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Haitao Cheng[a], Akihiko Yanase[b]

(a) Hitotsubashi University
(b) Nagoya University

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Hitotsubashi Institute for Advanced Study, Hitotsubashi University
2-1, Naka, Kunitachi, Tokyo 186-8601, Japan
tel:+81 42 580 8668 http://hias.hit-u.ac.jp/

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Haitao Cheng[†] Akihiko Yanase[‡]

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Abstract

Article 6 of the Paris Agreement seeks to foster international cooperation between developed and developing countries in curbing global carbon emissions. Central to this provision is the facilitation of international transfers of green technology and carbon mitigation outcomes. Through this mechanism, developed countries transfer their green technology to developing countries to help them mitigate emissions. In return, developing countries transfer emission permits equivalent to the mitigated outcomes to developed countries to alleviate their abatement burden. This study employs an international oligopoly model to explore the implications of green technology transfer (GTT) and international transfer of mitigated outcomes (ITMO) on welfare, emission permit issuance and global emissions. We find that once successfully implemented, these transfers consistently improve global welfare. Moreover, when permits are determined non-cooperatively by the countries, the implementation of GTT and ITMO leads to a reduction in global emissions.

Keywords: Green technology transfer; Internationally transferred mitigation outcomes; Permit markets; International coordination; Paris Agreement
JEL classification: F12; F18; H23; Q54

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[†]Hitotsubashi Institute for Advanced Study, Hitotsubashi University; E-mail: haitaoecon@gmail.com

[‡]Graduate School of Economics, Nagoya University; E-mail: yanase@soec.nagoya-u.ac.jp

1 Introduction

Over the past century, carbon dioxide (CO_2) emissions from fossil fuels have drastically increased, rising from 3.69 billion tonnes in 1923 to 37.79 billion tonnes in 2023.[1] This significant increase in carbon emissions has warmed the atmosphere, ocean and land, leading to severe consequences such as the 2003 heatwave that caused more than 70,000 fatalities in Europe. To address global warming, both developed and developing countries have committed to reducing their carbon emissions under the Paris Agreement adopted in 2015.

However, reducing emissions poses significant challenges for both types of countries. Developed countries face high marginal abatement costs since their emission levels are already low. By contrast, developing countries struggle with outdated technologies that impede effective emission reductions despite their potential to decrease emissions further. To address these challenges and enhance international collaborations for more effective reductions of global emissions, Article 6 in the Paris Agreement allows countries to utilize green technology transfer (GTT) and international transfer of mitigation outcomes (ITMO). By embracing these mechanisms, countries are expected to fulfill their emission reduction targets more successfully.[2]

Specifically, developed countries can transfer their green technologies to developing countries to help them reduce emissions. In exchange, developing countries transfer emission permits equivalent to the mitigated emissions to developed countries. This mechanism enables developed countries to ease their emission constraints while helping developing countries adopt advanced technologies and reduce emissions.

A notable example of GTT and ITMO in action is the Joint Crediting Mechanism (JCM) initiated by the Japanese government. As of December 2024, Japan has signed bilateral agreements with 29 countries for 255 JCM projects. These projects involve transfers of green technologies, encompassing solar technology, energy saving technology and highly efficient cooling systems. For instance, Japan's solar power projects in Saudi Arabia are expected to reduce 620,766 tonnes of CO_2-equivalent emissions per year.[3] Switzerland and Thailand have also successfully embarked on the mechanism of ITMO. On 15 December 2023, 1916 tonnes of carbon mitigation outcomes are

[1] `https://ourworldindata.org/co2-emissions`

[2] The Paris Agreement underscores the significance of GTT in Articles 6, 10, and 13, emphasizing its role in supporting the transition of developing countries to low-carbon economies. For instance, Article 10, Paragraph 2 of the Paris Agreement states that "*Parties, noting the importance of technology for the implementation of mitigation and adaptation actions under this Agreement and recognizing existing technology deployment and dissemination efforts, shall strengthen cooperative action on technology development and transfer.*" In addition to the mechanism of ITMO, international transfers of environmentally sound technologies for low carbon between developed and developing countries have also be undertaken through the Climate Technology Centre and Network (CTCN) under the United Nations Framework Convention on Climate Change. In 12 February 2024, the European Commission initiated a EUR 2 million grant to support technology for climate action in developing countries through the CTCN.

[3] Source: `https://gec.jp/jcm/projects/`

transferred from Thailand to Switzerland.[4]

Despite the practical relevance and active implementation of these mechanisms in many countries, existing literature lacks a formal analysis of how GTT facilitates ITMO and their impacts on emissions and welfare. This study aims to fill this gap by addressing the following questions:

- Under what conditions can GTT reduce total emissions in the developing country?
- How do GTT and ITMO affect welfare outcomes for developed and developing countries?
- How do countries issue emission permits non-cooperatively, and what are the implications for global emissions and overall welfare?

Specifically, we employ an international oligopoly model, motivated by the fact that some polluting industries, such as cement, iron and steel, exhibit strong characteristics of oligopoly. There are two countries, namely developed and developing countries. They differ in their environmental technologies, which stems from their usage of renewable energy and fossil fuels during production. We examine scenarios under business as usual (BAU) and GTT with ITMO settings. Under BAU, firms in the developed country use green technology for production, while firms in the developing country rely on dirty technology. The developed country has an option to transfer its green technology to the developing country, allowing the firms to adopt greener production methods. If this technology transfer results in reduced emissions in the developing country, an equivalent quantity of emission permits—reflecting the emissions reduction—is transferred to the developed country.

We begin with the scenario with exogenous emission permits, and find that GTT might lead to an increase in total emissions in the developing country. Intuitively, GTT decreases the emissions per unit of production but increases total production in the developing country. If the latter effect dominates the former, total emissions could increase. In this case, ITMO cannot be certified and implemented.

Even in the scenarios where GTT successfully reduces emissions in the developing country, the implementation of GTT and ITMO may not necessarily improve the welfare of both developed and developing countries concurrently. This is because although GTT and ITMO increase total consumption and thus consumer surplus in each country, they could also lead to a decrease in producers' sales profits, harming a country's welfare eventually. However, we find that GTT and ITMO consistently contribute to an increase in global welfare.

We move on to the case with endogenous emission permits, and explore how countries determine their emission permits non-cooperatively under BAU and ITMO. We observe that compared with

[4]See more examples at the World Bank's Carbon Pricing Dashboard: https://carbonpricingdashboard.worldbank.org/credits/cooperative-approaches

BAU, GTT and ITMO decrease global emissions and enhance global welfare at equilibrium, as GTT improves global production efficiency.

1.1 Relation to the literature

The rationale of ITMO can be traced back to the discussion about the joint implementation (JI) and the clean development mechanism (CDM) under the Kyoto Protocol, e.g., Breton et al. (2006), Hagem (2009), Bréchet et al. (2016) and Calel et al. (2025). Under the Kyoto Protocol, only Annex B (developed) countries committed to reducing carbon emissions, while non-Annex B (developing) countries had no such obligations. Article 6 and Article 12 of the Kyoto Protocol facilitated the international transfer of emission reduction units. These transfers occurred between Annex B countries through the JI and between Annex B and non-Annex B countries through the CDM. Among others, Bréchet et al. (2016) employ a non-cooperative climate policy game to study the effects of CDM on countries' and global carbon emissions. They find that when a portion of the CDM rents is allocated to non-Annex B countries, Annex B countries have an incentive to issue more emission permits, potentially leading to an increase in global emissions. Our study is closely related to Bréchet et al. (2016) because they also analyze international transfers of green technology and carbon emission rights. However, our model setting is different from theirs. In contrast to their game-theoretic climate policy model that does not explicitly account for production or international trade, we employ an international oligopoly model, which better describes the features of polluting industries, such as chemicals and cement. Another key distinction lies in the context. Bréchet et al. (2016) focus on the CDM under the Kyoto Protocol where only the developed countries enforce environmental regulations while the developing countries do not. By contrast, we study the ITMO under the Paris Agreement where both types of countries impose environmental regulations to control emissions. Distinct from our approach, Breton et al. (2006) and Hagem (2009) respectively investigate the attainment of emissions reduction units through foreign investment in environmental projects and the provision of financial support for the implementation of green technology. Notably, neither of them examine the channel of green technology transfer.

