

Comparing the expected profits associated with the carbon tax policy and the cap-and-trade policy, we have

$$\Pi_C^* - \Pi_T^* = \underbrace{\Pi(\gamma_C^*) - \Pi(\gamma_T^*)}_{\substack{\text{investment distortion effect under} \\ \text{the cap-and-trade policy}(\leq 0)}} + \underbrace{\frac{\gamma_C^*(\gamma_C^* - 2\tilde{\rho})\sigma^2}{4b}}_{\substack{\text{production flexibility effect under the cap-and-} \\ \text{trade policy}(<0/>0,\ \text{depending on } \tilde{\rho})}}. \tag{7}$$

The first component $\Pi(\gamma_C^*) - \Pi(\gamma_T^*) \leq 0$ in Equation (7) indicates that the firm is less effective in clean technology investment under the cap-and-trade policy. To see this, by using the expression of $\Pi(\gamma)$ in (6), one can derive that $\gamma_T^* = \arg\max_\gamma \Pi(\gamma)$. In other words, the carbon tax policy induces the most effective level of investment, whereas the cap-and-trade policy causes distortion in investment and results in less investment effectiveness. This is because under the cap-and-trade policy, the firm's investment decision is made in the presence of permit price uncertainty, which distorts the efficiency of the technology investment. We refer to this as *investment distortion effect* under the cap-and-trade policy. This effect is documented in the study of IEA (2007). They analyzed the interaction between carbon price uncertainty and investment in clean technology. They found that uncertainty could result in investment that would appear suboptimal in a world of greater certainty.

The second component in Equation (7) captures the difference in the value of production flexibility under the two policies, which is negative when ρ is large. This is because an increase in the correlation coefficient between the market potential and the permit price will constrain the value of production flexibility under the cap-and-trade policy. We refer to this as *production flexibility effect*. The profit comparison is shaped by the interaction between these two effects, as summarized in the following proposition.

Proposition 2. *Comparing the firm's expected profits associated with the carbon tax policy and the cap-and-trade policy, we get that:*

(a) *There exists a threshold R with $0 < R < R_0$ such that a higher expected profit is generated under the carbon tax policy if and only if $\rho > R$, where*

$$R = \begin{cases} \rho_0 & \text{if } \rho_0 > \dfrac{(\bar{k}^2 + \sigma^2)\gamma^+ - \bar{a}\bar{k}}{\sigma_D \sigma} \\ \rho_1 & \text{if } \rho_0 \leq \dfrac{(\bar{k}^2 + \sigma^2)\gamma^+ - \bar{a}\bar{k}}{\sigma_D \sigma}, \end{cases}$$

with ρ_0 determined by the equation $R_0 + \frac{\sigma_D \sigma \rho_0^2}{4b\beta\gamma^+ - \bar{a}\bar{k}} - 2\rho_0 = 0$ and $\rho_1 = \frac{\bar{a}\bar{k}^2(2\bar{k}\gamma^+ - \bar{a}) + (4b\beta\sigma^2 - \sigma^2\bar{k}^2 - \bar{k}^4)(\gamma^+)^2}{2\sigma_D\sigma(4b\beta - \bar{k}^2)\gamma^+}$.

(b) *The threshold R (focusing on the solution ρ_0 which is calculated in the case when γ_C^* is an inner solution) has the following properties:* (i) *it is decreasing in $\bar{a}$;* (ii) *there exists at most a positive threshold of $\bar{k}$ such that R is increasing in $\bar{k}$ if $\bar{k}$ is larger than this threshold;* (iii) *it is decreasing in σ_D; and* (iv) *it is increasing in σ.*

Recall that $\rho = R_0$ is the threshold at which the investments under the two policies are at the same level (i.e., $\gamma_T^* = \gamma_C^*$; see Proposition 1), and there is no investment distortion under the cap-and-trade policy. When ρ is large (i.e., $\rho > R$), the investment under the cap-and-trade policy *can* be largely distorted, resulting in less investment effectiveness. Meanwhile, the value of production flexibility under the cap-and-trade policy is also constrained by a large correlation ρ. Both effects of investment distortion and production flexibility reduce the firm's expected profit under the cap-and-trade policy, making it less appealing to the firm. When ρ is small (i.e., $\rho < R$), despite the investment distortion under the cap-and-trade policy, the value of production flexibility is enhanced significantly and dominates the investment distortion effect. In this case, the cap-and-trade policy yields more expected profit for the firm.

Next, we discuss how the profit comparison between the two policies is affected by market characteristics. As $\bar{a}$ increases, the cap-and-trade policy is less appealing to the firm (i.e., R decreases in $\bar{a}$). Although a larger $\bar{a}$ benefits the firm in terms of investment effectiveness under both policies, it has an additional impact on the firm's production flexibility under the cap-and-trade policy. The firm invests more as $\bar{a}$ enlarges, but the high investment ex ante is a commitment to high production in the future, which impairs the value of production flexibility. Therefore, the dominant region of the carbon tax policy, in terms of the firm's expected profit, is enlarged with $\bar{a}$. Similar analysis applies to the impact of $\bar{k}$, and we omit it here to avoid duplication. The fluctuation of permit price increases the value of production flexibility when ρ is small (see Lemma 2) and improves the firm's expected profit under the cap-and-trade policy (i.e., R increases in σ). However, the volatility of market potential amplifies the effect from positive correlation between a and k and undermines the value of production flexibility (see Proposition 1), reducing the firm's expected profit under the cap-and-trade policy (i.e., R decreases in σ_D).

After distilling the influence of the implemented policy on the firm's investment decision and expected profit, we next analyze the impact of carbon policies on the consumer surplus and the total amount of CO_2 emissions.