Tripathy et al. (2023) also analyze ITMO within the framework of the Paris Agreement, as we do. They consider two countries, one producing a low-carbon fuel and the other a high-carbon fuel. They find that trade in low-carbon fuel can benefit both countries, even without the implementation of ITMO. However, the introduction of ITMO can generate Pareto improvements for both countries by expanding the volume of low-carbon fuel trade. Our study differs from Tripathy et al. (2023) in several aspects. First, they consider the exports of low-carbon fuel between two signatory countries as the tool to achieve carbon mitigation outcomes, while we examine green technology transfer. Second, they study carbon taxes on the production of energy; by contrast, we focus on emission permits on the production of dirty goods.[5] Additionally, carbon taxes are exogenous in their paper; however, we allow endogenous and optimal choices of emission permits by countries.

Many papers have investigated green technology transfer across countries through different channels, such as international joint ventures or FDI (Abe and Zhao, 2005; Ma and Yomogida, 2021), licensing (Qiu and Yu, 2009; Iida and Takeuchi, 2011; Asano and Matsushima, 2014), and government aid or subsidy (Helm and Pichler, 2015; Nimubona and Rus, 2015). In our analysis, green technology transfer is modeled as the developed country's investment in green technology (e.g., renewable energy) in the developing country, which eventually decreases the emissions per unit of production there.[6]

In the broader context, our study also contributes to the literature on linkages between emission permit markets. Previous papers focus on the bilateral linkages between permit markets, which enable international emissions trading of all the permits from both countries. Recent examples include Antoniou and Kyriakopoulou (2019), Doda et al. (2019), Holtsmark and Midttømme (2021), Cheng (2024), Ishikawa et al. (2024) and Tsakiris et al. (2024). By contrast, our study analyzes the unilateral linkage between permit markets, in which case ITMO from the developing country can only be used and traded domestically in the developed country. Importantly, none of these papers examine international transfers of green technology.

The remainder of this paper is organized as follows. Section 2 introduces the basic setup of the model. In Section 3, we study the BAU scenario, without the implementation of GTT and ITMO. Section 4 introduces GTT and ITMO into the model, exploring their impacts on the results outlined in Section 3. Emission permits are exogenously given in Sections 3 and 4. In Section 5, we relax this assumption and scrutinize how the developed and developing countries decide on their levels of emission permits non-cooperatively. Section 6 discusses the assumptions of our model. Section 7 concludes the paper.

2 Basic model

There are two countries, a developed country, referred to as Home ("H"), and a developing country, referred to as Foreign ("F"). Each country has a continuum of polluting industries, denoted by $z \in [0, 1]$, with a single firm in each industry.[7] All the industries are symmetric. In each industry z, firms from the two countries produce homogeneous goods z with identical fixed and marginal

[5] For the comparison of carbon taxes and emission permits in an open economy, please refer to Kiyono and Ishikawa (2013), Eichner and Pethig (2015, 2019), Ishikawa and Okubo (2017) and Lai (2022).

[6] Alternatively, green technology transfer can be interpreted as licensing. The developed country licenses its green technology to the developing country, and licensees in the developing country pay licensing fees using emission permits equivalent to carbon mitigation outcomes, rather than through royalties or fixed payments.

[7] Considering more than one firm in each industry would not affect our analysis.

costs, both of which are normalized to zero for simplicity. The markets in Home and Foreign are segmented, and firms engage in Cournot competition in each market. Preferences towards different goods from different industries are additively separable. The demand for goods z is the same between the two markets. Specifically, we assume a linear demand function:[8]

$$p_i(z) = a - X_i(z); \quad i \in \{H, F\}. \tag{1}$$

$p_i(z)$ is the consumer price of goods z in country i. $X_i(z) = \sum_{j\in\{H,F\}} x_{ji}(z)$ is country i's total demand for goods z. In the subscripts of x, the first and second letters denote the country of production and consumption, respectively. Specifically, $x_{ji}(z)$ represents the quantity of goods z produced in country j and consumed in country i. a is a parameter.

Carbon emissions are generated during the production process of goods. In each industry z, the firm in Home employs a greener technology than the firm in Foreign does. Therefore, the emissions per unit of production in Home, denoted by $k_H(z)$, are lower than that in Foreign, denoted by $k_F(z)$. We assume that the environmental technology is the same across different industries, i.e., $k_H(z) = k_H$ and $k_F(z) = k_F$, with $0 < k_H = k < k_F = 1$. To control emissions, countries issue emission permits in their domestic permit markets. Each unit of carbon emissions requires one unit of permits for compliance. Permit markets are perfectly competitive and all the permits are auctioned off to the domestic firms. The permit price is endogenously determined by the interplay of supply and demand in each permit market. The permit quantities and prices in Home and Foreign are denoted by E_H, t_H, E_F and t_F, respectively. Emission permits are exogenously given and fixed in Sections 3 and 4 but are endogenous in Section 5.

Before proceeding, we make a remark on our model setup. We extend the conventional international duopoly model (e.g., Greaker, 2003; Ulph and Ulph, 2007), by incorporating a continuum of symmetric industries. This approach addresses two primary issues inherent in the traditional model. First, it resolves the inconsistency problem commonly observed in imperfect competition models with vertically related markets (e.g., Ishikawa and Spencer, 1999). Specifically, in our analysis, firms act as oligopolists in the goods markets but are price takers in the permit markets. Second, this approach clarifies how the permit price is determined and affected. In the conventional international duopoly model, the existence of only one firm per country implies that the impact of environmental policies on a firm's demand for permits, and consequently on the permit price, is negligible. As a result, the permit price tends to be fixed. Assuming a continuum of industries ensures that firms are large in their own industry and goods market but are small in the economy-wide permit mar-

[8] This demand function can be derived from a quasilinear and quadratic utility function: $U_i = \int_0^1 \left[aX_i(z) - X_i(z)^2/2\right] dz + A_i$, where A_i represents the consumption of the numeraire good, which is assumed to be clean. Note that the assumption of linear demands is adopted for clarity and not crucial for our main findings.

ket, thereby resolving the inconsistency problem (e.g., Yanase and Kamei, 2022). This assumption also allows environmental policies to influence a large number of firms across various industries. Therefore, it is reasonable to consider that the permit prices are endogenously determined by the market rather than being fixed. While there are alternative methods to address these concerns, our approach is preferred for its tractability and for yielding qualitatively the same results as those of the conventional international duopoly model.[9]

Each country's welfare is defined as the sum of consumer surplus (CS), firm profits (π), and permit revenues (PR), minus environmental damage from global emissions (D):

$$W_i = \int_0^1 CS_i(z)dz + \int_0^1 \pi_i(z)dz + PR_i - D_i(E_H + E_F), \quad i \in \{H, F\}. \tag{2}$$

When E_H and E_F are endogenous, countries have an incentive to collaborate through green technology transfer (GTT) and international transfer of mitigation outcomes (ITMO) to decrease global emissions. However, even when they are exogenously given, countries may still have an incentive to do so to improve consumer surplus, firm profits and permit revenues.[10]

The process of GTT and ITMO unfolds as follows. First, the developed country Home transfers its green technology to the developing country Foreign, so that Foreign firms can employ it for production.[11] Second, the two countries and a body designated by the Conference of the Parties to the Paris Agreement examine the impact of GTT on the developing country's emissions. If emissions decrease compared with the BAU case, Foreign transfers a quantity of permits equal to the mitigated outcomes to Home. Home acknowledges the validity of transferred emission permits and sells them in its domestic permit market. If Foreign emissions increase because of GTT, ITMO cannot be certified and implemented.

[9] Many studies have addressed the inconsistency problem by considering market power in the permit market, such as Wirl (2009), Lange (2012), Antoniou et al. (2014) and Haita (2014). However, this assumption is becoming increasingly implausible, as more and more industries and producers are regulated by the emissions trading systems, thereby diluting the market power of any single producer. For instance, over 12,000 plants are currently regulated by the EU ETS (Makridou et al., 2019). Another potential solution is adopting a monopolistic competition model, as seen in Ishikawa and Okubo (2017) and Cheng (2024). However, welfare analysis would become intractable in the presence of asymmetric countries.

[10] In our analysis, GTT between Home and Foreign does not occur without the collaboration through ITMO mechanism. According to the Paris Agreement, ITMO certification is contingent upon emission reductions being deemed *additional* to the benchmark (or BAU) case. Therefore, if GTT has already occurred under BAU, the ITMO mechanism is not applicable, as emission reductions have been realized.

[11] Taking into account the costs of adopting the green technology would not affect our analysis. See Section 6.3 for further discussion.

3 Business as usual

In this benchmark scenario, firms produce goods with their own technologies. In each industry z, a firm's profit is equal to its sales profit in the two markets minus its purchase of emission permits:

$$\pi_i(z) = \sum_{j\in\{H,F\}} p_j(z)x_{ij}(z) - t_i k_i \sum_{j\in\{H,F\}} x_{ij}(z); \quad i \in \{H, F\}. \tag{3}$$

Solving the two firms' profit maximization problems simultaneously gives each firm's supply of goods z to the two markets:

$$x_{HH}(z) = x_{HF}(z) = \frac{a - 2kt_H + t_F}{3}; \quad x_{FF}(z) = x_{FH}(z) = \frac{a - 2t_F + kt_H}{3}. \tag{4}$$

Because industries are symmetric and the mass of them is one with $z \in [0, 1]$, the right-hand sides of the respective two expressions above are also firms' total supply for each market. In the following analysis, we suppress z when it does not cause any confusion.

In each domestic permit market, firms' total demand for emission permits is $k_i \sum_{j\in\{H,F\}} x_{ij}$, while country i's supply of emission permits is E_i. With the market clearing condition of permits, i.e., $k_i \sum_{j\in\{H,F\}} x_{ij} = E_i$, we derive the permit prices in both countries:

$$t_H = \frac{1}{k}\left(a - \frac{E_H}{k} - \frac{E_F}{2}\right); \quad t_F = a - E_F - \frac{E_H}{2k}. \tag{5}$$

A country's level of emission permits affects not only its own permit price but also the other country's permit price. For instance, as E_H increases, total supply of permits in Home increases, lowering the permit price there. This in turn induces Home firms to produce more. Since goods are perfect substitutes in each industry, Foreign firms tends to produce less and their demand for emission permits decreases. Less demand in the permit market leads to a lower permit price in Foreign.

Firms' outputs and profits, consumer prices and consumer surplus in equilibrium are obtained as follow.

$$x_{HH} = x_{HF} = \frac{E_H}{2k}; \quad x_{FF} = x_{FH} = \frac{E_F}{2}; \tag{6}$$

$$p_H = p_F = a - \frac{E_H}{2k} - \frac{E_F}{2}; \tag{7}$$

$$CS_H = CS_F = \int_0^{X_H} p_H(x)dx - p_H X_H = \frac{1}{8}\left(\frac{E_H}{k} + E_F\right)^2; \tag{8}$$

$$\pi_H = 2p_H x_{HH} - 2t_H k_H x_{HH} = \frac{1}{2}\left(\frac{E_H}{k}\right)^2; \quad \pi_F = 2p_F x_{FF} - 2t_F k_F x_{FF} = \frac{1}{2}(E_F)^2. \tag{9}$$

Permit revenues in Home and Foreign are

$$PR_H = t_H E_H = \frac{E_H}{k}\left(a - \frac{E_H}{k} - \frac{E_F}{2}\right); \quad PR_F = t_F E_F = E_F\left(a - E_F - \frac{E_H}{2k}\right). \tag{10}$$

Each country's welfare is then given by

$$W_i = \int_0^{X_i} p_i(x)dx - p_i X_i + p_H x_{iH} + p_F x_{iF} - D_i(E_H + E_F), \quad i \in \{H, F\}. \tag{11}$$

The third and fourth terms on the right-hand side are firms' sales profits on the Home and Foreign markets which are the sum of firm profits and permit revenues.

4 International transfer of mitigation outcomes

In this section, we investigate how GTT affects firms' production, emissions and profits and whether ITMO can be certified and implemented based on GTT. We also explore how GTT and ITMO affect each country's and global welfare.

Suppose that Home transfers its green technology to Foreign and receives Φ units of carbon mitigation outcomes in return. Then, the supply of emission permits in Home and Foreign becomes $E_H + \Phi$ and $E_F - \Phi$, respectively. The profit functions for firms in the two countries under GTT and ITMO are similar to that in equation (3), except that the emissions per unit of production in Foreign become k. Each country's supply of goods to the two markets is obtained as[12]

$$\hat{x}_{HH} = \hat{x}_{HF} = \frac{a - 2k\hat{t}_H + k\hat{t}_F}{3}; \quad \hat{x}_{FF} = \hat{x}_{FH} = \frac{a - 2k\hat{t}_F + k\hat{t}_H}{3}. \tag{12}$$

The total demand for emission permits is $k(\hat{x}_{HH} + \hat{x}_{HF})$ for Home firms and $k(\hat{x}_{FF} + \hat{x}_{FH})$ for Foreign firms.

The market clearing conditions of permits are $k(\hat{x}_{HH} + \hat{x}_{HF}) = E_H + \Phi$ in Home and $k(\hat{x}_{FF} + \hat{x}_{FH}) = E_F - \Phi$ in Foreign. Solving them gives

$$\hat{t}_H = \frac{a}{k} - \frac{E_H}{k^2} - \frac{E_F}{2k^2} - \frac{\Phi}{2k^2}; \quad \hat{t}_F = \frac{a}{k} - \frac{E_H}{2k^2} - \frac{E_F}{k^2} + \frac{\Phi}{2k^2}. \tag{13}$$

Not surprisingly, permit prices are dependent on Φ. This indicates that we cannot determine the specific permit prices because there are three unknows, $\hat{t}_H$, $\hat{t}_F$ and Φ, but only two market clearing conditions. However, the total consumption of goods in each country is always equal to half of the

[12]Variables with hats denote those under the ITMO regime.

global production level, regardless of Φ:

$$\hat{X}_H = \hat{X}_F = \frac{E_H + E_F}{2k}. \tag{14}$$

As a result, the price of goods is also irrelevant to Φ:

$$\hat{p}_H = \hat{p}_F = a - \frac{E_H + E_F}{2k}. \tag{15}$$

For further analysis, we assume that Φ is determined so that the permit price in Foreign remains the same under BAU and under GTT and ITMO, i.e., $\hat{t}_F = t_F$.[13] With this assumption, the quantity of ITMO and the permit price in Home are derived as

$$\Phi = (1-k)\left[E_H + 2(1+k)E_F - 2ka\right]; \tag{16}$$

$$\hat{t}_H = \frac{2-k}{k}a - \frac{3-k}{2k^2}E_H - \frac{3-2k^2}{2k^2}E_F. \tag{17}$$

Note that $\frac{\partial \Phi}{\partial E_F} > 0$ and $\frac{\partial \Phi}{\partial E_H} > 0$ hold. A larger E_F means a larger production base in Foreign under BAU. Therefore, GTT tends to decrease Foreign's emissions more. This in turn leads to more permits transferred to Home. An increase in E_H also increases Φ through the substitution effect of dirty goods. More permits in Home induce Home firms to produce more and Foreign firms to produce less. Less production in Foreign generates fewer emissions and more ITMO. Because ITMO increases the total supply of emission permits in Home, the permit price decreases there, i.e., $\hat{t}_H < t_H$.[14] It is likely that ITMO makes emission permits in Home unbinding. However, this case does not comply with the Paris Agreement which encourages all its parties to control emissions. To ensure $\hat{t}_H > 0$, we assume $a > \frac{3-k}{2k(2-k)}E_H + \frac{3-2k^2}{2k(2-k)}E_F \equiv a_1$. Similar to that under BAU, an increase in a country's emission permits decreases the permit prices in both countries.

At equilibrium, firms' supply of goods to the two countries can be expressed as

$$\hat{x}_{HH} = \hat{x}_{HF} = \frac{E_H + \Phi}{2k}; \quad \hat{x}_{FF} = \hat{x}_{FH} = \frac{E_F - \Phi}{2k}. \tag{18}$$

An increase in Home's emission permits increases Home firms' production but decreases Foreign firms' production due to an increase in ITMO. An increase in Foreign's emission permits also increases Home firms' production because more permits in Foreign mean international transfers of more mitigation outcomes. However, the effect of Foreign's emission permits on Foreign firms'

[13]Mathematically, this assumption enables us to solve the model analytically because there are three conditions now. In reality, Home and Foreign may negotiate the division of carbon mitigation outcomes and transfer only a proportion of them. In this case, Foreign permit price under ITMO can be different from that under BAU. We discuss how the bargaining power over ITMO affects our results in Section 6.