5. Analysis of Consumer Surplus and Carbon Emissions

In this section, we investigate the influence of carbon policies on the consumer surplus and the total amount of emissions. Based on the well-defined concept of consumer surplus, the expected consumer surpluses associated with the two carbon policies are as follows:

$$CS_T = \mathbb{E}_a\left[\frac{b(q_T^*)^2}{2}\right] = \frac{(\bar{a}-\gamma_T^*\bar{k})^2}{8b} + \frac{\sigma_D^2}{8b},$$
$$CS_C = \mathbb{E}_{\{a,k\}}\left[\frac{b(q_C^*)^2}{2}\right] = \frac{(\bar{a}-\gamma_C^*\bar{k})^2}{8b} + \frac{\sigma_D^2+\gamma_C^*(\gamma_C^*-2\tilde{\rho})\sigma^2}{8b}, \tag{8}$$

where q^*, γ_T^*, and γ_C^* are given by Equations (1), (4), and (5), respectively. The expected amount of CO_2 emission is define as $S(\gamma, q) = \mathbb{E}[\gamma q]$. We can easily derive that

$$S_T = \frac{\bar{a}\gamma_T^* - \bar{k}(\gamma_T^*)^2}{2b}, \quad S_C = \frac{\bar{a}\gamma_C^* - \bar{k}(\gamma_C^*)^2}{2b}. \tag{9}$$

Policy comparison in terms of the consumer surplus and the total CO_2 emissions is characterized in the following corollary.

Corollary 1. *Comparing the expected consumer surplus and the expected total amount of emissions under the carbon tax policy and the cap-and-trade policy, we derive that*

(a) *There exist at most two thresholds R_1 and R_2 where $R_1 < R < R_0 < R_2$, such that if $R_1 < \rho < R_2$, then $CS_T > CS_C$; otherwise $CS_T \le CS_C$.*

(b) *(i) When $\rho < R_0$, if $\gamma_T^* + \gamma_C^* < \bar{a}/\bar{k}$, then $S_T < S_C$; otherwise $S_T \ge S_C$. (ii) When $\rho > R_0$, if $\gamma_T^* + \gamma_C^* < \bar{a}/\bar{k}$, then $S_T > S_C$; otherwise $S_T \le S_C$.*

Corollary 1(a) reveals the nonmonotonic impact of ρ on the comparison of the expected consumer surplus under the two policies. To understand this result, there is no correlation between the market potential and the carbon price under the carbon tax policy because the carbon price is fixed. Thus, the correlation ρ does not affect the expected consumer surplus under this policy. In contrast, the correlation ρ has the following two opposite effects on the expected consumer surplus under the cap-and-trade policy. From the expression of CS_C in (8), we know that the expected consumer surplus is mainly affected by the production quantity. On the one hand, an increase in ρ dampens the value of the firm's production flexibility, resulting in less expected consumer surplus (captured by the second term of CS_C, which is negative when ρ is large). On the other hand, because the production flexibility is undermined as ρ increases, the firm invests more in clean technology in advance to reduce the emission intensity and lower the marginal emission cost γk (see the analysis in Lemma 2). The reduction in marginal emission cost encourages the firm's production, resulting in more expected consumer surplus (captured by the first term in CS_C, which is increasing in ρ). The interaction of these two effects determines the U shape of CS_C with respect to ρ and sheds light on the result in Corollary 1(a).

When ρ is small, under the cap-and-trade policy, the value of production flexibility is sufficiently high, which compensates for the high marginal emission cost because of inadequate investment in clean technology. Therefore, a high expected consumer surplus is generated. As ρ increases, the value of production flexibility is weakened, resulting in a reduction in the expected consumer surplus. However, as ρ continues increasing and becomes sufficiently large, although the value of production flexibility is further constrained, the firm dramatically ramps up the technology investment, which leads to a significant reduction in the marginal emission cost. The benefit from cost reduction offsets the negative effect from constrained production flexibility, driving up the expected consumer surplus again. Gaining a clear understanding of the U shape of CS_C, it is easy to understand the result in Corollary 1(a): The cap-and-trade policy generates more consumer surplus than the carbon tax policy when the correlation ρ is sufficiently small (i.e., $\rho < R_1$) or sufficiently large (i.e., $\rho > R_2$).

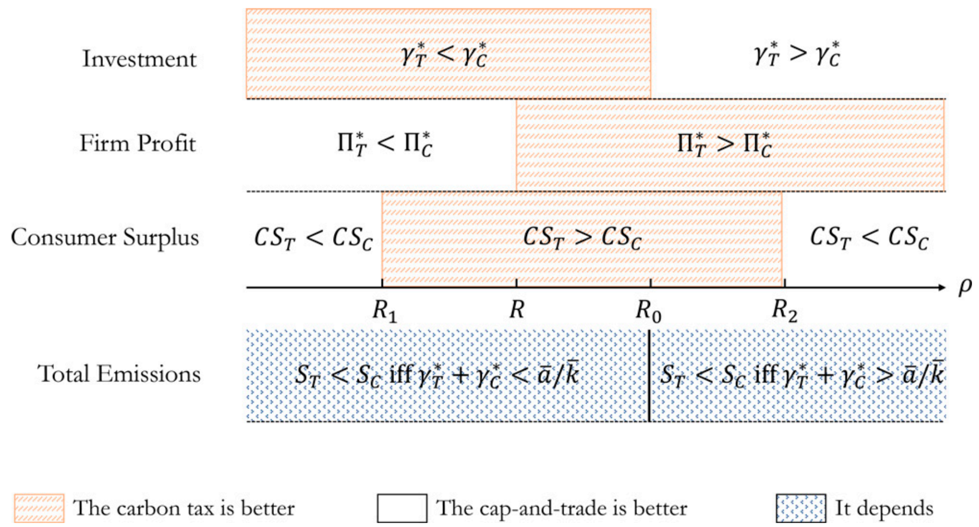
Corollary 1(b) compares the expected total amount of emissions under the two policies, which is jointly determined by the emission intensity and the production output. First consider the case where $\rho < R_0$. In this case, the investment under the carbon tax policy is higher than that under the cap-and-trade policy (i.e., $\gamma_T^* < \gamma_C^*$). When the condition $\gamma_T^* + \gamma_C^* < \bar{a}/\bar{k}$ is satisfied, there is not much difference in the emission intensity between the two policies. (Note that γ_T^* is irrelevant of ρ, whereas γ_C^* is decreasing in ρ. A small $\gamma_T^* + \gamma_C^*$ implies a relatively large ρ which is around R_0, the threshold at which the emission intensities are the same under the two policies.) As a result, the production outputs are also similar under the two policies. Under this situation, we observe that the comparison of the total emissions is mainly determined by the investment level. The cap-and-trade policy induces less investment and thus leads to more total emissions (i.e., $S_T < S_C$). In contrast, when the condition $\gamma_T^* + \gamma_C^* \geq \bar{a}/\bar{k}$ is satisfied, the comparison of the total emissions is mainly determined by the production output. Although the cap-and-trade policy induces much less investment and thus the emission intensity is high (implied by a relatively small ρ which is far away from R_0), the firm reduces his production output, which brings down the total emissions (i.e., $S_T \geq S_C$). A similar analysis can be applied to the case where $\rho > R_0$. We omit it here to avoid repetition.