[14]See Appendix A for the proof.

production can be positive or negative, depending on the values of k:

$$\frac{\partial(\hat{x}_{FF}+\hat{x}_{FH})}{\partial E_F}=\frac{\partial(E_F-\Phi)/k}{\partial E_F}=\frac{1}{k}-\frac{1}{k}\frac{\partial\Phi}{\partial E_F}. \tag{19}$$

As E_F increases, on the one hand, Foreign firms tend to produce more because they can purchase more permits with a lower permit price; on the other hand, the quantity of ITMO increases, which allows Home firms to produce more and crowds out Foreign firms' market shares. If $\sqrt{2}/2<k<1$, the former effect dominates and Foreign firms produce more goods with a larger E_F. However, if $0<k<\sqrt{2}/2$, the latter effect dominates and a higher level of emission permits in Foreign decreases its firms' production. The negative effect of E_F on Foreign firms' production through ITMO is crucial for our analysis. As shown below in Section 5, Foreign has an incentive to issue fewer permits to mitigate this negative effect.

For ITMO to be successfully certified and implemented, GTT needs to decrease Foreign emissions. That is, Foreign firms' emissions with GTT, given by $k(\hat{x}_{FF}+\hat{x}_{FH})$, should be lower than their emissions under BAU, given by E_F, so that $\Phi>0$ holds. Note that GTT decreases Foreign firms' emissions per unit of production from 1 to k. Therefore, how GTT affects Foreign firms' total emissions depends on how it affects their production:

$$(\hat{x}_{FF}+\hat{x}_{FH})-(x_{FF}+x_{FH})=2(1-k)\left(a-\frac{1}{2k}E_H-\frac{1+2k}{2k}E_F\right). \tag{20}$$

GTT may increase or decrease Foreign firms' production, depending on the parameter values. If k is sufficiently small and E_F is sufficiently large so that $a<\frac{1}{2k}E_H+\frac{1+2k}{2k}E_F\equiv a_2$, GTT decreases Foreign firms' production. Intuitively, a small k means that Foreign firms' environmental cost would decrease significantly with the green technology, which in turn leads to more ITMO. Similarly, a larger E_F creates more ITMO for Home firms in the developed country. Both of these effects cause less production of Foreign firms. In this case, GTT decreases Foreign emissions and a positive quantity of carbon mitigation outcomes is transferred to Home. However, if $a>a_2$, GTT increases Foreign firms' production. If the increase in the production dominates the decrease in the emissions per unit of production, GTT increases Foreign firms' and thus Foreign's emissions, i.e.,

$$k(\hat{x}_{FF}+\hat{x}_{FH})>E_F;\quad\Longleftrightarrow\quad a>\frac{1}{2k}E_H+\frac{1+k}{k}E_F\equiv a_3. \tag{21}$$

Lemma 1 *GTT decreases Foreign's emissions and thus ITMO is successfully certified and implemented if* $a<a_3$.

To continue our analysis, we assume $a_1<a<a_3$ which implies that market sizes in the two countries are neither too large nor too small. To ensure $a_1<a_3$, we further assume $E_F>$

$\frac{1}{1+2k}E_H$. With the assumptions on a, we can show that $\frac{\partial \Phi}{\partial k} < 0$ holds in equation (16). An international transfer of a greener technology from Home to Foreign decreases Foreign's emissions more significantly, which leads to less demand for emission permits in Foreign and a larger quantity of ITMO.

Home and Foreign firms' profits under GTT and ITMO are

$$\hat{\pi}_H = 2(\hat{x}_{HH})^2 = 2\left(\frac{E_H + \Phi}{2k}\right)^2; \quad \hat{\pi}_F = 2(\hat{x}_{FF})^2 = 2\left(\frac{E_F - \Phi}{2k}\right)^2. \tag{22}$$

GTT and ITMO always increase Home firms' total production and profits. However, Foreign firms may suffer from them because they may decrease Foreign firms' total production, as discussed in the paragraph below equation (20).

Consumer surplus and permit revenues in each country are given by:

$$\widehat{CS}_H = \widehat{CS}_F = \int_0^{\hat{X}_i} \hat{p}_i(x)dx - \hat{p}_H \hat{X}_H = \frac{1}{8}\left(\frac{E_H}{k} + \frac{E_F}{k}\right)^2; \tag{23}$$

$$\widehat{PR}_H = \hat{t}_H(E_H + \Phi); \quad \widehat{PR}_F = \hat{t}_F(E_F - \Phi). \tag{24}$$

Comparing equations (23) and (24) with equations (8) and (10), we observe that GTT and ITMO increase consumer surplus in both countries and decrease permit revenues in Foreign. The effect on Home permit revenues is generally ambiguous because GTT and ITMO decrease the permit price but increase the amount of permits there.

Each country's welfare under ITMO takes the same form as that in equation (11):

$$\widehat{W}_i = \int_0^{\hat{X}_i} \hat{p}_i(x)dx - \hat{p}_i\hat{X}_i + \hat{p}_H\hat{x}_{iH} + \hat{p}_F\hat{x}_{iF} - \hat{D}_i(E_H + E_F), \quad i \in \{H, F\}. \tag{25}$$

We now compare each country's and global welfare under BAU and ITMO. Because global emissions $E_H + E_F$ are exogenously given, environmental damage remains the same in the two cases. Therefore, the impact of GTT and ITMO on welfare depends on their effect on consumer surplus and firms' sales profits. According to our analysis above, GTT and ITMO increase consumer surplus in each country, increase firm profits in Home and decrease the permit revenues in Foreign; however, their effects on Foreign firms' profits and Home permit revenues are ambiguous. Therefore, their effects on firms' sales profits and thus each country's welfare are also ambiguous. Or in other words, either Home or Foreign may lose from GTT and ITMO. To see how it happens, we give some specific examples below.

Note that in equation (25), only $\hat{x}_{ii}$ is dependent on the quantity of ITMO, while $\hat{X}_i$ and $\hat{p}_i$ are independent of it, as indicated in equations (14) and (15). An increase in Φ increases total production and welfare in Home but decreases total production and welfare in Foreign. We now consider an extreme case where GTT achieves no carbon mitigation outcomes, i.e., $\Phi = 0$, which happens when $a = a_3$. In this case, GTT decreases Home firms' but increases Foreign firms' sales profits because GTT makes Foreign firms more competitive in the markets. Therefore, Foreign always benefits from GTT, i.e., $(\widehat{W}_F - W_F)\Big|_{\Phi=0} = \frac{1-k}{4k^2}E_H E_F + \frac{5(1-k^2)}{8k^2}{E_F}^2 > 0$. The difference of Home's welfare under GTT and ITMO and under BAU is

$$(\widehat{W}_H - W_H)\Big|_{\Phi=0} = \frac{1-k}{8k^2}E_F\left[(1+k)E_F - E_H\right]. \tag{26}$$

If the level of emission permits is sufficiently high in Foreign, Home can also benefit from GTT because the increase in its consumer surplus caused by GTT dominates the decrease in Home firms' sales profits. However, if E_F is sufficiently small, Home loses from GTT as the decrease in Home firms' sales profits dominates.

In the second extreme episode, we assume that ITMO is sufficiently large so that the permit price in Home decreases to 0, i.e., $\Phi = \frac{1-k}{2-k}[(1+2k)E_F - E_H] \equiv \overline{\Phi}$, which happens when $a = a_1$. Our first example shows that Home tends to benefit from GTT and ITMO when the level of permits is sufficiently high in Foreign. Therefore, we further assume $E_F = 2E_H$ to ensure that E_F is sufficiently large. In this case, Home always benefits from GTT and ITMO, as we have imaged:

$$(\widehat{W}_H - W_H)\Big|_{\Phi=\overline{\Phi}, E_F=2E_H} = \frac{1-k}{8k^2(2-k)^2}{E_H}^2(12 + 72k - 60k^2) > 0. \tag{27}$$

The difference of Foreign welfare under GTT and ITMO and under BAU is now given by

$$(\widehat{W}_F - W_F)\Big|_{\Phi=\overline{\Phi}, E_F=2E_H} = \frac{1-k}{2k^2(2-k)^2}{E_H}^2(17 - 32k - 10k^2 + 21k^3), \tag{28}$$

which is positive when k is sufficiently small and negative when k is sufficiently large. Therefore, Foreign can also lose from GTT and ITMO.