To display the whole picture of our main results, we summarize in Figure 5 the comparison results in terms of the optimal investment decision characterized in Proposition 1, the expected profit demonstrated in Proposition 2, the expected consumer surplus, and the total emissions presented in Corollary 1. Several important implications are observed as follows.

First, when $R < \rho < R_0$, the carbon tax policy results in a multiwin situation, that is, the investment in clean technology is enhanced, the firm's expected profit is improved, consumer's surplus is increased, and the total emissions could be reduced if $\gamma_T^* + \gamma_C^* < \bar{a}/\bar{k}$. This result demonstrates that, although the original intention for researchers to propose the carbon tax policy is a higher probability of reaching a price commitment than a quantity commitment (Cramton et al. 2017), the carbon tax policy has an outstanding strategic advantage relative to the cap-and-trade policy.

Second, different market characteristics might exert different influences on the multiwin region $R < \rho < R_0$. For instance, Propositions 1 and 2 show that the thresholds R_0 and R are both increasing in σ, indicating that the region expands from the top while shrinking from the bottom as the permit trading market becomes more fluctuated. A larger σ discourages the firm's investment but improves the firm's expected profit under the cap-and-trade policy. Relatively, the carbon tax policy becomes more appealing in terms of creating investment incentives but at the

Figure 5. (Color online) Summary of the Comparison Results



Note. Comparing each performance measure associated with the carbon tax and cap-and-trade policies, we observe that (1) when $\rho < R_0$, the firm has more incentive to invest in clean technology under the carbon tax policy, (2) when $\rho > R$, the firm will get a higher expected profit under the carbon tax policy, (3) when $R_1 < \rho < R_2$, the consumer surplus is more advanced under the carbon tax policy, and (4) the comparison results associated with the total CO_2 emissions will depend on the parameters.

expense of sacrificing firms' profits to some extent. Propositions 1 and 2 also show that the thresholds R_0 and R are both decreasing in σ_D, revealing a different impact of the volatility in the sales market. This is because, by complementing the effect from positive correlation between a and k, a larger σ_D further constrains the value of production flexibility, which leads to more investment but less expected profit for the firm under the cap-and-trade policy.

Third, we observe that the cap-and-trade policy cannot strictly dominate the carbon tax policy: (1) when a higher expected profit is produced under the cap-and-trade policy, we find that the technology investment level must be lower than that under the carbon tax policy; and (2) when there is a higher consumer surplus in the cap-and-trade policy, we find that the firm's expected profit or/and the technology investment level may be lower than that under the carbon tax policy.

6. Illustrative Case Studies

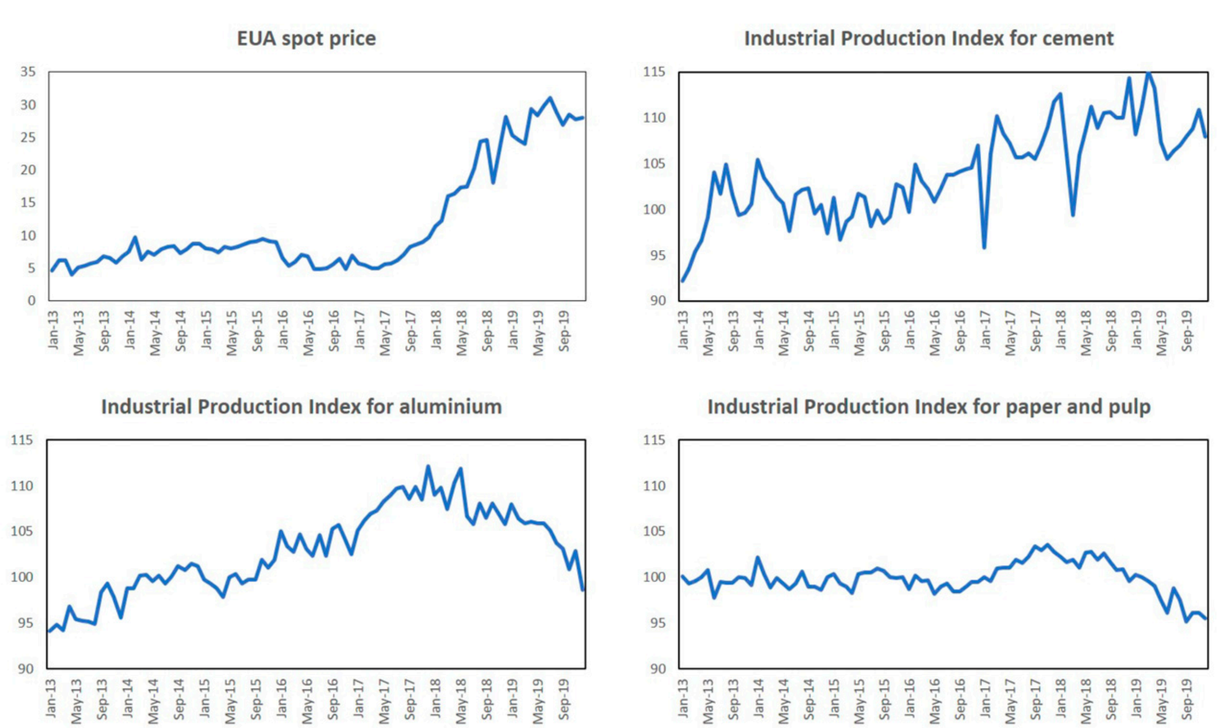
In this section, we provide some case studies to illustrate the main results and managerial implications. From Figure 5, the key factor that drives our results is the magnitude of the correlation ρ. Thus, in the following, we pin down our analysis to assess the correlations of different industries and check which region industries are comfortably within. We will focus on the region (R, R_0), in which the carbon tax policy generates a multiwin situation compared with the cap-and-trade policy.