Although GTT and ITMO may not improve both countries' welfare at the same time, they always improve global welfare. To understand the intuition behind this finding, we obtain global welfare in the two cases with equations (11) and (25):

$$W_H + W_F = \left[\int_0^{X_H} p_H(x)dx + \int_0^{X_F} p_F(x)dx\right] - (D_H + D_F); \tag{29}$$

$$\widehat{W}_H + \widehat{W}_F = \left[\int_0^{\hat{X}_H} \hat{p}_H(x)dx + \int_0^{\hat{X}_F} \hat{p}_F(x)dx\right] - \left(\hat{D}_H + \hat{D}_F\right). \tag{30}$$

On the right-hand sides of both equations, the second term is the sum of environmental damage in

Home and Foreign, which remains the same under BAU and ITMO because the global level of emission permits is exogenously given. The first term represents the sum of the two countries' consumer surplus and firms' sales profits, which reduces to the sum of these countries' gross consumption benefits. This term is only dependent on and increasing in a country's total consumption. Because GTT and ITMO increase total consumption in each country, i.e., $\hat{X}_H = \hat{X}_F > X_H = X_F$ holds, global welfare increases.

We conclude our findings in the following proposition:[15]

Proposition 1 *Suppose emission permits are exogenously given and $a_1 < a < a_3$. GTT and ITMO may harm either country's welfare. However, they always enhance global welfare.*

5 Endogenous emission permits

In this section, we investigate how Home and Foreign choose their levels of emission permits non-cooperatively in the long run. We assume that environmental damage is the same between the two countries and is increasing and convex in the global levels of emissions, i.e., $D_H = D_F = \frac{1}{2}\delta(E_H + E_F)^2$, where δ is a coefficient, measuring a country's evaluation of environmental damage.[16]

In the BAU case, the best response of each country, given the other country's choices, is obtained from the first-order condition where marginal benefit (MB) from emission permits is equal to marginal damage from them:

$$\underbrace{-p_i' X_i \frac{\partial X_i}{\partial E_i} + x_{iH} p_H' \frac{\partial X_H}{\partial E_i} + x_{iF} p_F' \frac{\partial X_F}{\partial E_i} + p_H \frac{\partial x_{iH}}{\partial E_i} + p_F \frac{\partial x_{iF}}{\partial E_i}}_{MB_i} = D_i', \quad i \in \{H, F\}. \tag{31}$$

Solving the two best response functions simultaneously yields the equilibrium emission permits:

$$E_H^* = \frac{2ak[1 + 2(1-k)\delta]}{2 + (3k^2 - 2k + 3)\delta}; \quad E_F^* = \frac{2a[1 - 2k(1-k)\delta]}{2 + (3k^2 - 2k + 3)\delta}; \tag{32}$$

where $0 < \delta < \frac{1}{4k(1-k)}$.[17] Note that Home does not necessarily issue fewer emission permits than Foreign at equilibrium. To understand the intuition behind this finding, we take the first derivatives of E_H^* and E_F^* with respect to δ:

$$\frac{\partial E_H^*}{\partial \delta} = \frac{2ak(1+k)(1-3k)}{[2 + (3k^2 - 2k + 3)\delta]^2}; \quad \frac{\partial E_F^*}{\partial \delta} = \frac{-2a(3-k)(1+k)}{[2 + (3k^2 - 2k + 3)\delta]^2} < 0. \tag{33}$$

[15]See Appendix B for the proof.

[16]Our main results would not change even if Home and Foreign have different evaluations of environmental damage. As illustrated below, our focus is on the comparison of global emissions under BAU and ITMO, which depends on the sum of marginal environmental damage in the two countries.

[17]The assumption of $\delta < \frac{1}{4k(1-k)}$ arises from our assumption of $E_F > \frac{1}{1+2k} E_H$.

When δ is sufficiently small so that environmental damage is negligible, $E_H^* < E_F^*$ holds because Home owns a greener technology and hence can produce the same level of goods with fewer permits. As δ becomes larger, Foreign issues fewer emission permits to decrease its environmental damage. If $k > \frac{1}{3}$, a larger δ also induces Home to issue fewer permits. However, the decrease of Home permits is slower than that of Foreign permits, i.e., $\frac{\partial E_H^*}{\partial \delta} > \frac{\partial E_F^*}{\partial \delta}$, because of the usage of a greener technology in Home. If $k < \frac{1}{3}$, a larger δ induces Home to issue more permits. This is because when the technology is sufficiently clean, in response to the decrease in Foreign permits, Home has an incentive to produce more by issuing more permits. Doing so increases consumer surplus and firms' sales profits at the expense of a relatively small increase in environmental damage. Eventually, when δ is sufficiently large, i.e., $\frac{1}{4k} < \delta < \frac{1}{4k(1-k)}$, Home issues more permits than Foreign.

Under BAU, the global level of emission permits at equilibrium is given by

$$E_H^* + E_F^* = \frac{2(1+k)a}{2 + (3k^2 - 2k + 3)\delta}. \tag{34}$$

Similarly, we derive the best response function for each country under GTT and ITMO:

$$\underbrace{-\hat{p}_i'\hat{X}_i \frac{\partial \hat{X}_i}{\partial E_i} + \hat{x}_{iH}\hat{p}_H' \frac{\partial \hat{X}_H}{\partial E_i} + \hat{x}_{iF}\hat{p}_F' \frac{\partial \hat{X}_F}{\partial E_i} + \hat{p}_H \frac{\partial \hat{x}_{iH}}{\partial E_i} + \hat{p}_F \frac{\partial \hat{x}_{iF}}{\partial E_i}}_{\widehat{MB}_i} = \hat{D}_i', \quad i \in \{H, F\}. \tag{35}$$

With $\hat{X}_H + \hat{X}_F = 2(\hat{x}_{HH} + \hat{x}_{FF})$, we sum both sides of above equations with $i \in \{H, F\}$ to obtain the global level of emission permits at equilibrium:[18]

$$\hat{E}_H^* + \hat{E}_F^* = \frac{2k(1 - k + 2k^2)a}{1 - k + 2k^2 + 4k^2\delta}. \tag{36}$$

Comparing the equilibrium global emission permits in the BAU and ITMO cases, we have the following proposition:[19]

Proposition 2 *Suppose emission permits are determined non-cooperatively by countries. GTT and ITMO always decrease global emissions.*

The intuition behind this proposition lies in the relationship between the sums of countries' marginal benefits and marginal damage. Under BAU and ITMO, for $i \in \{H, F\}$ in equations (31) and (35), we sum up both sides of the first order conditions to get

$$\text{BAU:} \quad MB_H + MB_F = D_H' + D_F'; \tag{37}$$

[18] The specific levels of equilibrium permits in each country and the corresponding quantity of ITMO are obtained in Appendix C.

[19] See Appendix C for the proof.

$$\text{ITMO:} \quad \widehat{MB}_H + \widehat{MB}_F = \hat{D}'_H + \hat{D}'_F. \tag{38}$$

The sums of marginal benefits on the left-hand sides are decreasing in each country's emission permits, while the sums of marginal damage on the right-hand sides are increasing in them. GTT and ITMO do not affect each country's marginal damage from emissions because only global level of emissions matters. We now investigate how they affect the two countries' marginal benefits.[20] First of all, both Home's and Foreign's marginal benefits from consumer surplus are higher under GTT and ITMO: $-\hat{p}'_i \hat{X}_i \frac{\partial \hat{X}_i}{\partial E_i} > -p'_i X_i \frac{\partial X_i}{\partial E_i}$, $i \in \{H, F\}$. Therefore, both countries have an incentive to issue more emission permits to increase their consumer surplus.