We base our case studies on the European Union Emissions Trading System (EU ETS). As a key tool to combat climate change, the EU ETS works based on the "cap-and-trade" principle. The EU ETS sets a cap and governs about 40% of the EU's GHG emissions, covering a wide range of industrial activities such as production for cement, aluminium, iron and steel, and paper and pulp. Firms under regulation are allowed to trade emission allowances (EUAs) as needed at a price established by the carbon market.

To assess correlations between the carbon price and the market size of different industries, we collect EUA price data from the EU ETS during the time period 2013–2019 and use the EU Industrial Production Index (from Eurostat) as a proxy for the market size of a specific industry.[4] The EUA price is gathered on a daily basis, whereas the Industrial Production Index is published on a monthly basis. Without loss of generality, we use the EUA price on the last day of each month for our case study, which is one of the common ways to process time series data with different frequencies. Figure 6 plots the EUA price and the Industrial Production Index of selected industries of cement, aluminium, and paper and pulp. Correlation between the EUA price and the Industrial Production Index is calculated for these industries.

The parameters regarding carbon market can be assessed directly from the EUA price data, which are

Figure 6. (Color online) EUA Price and Industrial Production Index of Selected Industries



given by $\bar{k} = 11.68$ and $\sigma = 8.13$. (Note that $\bar{k}$ and σ are common parameters shared by industries.) For the industry-specific parameters, that is, $\bar{a}$, σ_D, b, β, and γ^+, we take the aluminium industry as an example to illustrate how we obtain their values. To get $\bar{a}$, σ_D, and b, we collect data of aluminium price (from London Metal Exchange) and EU aluminium production (from World Bureau of Metal Statistics) during the period 2013–2019. The parameter b is related to the price elasticity of an industry.[5] The value of b is chosen to yield the price elasticity of –1, which is in line with the estimates for the price elasticity in the aluminium industry in the literature (Smale et al. 2006, Graichen et al. 2008). Using the value of b, we can obtain a series of value on a,[6] on which we can calculate $\bar{a}$ and σ_D. The parameter β measures the efficiency in technology investment, which is related to marginal abatement cost. We approximate the value of β by using marginal abatement cost multiplied by production. The marginal abatement cost of the aluminium industry is around 15 USD for abating per ton CO_2e (Erickson et al. 2011). The emission intensity γ^+ is around 8.5 tons CO_2e per ton aluminium production (European Aluminium 2019). Using these parameter values, we can calculate the values of R and R_0 for the aluminium industry. A similar process applies to the other two industries. Table 2 summarizes the assessed parameters for these industries. The sources of data are provided with the table. (The detailed calculation for the paper and pulp industry is not necessary. The assessed negative correlation is sufficient for us to make prediction because both R and R_0 are positive theoretically.)

We next discuss the implications by industry drawn from the case studies. The EU economic recovery from the financial crisis contributed to driving up the carbon price in the EU ETS. Among the industries we study, we observe a positive correlation in the aluminium industry (0.33) and the cement industry (0.61) and a negative correlation in the paper and pulp industry (–0.28).

Table 2. Assessed Values of Correlation and Other Parameters for Selected Industries

Industry	ρ	$\bar{a}$	σ_D	b	β	γ^+	R	R_0
Aluminium	0.33	3,706	164	2.43	1.14	8.5	0.20	0.40
Cement	0.61	332	13	7.28	9.11	0.7	0.17	0.35
Paper and pulp	−0.28	—	—	—	—	—	—	—

Notes. Sources of data: Bloomberg, Eurostat, World Bureau of Metal Statistics, Smale et al. (2006), Graichen et al. (2008), McKinsey and Ecofys (2006), McKinsey (2013), European Aluminium (2019), and Statista (2019). For the values of b, the orders of magnitude for the aluminium and cement industries are –4 and –7, respectively. For the values of β, the orders of magnitude for the aluminium and cement industries are 8 and 9, respectively.

We start with the paper and pulp industry. Digitalization reduces the demand in the paper and pulp industry (European Commission 2020), which explains the negative correlation observed in this industry to some extent. Since the theoretical thresholds R and R_0 are both positive, our results predict that the paper and pulp industry lies to the left of the region (R, R_0). Thus, the carbon tax policy induces more investment but leads to less firm profit.

The EU aluminium industry sees an overall upward trend (but with a recent drop) in demand (European Aluminium 2019) and has a positive (but relatively smaller) correlation with the carbon price in EU ETS. Our case studies show that the aluminium industry falls into the multiwin region (R, R_0). Hence, our theoretical results predict that carbon tax may be a preferred policy that generates a multiwin situation for this industry.

European demand for cement has been growing in recent years, which could be driven by the increasing government spending on residential and infrastructure construction such as housing schemes, roads network, bridges, and airports (Commodity Inside 2019). Emissions from the cement industry represents around 10% of the total EU emissions (Global Cement 2019), implying that the cement industry has a large demand for emission allowances and plays an important role in influencing the carbon price in the EU ETS. This may help explain the positive and high correlation observed in this industry. The case studies show that the cement industry falls to the right of the region (R, R_0). Our theoretical results predict that the cap-and-trade policy incentivizes more investment in clean technology but leads to less firm profit for this industry (Figure 5). As the EU ETS sees a trend of EUA price fluctuations (Fjellheim 2018), the incentive role of cap-and-trade in technology investment may diminish. Instead, carbon tax could gradually become a preferred policy for the cement industry (because both R and R_0 increase with σ; see Propositions 1 and 2).

A more quantitative analysis of these industries is provided in the online appendix. Using the estimated parameter values, we construct hypothetical sample firms in selected industries. We allow the parameters of interest to vary near the representative firms. Based on this, we analyze how the changes of market characteristics affect the policy comparison for the sample firms in terms of the difference of investment, firm profit, consumer surplus, and total emissions.

In summary, correlation between the carbon price and the market potential differs by industry in terms of the sign and the magnitude. The empirical findings in Chevallier (2011) provide us a way to measure and interpret such correlation of a specific industry, making the theoretical results of our paper more practical implications. Based on the measured correlations, our results could help predict/identify the impact of carbon policies on technology investment, firm profit, and consumer surplus for a specific industry, which provides guidance for carbon policy making.

7. Discussion

7.1. Sales Competition

Our main results are derived under the monopoly case. The model can be extended to study competition in a duopoly case where symmetric firms sell substitutable products to the market. Firm i's inverse demand function is given by $p_i = a - bq_i - btq_j$, where t is the degree of product substitutability, ranging from zero for independent products to one for perfect substitutes. We can interpret t as competition intensity between the two firms, with a larger t representing fiercer competition. Our analysis shows that all the main results and intuitions obtained in the base model remain valid in this extended setting. The detailed analysis is presented in the online appendix. In what follows, we focus on examining the impact of the competition intensity t.

We find that as competition becomes more intensified, the investment in clean technology is first decreasing and then increasing under both carbon policies. This result is driven by the tradeoff between (1) the firm's desire for gaining a competitive edge over the rival by investing more and (2) the firm's desire for restraining competition to keep "monopolistic" power by investing less. More specifically, by investing more in clean technology, the firm can lower down the marginal emission cost and obtain a competitive advantage for production. Conversely, the investment is a qualified signal of the expected production quantity in the future; high investment in the first stage induces a severe competition in the second stage. By investing less, the firm can mitigate such future competition. When $t = 0$, the firm could obtain the highest profit as under the monopoly case. When the competition intensity t is at a low level (i.e., around zero), it is beneficial for the firm to avoid competition and keep his "monopolistic" power. In this case, each firm shall invest less to mitigate the intensified competition caused by a larger t. In contrast, when the competition intensity t is at a high level already (i.e., around one), the benefit generated from restraining competition is limited. In this case, each firm is eager to gain a competitive edge over the rival by intensively investing in clean technology and cutting down the emission cost. As a result, the investment is increasing in the competition intensity. Furthermore, we find that the multiwin region of the carbon tax policy expands first and then shrinks as the competition intensity increases. The implication from this result is that the carbon tax is more appealing than the cap-and-trade in terms of creating investment incentives, generating firm profit and increasing consumer welfare for an industry with moderate competition intensity. Governments need to take the competitive environments into account when designing carbon policies.

7.2. Technology-Choice Dependent Production Cost

In our base model, we assume that the production cost is independent of the technology choice. Furthermore, as the constant production cost has no impact on the final results, we normalize the production cost to zero without loss of generality. In this section, we extend our analysis to the case where the production cost is dependent on the technology level γ and assume that a cleaner technology results in a higher production cost. Specifically, we model the per unit production cost as follows:

$$C(\gamma) = c\left[1 + \frac{d(\gamma^+ - \gamma)}{\gamma^+}\right],$$

where c is the initial production cost, d captures the degree of cost increment because of technology upgrading, and $(\gamma^+ - \gamma)/\gamma^+$ is the percentage of emission intensity reduction because of technology upgrading. With this production cost function, the firm's marginal profit (i.e., price minus marginal costs of emission and production) in this extended model is as follows:

$$a - bq - \gamma k - C(\gamma) = a - (1 + d)c - bq - \gamma\left(k - \frac{dc}{\gamma^+}\right).$$

Recall that the firm's marginal profit in the base model is $a - bq - \gamma k$. By comparing these two expressions, we see that the marginal profit in the extended model can be obtained by replacing a and k with $a - (1 + d)c$ and $k - (dc/\gamma^+)$, respectively.[7] Actually, we can get the results in this model by simply replacing $\bar{a}$ and $\bar{k}$ in the base model with $\bar{a} - (1 + d)c$ and $\bar{k} - (dc/\gamma^+)$. Therefore, the main results in the base model continue to hold with slightly different threshold values.

We next focus particularly on how the production cost affects the firm's investment decision. The results are summarized in the following corollary.