How GTT and ITMO affect the marginal benefits from Home firms' sales profits is ambiguous. Their effect on the marginal benefits from Foreign firms' sales profits can be expressed as

$$\frac{\partial(\hat{p}_F \hat{x}_{FF} + \hat{p}_H \hat{x}_{FH})}{\partial E_F} - \frac{\partial(p_F x_{FF} + p_H x_{FH})}{\partial E_F} = -\frac{1-k}{k}\left(\frac{1}{2k}E_H + \frac{1+k}{k}E_F - a\right) + \frac{\Phi}{2k^2} - \frac{1}{k}\hat{p}_F \frac{\partial \Phi}{\partial E_F}. \tag{39}$$

On the right-hand side, the first term captures the effect of GTT. This term is negative because GTT improves the production efficiency of Foreign firms, prompting Foreign to issue fewer permits. The second term is positive, as Foreign must issue more permits, given that some are transferred to Home. The third term reflects the negative effect of ITMO on Foreign firms: an increase in E_F leads to a larger quantity of ITMO, which is harmful to Foreign firms. As a result, Foreign has an incentive to issue fewer emission permits to mitigate the decrease in its firms' sales profits. Since the first and second terms offset each other, the overall effect of GTT and ITMO always results in a reduction in the marginal benefits of Foreign firms' sales profits.

Consequently, GTT and ITMO decrease the sum of marginal benefits, i.e., $\widehat{MB}_H + \widehat{MB}_F < MB_H + MB_F$. This implies that either or both countries would adjust the levels of emission permits to decrease the global level of them. As a result, global emissions are lower under GTT and ITMO.

Last, we examine how GTT and ITMO affect global welfare. On the one hand, they decrease the global level of permits, mitigating environmental damage from global emissions, compared with the BAU case. On the other hand, fewer permits may lead to less consumption and lower consumer surplus, despite that GTT improves production efficiency in Foreign. However, we find that the mitigation of environmental damage outweighs the potential loss in consumption. Therefore, GTT and ITMO ultimately enhance global welfare in the non-cooperative game.[21]

Proposition 3 *Suppose emission permits are determined non-cooperatively by countries. GTT and*

[20] See Appendix C for detailed calculations.
[21] See Appendix E for the proof.

ITMO always improve global welfare.

6 Discussions

6.1 Bargaining over ITMO

In the main part, we assumed that Foreign transfers a *full* quantity of carbon mitigation outcomes Φ, which leads to $\hat{t}_F = t_F$.[22] However, in practice, it is likely that Home and Foreign bargain over ITMO and Foreign transfers only a portion of Φ, thereby reducing the permit price in Foreign.[23] In this section, we show how our results would change in the presence of bargaining over ITMO.

We denote by β the share of Φ that is reserved in Foreign, where $0 \leq \beta \leq 1$. β and $1-\beta$ represent Foreign's and Home's bargaining power over ITMO, respectively. The quantity of transferred carbon mitigation outcomes from Foreign to Home is $(1-\beta)\Phi$. Each firm's supply for the two countries is now given by

$$\tilde{x}_{HH} = \tilde{x}_{HF} = \hat{x}_{HH} - \frac{\beta\Phi}{2k}; \quad \tilde{x}_{FF} = \tilde{x}_{FH} = \hat{x}_{FF} + \frac{\beta\Phi}{2k}, \tag{40}$$

with $\Phi = E_F - k(\hat{x}_{FF} + \hat{x}_{FH})$, as defined in the main analysis. The total supply of goods and the goods price in each country are irrelevant to β and Φ: $\tilde{X}_H = \tilde{X}_F = \frac{E_H+E_F}{2k}$, $\tilde{p}_H = \tilde{p}_F = a - \frac{E_H+E_F}{2k}$, which are the same as those in the main part. Therefore, consumer surplus also remains the same. As shown in equations (29) and (30), global welfare is also irrelevant to β and Φ. Therefore, when emission permits are exogenously given, GTT and ITMO still increase global welfare.

However, firms' net profits and sales profits in each country's welfare are dependent on how carbon mitigation outcomes are divided, as shown in equations (22) and (25). More emission permits lead to more production and thus more profits and welfare. Therefore, a higher level of β benefits Foreign firms and Foreign but harms Home firms and Home. When emission permits are determined non-cooperatively under GTT and ITMO, the best response function for each country, in contrast to equation (35), is now given by:

$$-\hat{p}_i'\hat{X}_i\frac{\partial \hat{X}_i}{\partial E_i} + \tilde{x}_{iH}\hat{p}_H'\frac{\partial \hat{X}_H}{\partial E_i} + \tilde{x}_{iF}\hat{p}_F'\frac{\partial \hat{X}_F}{\partial E_i} + \hat{p}_H\frac{\partial \tilde{x}_{iH}}{\partial E_i} + \hat{p}_F\frac{\partial \tilde{x}_{iF}}{\partial E_i} = \hat{D}_i', \quad i \in \{H, F\}. \tag{41}$$

Only the terms related to $\tilde{x}_{iH}$ and $\tilde{x}_{iF}$ on the left-hand side are affected by β, while other terms

[22] A quantity of ITMO exceeding Φ would increase the permit price in Foreign, raising its environmental costs. However, the purpose of GTT and ITMO is to facilitate participating countries in achieving their emission mitigation targets more easily. More stringent environmental regulations would contradict this goal, which is why we refer to Φ as the *full* quantity of ITMO.

[23] For instance, in JCM projects, Japan and its partners share the emission reduction outcomes.

remain the same. Summing up both sides of above equations with $i \in \{H, F\}$ yields

$$2\hat{p}_H \left(\frac{\partial \tilde{x}_{HH}}{\partial E_H} + \frac{\partial \tilde{x}_{FF}}{\partial E_F} \right) = \hat{D}'_H + \hat{D}'_F. \tag{42}$$

With

$$\begin{aligned} \frac{\partial \tilde{x}_{HH}}{\partial E_H} + \frac{\partial \tilde{x}_{FF}}{\partial E_F} &= \frac{\partial \hat{x}_{HH}}{\partial E_H} + \frac{\partial \hat{x}_{FF}}{\partial E_F} + \frac{\beta}{2k} \left(1 - 2k \frac{\partial \hat{x}_{FF}}{\partial E_F} + 2k \frac{\partial \hat{x}_{FF}}{\partial E_H} \right) \\ &= \frac{1 - k + 2k^2 + \beta(1 + k - 2k^2)}{2k}, \end{aligned} \tag{43}$$

we derive the global level of emission permits at the equilibrium under GTT and ITMO in the presence of Foreign's bargaining power:

$$\tilde{E}^*_H + \tilde{E}^*_F = \frac{2k[1 - k + 2k^2 + \beta(1 + k - 2k^2)]a}{1 - k + 2k^2 + \beta(1 + k - 2k^2) + 4k^2\delta}. \tag{44}$$

The equilibrium global level of permits is increasing in Foreign's bargaining power β. With $\beta = 1$, we have

$$\left(\tilde{E}^*_H + \tilde{E}^*_F \right) \Big|_{\beta=1} = \frac{2ka}{1 + 2k^2\delta}, \tag{45}$$

which is always lower than the global level of permits at the equilibrium under BAU if $\delta < \min\left(\frac{1}{4k(1-k)}, \frac{1}{k(3-k)} \right)$. Therefore, as long as δ is sufficiently small, GTT and ITMO always decrease global emissions in the non-cooperative game, regardless of the bargaining power over ITMO. Proposition 2 holds. However, if $\frac{1}{3} < k < 1$ and $\frac{1}{k(3-k)} < \delta < \frac{1}{4k(1-k)}$, then $\left(\tilde{E}^*_H + \tilde{E}^*_F \right) \Big|_{\beta=1} > E^*_H + E^*_F$ holds. In this case, GTT and ITMO can increase global emissions when Foreign has a sufficiently large bargaining power over ITMO.

Proposition 4 *If Foreign has a sufficiently large bargaining power over ITMO, then GTT and ITMO can increase global emissions when emission permits are determined non-cooperatively by the countries.*

6.2 Fixed permit prices

In the main analysis, we assumed that GTT and ITMO affect the production and demand for emission permits in a continuum of industries. Therefore, permit prices are also affected and endogenously determined in the permit markets. However, if only a few firms participate in the projects of GTT and ITMO, then the change in demand and supply of permits is negligible in the economy-wide permit markets and permit prices would not change. In this section, we investigate how our results are modified if permit prices are fixed, given by t_H in Home and t_F in Foreign.

Here, we assume that there is only one firm in each country.