Corollary 2. *When the production cost is dependent on the choice of clean technology, the optimal investment decisions γ_C^* and γ_T^* have the following properties:*

(a) *Both γ_T^* and γ_C^* are increasing in d.*

(b) *The decreasing rate of γ_C^* on ρ $\left(i.e., \left|\frac{\partial \gamma_C^*}{\partial \rho}\right|\right)$ is decreasing in d.*

Corollary 2(a) shows that the optimal emission intensity is increasing in d under both policies. The underlying reason is straightforward. As the incremental production cost (i.e., $d(\gamma^+ - \gamma)/\gamma^+$) increases, the firm is reluctant to invest in clean technology, resulting in a high emission intensity. Corollary 2(b) sheds light on how the introduction of d affects the

Published in Management Science on March 25, 2022 as DOI: 10.1287/mnsc.2022.4365.
This article has not been copyedited or formatted. The final version may differ from this version.

impact of ρ and further alters the firm's investment incentive under the cap-and-trade policy. Recall that as ρ increases, the production flexibility is constrained, and the firm invests more to mitigate this effect. When the incremental production cost increases, the firm's incentive to mitigate the constrained production flexibility through investment is weakened. Thus, γ_C^* decreases in ρ at a slower rate when d becomes larger.

7.3. Constrained Production Flexibility

We assume in the base model that the firm has the flexibility to adjust his production quantity in the second stage after observing the market potential a and the permit price k. We shall extend our analysis to the case where the firm's production flexibility is constrained. To restrict the firm's production flexibility, we consider two separate cases: (1) *a predetermined quantity case* where the firm makes his production decision before observing the realization of a and k (i.e., the production process needs a long lead time) and (2) *a preannounced price case* where the firm preannounces his market price for the purpose of advertising or other business considerations. The detailed analysis of these two cases is presented in the online appendix. Here we only introduce the main derived results. First, we find that under the predetermined quantity case where the firm has no flexibility at all, all the measurements are identical under the two carbon policies. Second, when the market price is preannounced, we find that under the cap-and-trade policy, the firm is motivated to invest more, relative to our base model where the firm has ex ante full production flexibility. However, we observe that the firm's investment motivation stays the same under the carbon tax policy even if the production flexibility is restricted by a preannounced market price. The previous results imply that the carbon tax's advantage in investment diminishes when the firm's flexibility is limited by a preannounced market price. More importantly, as thecadvantage in technology investment diminishes, we observe that the dominant role of the carbon tax policy disappears and neither policy could obtain a strictly dominant position.

8. Conclusion

To examine the effectiveness of different carbon policies, we characterized the optimal technology investment level, the optimal production decision, and the corresponding performance measurements (i.e., expected profit, consumer surplus, and the amount of carbon emissions) associated with both the cap-and-trade policy and the carbon tax policy.

When the firm has a full ex ante production flexibility, our analysis reveals that (1) when the correlation coefficient between the sales market and the permit trading market is larger than a threshold, the monopoly firm could enjoy a higher expected profit under the carbon tax policy; (2) when the correlation coefficient is lower than a threshold, the technology investment level is higher under the carbon tax policy; and (3) when the correlation coefficient is moderate, a higher consumer surplus is generated under the carbon tax policy. In a word, our results provide theoretical evidence to help central planners to make their carbon policies better, especially when they have specific objectives. More importantly, we observe that the carbon tax policy could generate a multiwin situation (i.e., a higher level of technology investment, a higher expected profit, a higher consumer surplus, and a lower amount of carbon emissions), relative to the cap-and-trade policy. The cap-and-trade policy could not always strictly dominate the carbon tax policy. This result validates the strategic advantage of the carbon tax policy, although the original intention for researchers to propose the carbon tax policy is a higher probability of reaching a price commitment than a quantity commitment. The main results of the paper are summarized in Table 3.

In brief, from the operations perspective, our work examines the effectiveness of carbon policies in promoting clean technology investment, improving consumer surplus, and reducing the total amount of carbon emissions. Our analysis reveals that operational flexibility,

Table 3. Summary of the Comparison Results

Correlation of the sales market and permit market	Carbon tax	Cap-and-trade
Sufficiently high ($\rho > R_2$)	Higher firm profit	Higher consumer surplus Higher technology investment
Relatively high ($R_0 < \rho < R_2$) (e.g., cement industry)	Higher firm profit Higher consumer surplus	Higher technology investment
Moderate ($R < \rho < R_0$) (e.g., aluminium industry)	Higher firm profit Higher consumer surplus Higher technology investment	
Relatively low ($R_1 < \rho < R$)	Higher consumer surplus Higher technology investment	Higher firm profit
Sufficiently low ($\rho < R_1$)	Higher technology investment	Higher firm profit Higher consumer surplus

which is determined by the correlation relationship between the sales market and the permit trading market and the firm's ex ante capability in flexible production, will significantly influence the performance of carbon policies, and hence, it should be paid more attention in the process of policy development.

Acknowledgments
The authors thank Charles Corbett, the anonymous associate editor, and reviewers for helpful comments and suggestions.

Endnotes

[1] The reader is referred to WMO Statement on the State of the Global Climate in 2018.

[2] We consider the case where the firm has a single type of technology. Specifically, if the firm invests in improving the technology, the retrofits occur at the firm level at all its plants rather than at a portion of its plants. This is common in practice. For example, Siemens, the world's largest industrial manufacturer, made a commitment to be entirely carbon neutral at all production facilities and buildings worldwide by using renewable energy (Impact Hub 2018, Siemens 2018). Similar practices have been taken by S.C. Johnson and Apple (Forbes 2019). It is also possible for a firm to opt to retrofit only a portion of its plants, and thus it owns two types of technology with different levels of emission intensity after investment. We focus on the single-type setting to deliver clean and sharp insights efficiently while leaving the study of multiple types of technology to future research.