Under BAU, each firm's supply for the two markets is derived as $x_{HH} = x_{HF} = (a - 2kt_H + t_F)/3$ and $x_{FF} = x_{FH} = (a - 2t_F + kt_H)/3$, which are the same as those in the main part, except that t_H and t_F are now exogenously given. The two firms' emissions are $e_H = k(x_{HH} + x_{HF})$ and $e_F = x_{FH} + x_{FF}$. Consumer surplus, firm profits and permit revenues also take the same forms as those in the main part.

GTT from Home to Foreign decreases Foreign firm's environmental cost and thus increases its production and profits, i.e., $\hat{x}_{FF} = (a - 2kt_F + kt_H)/3 > x_{FF}$, $\hat{\pi}_F = 2(\hat{x}_{FF})^2 > \pi_F$. Foreign firm's emissions are $\hat{e}_F = k(\hat{x}_{FH} + \hat{x}_{FF})$. Similar to the main part, GTT has two opposing effects on Foreign firm's emissions. On the one hand, it decreases the emissions per unit of production; on the other hand, it increases total production in Foreign. Therefore, it is likely that GTT increases Foreign firm's and thus Foreign's total emissions, in which case ITMO would not be certified and implemented. To make sure that Foreign emissions decrease, we assume $\hat{e}_F < e_F$. Then, the quantity of ITMO is $\Phi = e_F - \hat{e}_F$. Home government sells these emission permits of ITMO to Home firm in the domestic permit market. For Home firm, its production decreases because Foreign firm's production increases, i.e., $\hat{x}_{HH} = (a - 2kt_H + kt_F)/3 < x_{HH}$. Therefore, GTT and ITMO decrease firm profits, emissions and permit revenues in Home. Consequently, global emissions and both countries' environmental damage decrease. Similar to the main part, GTT and ITMO increase both countries' consumer surplus and decrease Foreign permit revenues.

By investigating and comparing each country's welfare under BAU and ITMO, we find that Foreign always benefits from GTT and ITMO because its consumer surplus and sales profits increase while its environmental damage decreases. However, it is ambiguous how GTT and ITMO affect Home welfare because they decrease the sales profits there. Again, GTT and ITMO always increase global welfare as they increase total consumption of dirty goods and decrease environmental damage in both countries.

6.3 Costs of adopting green technology

We assumed that Foreign firms do not incur any cost when adopting the green technology under GTT and ITMO. However, introducing such costs would not alter the main findings of our analysis. First, the existence of a fixed cost, such as the expense of purchasing new equipment, does not affect firms' production decisions or countries' emission permit choices. Therefore, the effects of GTT and ITMO on emissions remain unchanged. However, with a fixed cost, Foreign firms and the Foreign country are more likely to lose from GTT and ITMO. Nevertheless, as long as the fixed cost is not sufficiently large, our conclusions regarding the welfare effects of GTT and ITMO remain valid.

Next, we consider the scenario where the adoption of green technology involves a marginal cost.

A marginal cost decreases Foreign firms' production and their demand for emission permits, which in turn tends to increase the quantity of ITMO. The increased ITMO allows Home firms to expand their production. As shown in equation (25), higher domestic production improves welfare, given each country's emission permits. As a result, Home benefits from the marginal cost, while Foreign loses from it. Global welfare, however, remains unchanged, as the marginal cost does not affect total consumption in each country. When emission permits are endogenously determined under GTT and ITMO in equation (35), Home tends to issue fewer permits, while Foreign tends to issue more. This is because the marginal cost increases the volume of ITMO, leading to higher $\hat{x}_{HH}$ and $\hat{x}_{HF}$ in Home and lower $\hat{x}_{FF}$ and $\hat{x}_{FH}$ in Foreign. However, global permit levels and welfare remain unchanged, as total production is not affected by the marginal cost.

6.4 Cooperative choices of emission permits

In the main analysis, we investigated countries' choices of emission permits in a non-cooperative setting under BAU and ITMO. Because the Paris Agreement encourages cooperation among countries, it is also likely that Home and Foreign decide on their levels of emission permits cooperatively to maximize their joint welfare $W_H + W_F$. We provide a formal analysis in Appendix D and briefly discuss the main findings here.

In the cooperative setting, the implementation of GTT and ITMO does not impact global emissions or welfare. Intuitively, under BAU, firms in the developed country can produce more goods with any given level of emission permits; therefore, it is optimal to let these firms supply all the goods for the two markets. Under GTT and ITMO, all firms in both countries use the green technology for production. The optimal levels of emission permits are the same in the two policy scenarios because all goods are produced using the same technology. Consequently, global welfare also remains the same under BAU and ITMO.[24]

Lemma 2 *Suppose emission permits are determined cooperatively by countries. GTT and ITMO do not affect global emissions and welfare.*

We next compare global emissions and welfare at the non-cooperative and cooperative equilibria under BAU and ITMO. Under BAU, global emissions are lower and global welfare is higher in the cooperative solution than at the non-cooperative equilibrium. This is because in the cooperative setting, both countries maximize their joint welfare and are incentivized to mitigate the adverse

[24]This result relies on the assumption of homogeneous goods within each industry. If Home and Foreign produce differentiated varieties, consumers would consume Foreign goods even though Foreign firms employ inferior technology. In that case, Foreign might issue a positive level of permits in the cooperative equilibrium under BAU, and GTT and ITMO could affect global emissions and welfare. Although interesting, incorporating within-industry product differentiation would render our analysis intractable, so we leave it for future research.

environmental impacts of emissions on each other. However, under ITMO, cooperative levels of global emissions can be either lower or higher than non-cooperative levels, while global welfare in the cooperative scenario is always higher. Intuitively, ITMO results in increased production in the developed country but reduced production in the developing country. Therefore, in the non-cooperative game, the developed country has an incentive to issue more permits for more ITMO, while the developing country has an incentive to issue fewer permits to lower ITMO. If the latter incentive is sufficiently strong, the level of total emission permits at the non-cooperative equilibrium is too low. In this case, cooperative choices of permits improve global welfare by increasing total emission permits in the cooperative solution.

Proposition 5 *Under BAU, global emissions are lower and global welfare is higher at the cooperative equilibrium compared to the non-cooperative equilibrium. Under GTT and ITMO, global welfare remains higher under cooperative setting, while global emissions may be either lower or higher than in the non-cooperative case.*

7 Conclusion

In this study, we employed the international oligopoly model to investigate green technology transfer (GTT) and international transfer of mitigated outcomes (ITMO) under the Paris Agreement. We found that GTT and ITMO may not work as well as we have imagined. First of all, GTT may increase the developing country's emissions. Even if GTT decreases its emissions, GTT and ITMO may not improve the two countries' welfare at the same time. However, GTT and ITMO always increase global welfare. These findings, on the one hand, underscore the potential advantages of collaborative efforts in addressing environmental challenges under the Paris Agreement. On the other hand, they imply that to ensure mutual gains for both developed and developing countries, a side payment or compensation mechanism may be necessary in the design of ITMO frameworks.

We also investigated how countries decide on their levels of emission permits non-cooperatively in the BAU and ITMO scenarios. We found that the global level of permits is lower under ITMO than under BAU, suggesting that they facilitate a more effective achievement of the two countries' emission reductions. Consequently, the mechanism of GTT and ITMO improves global welfare at equilibrium.

We make two final remarks to conclude. First, we showed that although GTT and ITMO always increase global welfare, they may not increase the two countries' welfare at the same time. To guarantee that both countries gain from GTT and ITMO, the developed and developing countries can negotiate an international transfer of coordination benefits. However, the developing country may not be willing to do so when GTT and ITMO increase its welfare but decrease the developed country's welfare. Therefore, more effort is needed to design a more feasible mechanism of GTT and ITMO.