[3] To make it clearer, notice that $\Pi(\gamma)$ can be rewritten as $\Pi(\gamma) = \pi(q^*(\gamma,\overline{a},\overline{k});\gamma,\overline{a},\overline{k}) - \beta(\gamma^+ - \gamma)^2$, which is the firm's profit for a given γ under the deterministic case without volatility in the market potential and carbon price (i.e., with a and k fixed at $\overline{a}$ and $\overline{k}$, respectively). With uncertainty excluded, the magnitude of the profit $\Pi(\gamma)$ is only affected by the firm's investment decision γ, reflecting how effective the firm is in clean technology investment.

[4] the Industrial Production Index is widely recognized as a good proxy for macroeconomic activity in empirical studies (Bradley and Jansen 2004, Chevallier 2011). See Remarks 2 and 3 in the online appendix for more details.

[5] More specifically, the inverse demand function is given by $p(q) = a - bq$, yielding a price elasticity (denoted by e) of $-(1/b)(p/q)$. Then the value of b can be obtained by using the data of price elasticity, average price and average production (i.e., $b = -(1/e)(\overline{p}/\overline{q})$).

[6] Because $p_t = a_t - bq_t$, we have $a_t = p_t + bq_t$, where t denotes the time of the data generated.

[7] Note that $a - (1+d)c$ and $k - (dc/\gamma^+)$ can be regarded as the effective market potential and the effective carbon price, respectively. To avoid unreasonable cases, we focus on the case where both the effective market potential and effective carbon price are positive (i.e., $a - (1+d)c > 0$ and $k - (dc/\gamma^+) > 0$).

References

Anand KS, Giraud-Carrier FC (2020) Pollution regulation of competitive markets. *Management Sci.* 66(9):4193–4206.

Blyth W, Yang M, Bradley R (2007) *Climate Policy Uncertainty and Investment Risk* (International Energy Agency, Paris).

Bradley MD, Jansen DW (2004) Forecasting with a nonlinear dynamic model of stock returns and industrial production. *Internat. J. Forecasting* 20(2):321–342.

Burtraw D, Palmer K, Kahn D (2006) *Dynamic Adjustment to Incentive Based Policy to Improve Efficiency and Performance* (Resources for the Future, Washington, DC).

Bushnell J, Chen Y (2012) Allocation and leakage in regional cap-and-trade markets for CO_2. *Resources Energy Econom.* 34(4):647–668.

Caro F, Corbett CJ, Tan T, Zuidwijk R (2013) Double counting in supply chain carbon footprinting. *Manufacturing Service Oper. Management* 15(4):545–558.

Chevallier J (2011) A model of carbon price interactions with macroeconomic and energy dynamics. *Energy Econom.* 33(6):1295–1312.

Commodity Inside (2019) Cement market in Europe. Accessed July 16, 2020, https://commodityinside.com/reports/cement-market-in-europe/.

Cramton P, Ockenfels A, Stoft S (2017) An international carbon-price commitment promotes cooperation. Cramton P, MacKay DJ, Ockenfels A, eds. *Global Carbon Pricing: The Path to Climate Cooperation* (MIT Press, London), 221.

Demailly D, Quirion P (2006) CO_2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: Grandfathering vs. output-based allocation. *Climate Policy* 6(1):93–113.

Drake DF (2018) Carbon tariffs: Effects in settings with technology choice and foreign production cost advantage. *Manufacturing Service Oper. Management* 20(4):667–686.

Drake DF, Kleindorfer PR, Van Wassenhove LN (2016) Technology choice and capacity portfolios under emissions regulation. *Production Oper. Management* 25(6):1006–1025.

Erickson P, Lazarus M, Chandler C, Egenhofer C (2011) *Scoping paper "the potential for CDM induced leakage in energy intensive sectors"*. SEI and CEPS. Research paper, European Commission. https://ec.europa.eu/clima/system/files/2017-02/potential_leakage_en_0.pdf.

European Aluminium (2019) Vision 2050: European aluminium's contribution to the EU mid-century low carbon roadmap. Accessed July 15, 2020, https://www.european-aluminium.eu/vision-2050/.

European Commission (2020) Pulp and paper industry. Accessed July 15, 2020, https://ec.europa.eu/growth/sectors/raw-materials/related-industries/forest-based-industries/pulp-and-paper-industry_en.

Fjellheim H (2018) Will high European carbon prices last. Accessed July 25, 2020, https://www.refinitiv.com/perspectives/market-insights/will-high-european-carbon-prices-last/.

Forbes (2019) 101 companies committed to reducing their carbon footprint. Accessed October 20, 2020, https://www.forbes.com/sites/blakemorgan/2019/08/26/101-companies-committed-to-reducing-their-carbon-footprint/.

Gilbert A, Blinde P, Lam L, Blyth W (2014) Cap-setting, price uncertainty and investment decisions in emissions trading systems. Accessed July 20, 2020, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/311914/EU_ETS_cap-setting_project_REPORT.pdf.

Global Cement (2019) European Union CO_2 emissions data from cement plants in 2018. Accessed July 20, 2020, https://www.globalcement.com/news/item/9060-european-union-co2-emissions-data-from-cement-plants-in-2018.

Gong X, Zhou SX (2013) Optimal production planning with emissions trading. *Oper. Res.* 61(4):908–924.

Graichen V, Schumacher K, Matthes F-C, Mohr L, Duscha V, Schleich J, Diekmann J (2008) *Impacts of the EU Emissions Trading Scheme on the Industrial Competitiveness in Germany* (German Federal Environment Agency, Berlin).

Hartman RS, Wheeler D, Singh M (1997) The cost of air pollution abatement. *Appl. Econom.* 29(6):759–774.

Hepburn C (2006) Regulation by prices, quantities, or both: A review of instrument choice. *Oxford Rev. Econom. Policy* 22(2):226–247.

Huang X, Tan T, Toktay LB (2021) Carbon leakage: The impact of asymmetric regulation on carbon-emitting production. *Production Oper. Management* (Wiley Online Library), 30(6):1886–1903.

IEA (2007) Climate policy uncertainty and investment risk. Accessed July 15, 2020, https://www.iea.org/reports/climate-policy-uncertainty-and-investment-risk.

Impact Hub (2018) 5 big companies reducing their carbon footprints. Accessed October 20, 2020, https://impacthub.net/5-big-companies-reducing-their-carbon-footprints/.

Islegen O, Plambeck E, Taylor T (2015) *The Impacts of Climate Policy on Facility Location, Production and Shipping. Environmentally Responsible Supply Chains* (Springer, New York).

Krass D, Nedorezov T, Ovchinnikov A (2013) Environmental taxes and the choice of green technology. *Production Oper. Management* 22(5):1035–1055.

Krysiak FC (2008) Prices vs. quantities: The effects on technology choice. *J. Public Econom.* 92(5-6):1275–1287.

Laffont J-J, Tirole J (1996) Pollution permits and environmental innovation. *J. Public Econom.* 62(1-2):127–140.

Lee S-H (1999) Optimal taxation for polluting oligopolists with endogenous market structure. *J. Regulatory Econom.* 15(3):293–308.

MacKay DJ, Cramton P, Ockenfels A, Stoft S (2015) Price carbon—I will if you will. *Nature* 526(7573):315–316.

Mansur ET (2013) Prices vs. quantities: Environmental regulation and imperfect competition. *J. Regulatory Econom.* 44(1):80–102.

McKinsey (2013) Pathways to a low carbon economy: Version 2 of the global greenhouse gas abatement cost curve. Accessed October 10, 2020, https://www.mckinsey.com/business-functions/sustainability/our-insights/pathways-to-a-low-carbon-economy.

McKinsey, Ecofys (2006) *EU ETS Review: Report on International Competitiveness* (European Commission Directorate General for Environment, Brussels). https://ec.europa.eu/clima/system/files/2016-11/report_int_competitiveness_20061222_en.pdf.

Mendelsohn R (1984) Endogenous technical change and environmental regulation. *J. Environ. Econom. Management* 11(3):202–207.

Metcalf GE (2009) Designing a carbon tax to reduce US greenhouse gas emissions. *Rev. Environ. Econom. Policy* 3(1):63–83.

Montero J-P (2002) Permits, standards, and technology innovation. *J. Environ. Econom. Management* 44(1):23–44.

Nguyen J, Donohue K, Mehrotra M (2018) Closing a supplier's energy efficiency gap through assessment assistance and procurement commitment. *Management Sci.* 65(1):122–138.

Nordhaus WD (2013) *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World* (Yale University Press, New Haven, CT).

Pizer WA (2002) Combining price and quantity controls to mitigate global climate change. *J. Public Econom.* 85(3):409–434.

Requate T (1993) Pollution control in a cournot duopoly via taxes or permits. *J. Econom.* 58(3):255–291.

Requate T (1998) Incentives to innovate under emission taxes and tradeable permits. *Eur. J. Political Econom.* 14(1):139–165.

Requate T (2006) Environmental policy under imperfect competition. *Internat. Yearbook Environ. Resource Econom.* 2007:120–207.

Schmalensee R, Stavins RN (2017) Lessons learned from three decades of experience with cap and trade. *Rev. Environ. Econom. Policy* 11(1):59–79.

Seade J (1985) Profitable cost increases and the shifting of taxation: Equilibrium responses of markets in oligopoly. Technical report, The University of Warwick, Coventry.

Shaffer S (1995) Optimal linear taxation of polluting oligopolists. *J. Regulatory Econom.* 7(1):85–100.

Siemens (2018) Siemens is going carbon neutral by 2030. Accessed October 20, 2020, https://press.siemens.com/global/en/feature/siemens-going-carbon-neutral-2030.

Smale R, Hartley M, Hepburn C, Ward J, Grubb M (2006) The impact of CO2 emissions trading on firm profits and market prices. *Climate Policy* 6(1):31–48.

Statista (2019) Cement prices in the United States from 2007 to 2019. Accessed July 16, 2020, https://www.statista.com/statistics/219339/us-prices-of-cement/.

Subramanian R, Gupta S, Talbot B (2007) Compliance strategies under permits for emissions. *Production Oper. Management* 16(6):763–779.

von der Fehr N-HM (1993) Tradable emission rights and strategic interaction. *Environ. Resources Econom.* 3(2):129–151.

Wang X, Cho S-H, Scheller-Wolf A (2021) Green technology development and adoption: Competition, regulation, and uncertainty—A global game approach. *Management Sci.* 67(1):201–219.

Weitzman ML (1974) Prices vs. quantities. *Rev. Econom. Stud.* 41(4):477–491.

Weitzman ML (2015) Internalizing the climate externality: Can a uniform price commitment help? *Econom. Energy Environ. Policy* 4(2):37–50.

Yalabik B, Fairchild RJ (2011) Customer, regulatory, and competitive pressure as drivers of environmental innovation. *Internat. J. Production Econom.* 131(2):519–527.

Yuan Q, Chen Y, Yang J, Zhou Y (2018) Joint control of emissions permit trading and production involving fixed and variable transaction costs. *Production Oper. Management* 27(8):1420–1454.

Zhao J (2003) Irreversible abatement investment under cost uncertainties: Tradable emission permits and emissions charges. *J. Public Econom.* 87(12):2765–2789.

Zhao J, Hobbs BF, Pang J-S (2010) Long-run equilibrium modeling of emissions allowance allocation systems in electric power markets. *Oper. Res.* 58(3):529–548.