Second, GTT can take the form of investment in renewable energy in the developing country, so that the emissions per unit of production decrease there. However, we did not take into account energy markets in our study. By conjecture, our results would not change if the downstream goods producers are clean and only require energy for production, and the upstream energy producers are perfectly competitive, only provide energy to the local downstream goods producers and generate carbon emissions during energy production. In this case, the price of energy is equal to the price of permits, with choices of coefficients in the model. However, the analysis would become complicated if the goods producers also generate carbon emissions and the upstream energy producers are imperfectly competitive, due to the strategic effects of producer behaviors on different factor markets. For instance, the energy producers have an incentive to produce less energy, because doing so decreases the goods producers' production and their demand for emission permits, which in turn decreases permit prices and benefits the energy producers. The detailed analysis of energy markets goes beyond the scope of our study and is left for future research.[25]

Appendix

Appendix A: Proof of $\hat{t}_H < t_H$

The difference between Home permit prices in the BAU and IMTO cases is

$$t_H - \hat{t}_H = \frac{1}{k^2}\left[-(1-k)ka + \frac{1}{2}(1-k)E_H + \frac{1}{2}(3-k-2k^2)E_F\right]. \tag{46}$$

As $a < \frac{1}{2k}E_H + \frac{1+k}{k}E_F$, we can establish

$$\begin{aligned} & t_H - \hat{t}_H \\ > & \frac{1}{k^2}\left[-(1-k)k\left(\frac{1}{2k}E_H + \frac{1+k}{k}E_F\right) + \frac{1}{2}(1-k)E_H + \frac{1}{2}(3-k-2k^2)E_F\right] \\ = & \frac{1-k}{2k^2}E_F \\ > & 0. \end{aligned} \tag{47}$$

Therefore, GTT and ITMO decrease Home permit price.

[25]Tripathy et al. (2023) study energy markets under ITMO. However, they do not consider goods markets. For other differences between theirs and our paper, see the literature review.

Appendix B: Proof of Proposition 1

The difference in Home welfare under BAU and ITMO, $\widehat{W}_H - W_H$, is given by

$$\begin{aligned} &\widehat{W}_H - W_H = (\widehat{CS}_H + \hat{\pi}_H + \widehat{PR}_H) - (CS_H + \pi_H + PR_H) \\ &= (1-k)\left[-2a^2 + \left(\frac{2}{k}E_H + \frac{3+2k}{k}E_F\right)a - \frac{1}{2k^2}{E_H}^2 - \frac{7+4k}{4k^2}E_H E_F - \frac{7}{8}\frac{1+k}{k^2}{E_F}^2\right] \end{aligned} \tag{48}$$

The corresponding difference in Foreign welfare, $\widehat{W}_F - W_F$, is expressed as

$$\begin{aligned} &\widehat{W}_F - W_F = (\widehat{CS}_F + \hat{\pi}_F + \widehat{PR}_F) - (CS_F + \pi_F + PR_F) \\ &= (1-k)\left[2a^2 - \left(\frac{2}{k}E_H + \frac{2+2k}{k}E_F\right)a + \frac{1}{2k^2}{E_H}^2 + \frac{5+4k}{4k^2}E_H E_F + \frac{5}{8}\frac{1+k}{k^2}{E_F}^2\right] \end{aligned} \tag{49}$$

The difference in global welfare between BAU and ITMO is

$$\begin{aligned} &\widehat{W}_H - W_H + \widehat{W}_F - W_F \\ &= (\widehat{CS}_H + \hat{\pi}_H + \widehat{PR}_H) - (CS_H + \pi_H + PR_H) + (\widehat{CS}_F + \hat{\pi}_F + \widehat{PR}_F) - (CS_F + \pi_F + PR_F) \\ &= \frac{1-k}{k}E_F\left(a - \frac{1}{2k}E_H - \frac{1+k}{4k}E_F\right), \end{aligned} \tag{50}$$

which is positive because $a > a_1 > \frac{1}{2k}E_H + \frac{1+k}{4k}E_F$. Therefore, GTT and ITMO always enhance global welfare.

Appendix C: Proof of Proposition 2

Under ITMO, the equilibrium levels of emission permits for each country and the quantity of ITMO are respectively obtained as

$$\hat{E}_H^* = \frac{1+k-4k^2+8k^3-8k^4-4k^2(1-k)(2k+5)\delta}{(1-k+2k^2+4k^2\delta)(1-2k)}a; \tag{51}$$

$$\hat{E}_F^* = \frac{-1+k-2k^2+4k^2(1-k)(2k+5)\delta}{(1-k+2k^2+4k^2\delta)(1-2k)}a; \tag{52}$$

$$\Phi^* = \frac{(1-k)\left[4k^2(5-4k^2)(1+k)\delta-(1+2k)(1-k+2k^2)\right]}{(1-k+2k^2+4k^2\delta)(1-2k)}a. \tag{53}$$

To make sure that $\hat{E}_H^* > 0$, $\hat{E}_F^* > 0$, and $\hat{E}_F^* > \frac{1}{1+2k}\hat{E}_H^*$, we need to impose more restrictions on the parameter values. When $k > \frac{1}{2}$, the environmental damage parameter δ should satisfy

$\max(0, \delta_2) < \delta < \min\left(\frac{1}{4k(1-k)}, \delta_1\right)$, where

$$\delta_1 = \frac{1 + k - 4k^2 + 8k^3 - 8k^4 + (1+2k)(1-k+2k^2)}{8k^2(1-k)(1+k)(2k+5)}; \tag{54}$$

$$\delta_2 = \frac{1 + k - 4k^2 + 8k^3 - 8k^4}{4k^2(1-k)(2k+5)}. \tag{55}$$

$\delta_1 > \delta_2$ and $\frac{1}{4k(1-k)} > \delta_2$ hold for $k > \frac{1}{2}$. When $k < \frac{1}{2}$, the environmental damage parameter δ should satisfy $\delta_1 < \delta < \min\left(\frac{1}{4k(1-k)}, \delta_2\right)$. $\delta_2 > \delta_1$ holds for $k < \frac{1}{2}$ and there exists a threshold value $\tilde{k}$ with which $\frac{1}{4k(1-k)} > \delta_1$ holds for $\tilde{k} < k < \frac{1}{2}$. Since our analysis does not depend on these assumptions, we do not include them in the main part.

We now investigate how GTT and ITMO affect Home's and Foreign's marginal benefits. First of all, both Home's and Foreign's marginal benefits from consumer surplus are higher under GTT and ITMO:

$$-\hat{p}'_H \hat{X}_H \frac{\partial \hat{X}_H}{\partial E_H} = \frac{E_H + E_F}{4k^2} > -p'_H X_H \frac{\partial X_H}{\partial E_H} = \frac{E_H + kE_F}{4k^2}; \tag{56}$$

$$-\hat{p}'_F \hat{X}_F \frac{\partial \hat{X}_F}{\partial E_F} = \frac{E_H + E_F}{4k^2} > -p'_F X_F \frac{\partial X_F}{\partial E_F} = \frac{E_H + kE_F}{4k}. \tag{57}$$

How GTT and ITMO affect the marginal benefits from Home firms' sales profits is ambiguous:

$$\left(2\hat{x}_{HH}\hat{p}'_H \frac{\partial \hat{X}_H}{\partial E_H} + 2\hat{p}_H \frac{\partial \hat{x}_{HH}}{\partial E_H}\right) - \left(2x_{HH}p'_H \frac{\partial X_H}{\partial E_H} + 2p_H \frac{\partial x_{HH}}{\partial E_H}\right) = \frac{1-k}{k}\left(2a - \frac{1}{k}E_H - \frac{2+k}{k}E_F\right). \tag{58}$$

However, they always decrease marginal benefits from Foreign firms' sales profits:

$$\left(2\hat{x}_{FF}\hat{p}'_F \frac{\partial \hat{X}_F}{\partial E_F} + 2\hat{p}_F \frac{\partial \hat{x}_{FF}}{\partial E_F}\right) - \left(2x_{FF}p'_F \frac{\partial X_F}{\partial E_F} + 2p_F \frac{\partial x_{FF}}{\partial E_F}\right) = -\frac{2(1-k^2)}{k}\left(a - \frac{1}{2k}E_H - \frac{1}{2k}E_F\right) < 0. \tag{59}$$

The difference between the sums of marginal benefits under BAU and ITMO is

$$\begin{aligned}
&(MB_H + MB_F) - (\widehat{MB}_H + \widehat{MB}_F) \\
&= 2(1-k)\left(a - \frac{1+4k}{8k^2}E_H + \frac{2-k}{8k^2}E_F\right) \\
&> 2(1-k)\left[\frac{3-k}{2k(2-k)}E_H + \frac{3-2k^2}{2k(2-k)}E_F - \frac{1+4k}{8k^2}E_H + \frac{2-k}{8k^2}E_F\right] \\
&= 2(1-k)\left[\frac{5k-2}{8k^2(2-k)}E_H + \frac{4+8k+k^2-8k^3}{8k^2(2-k)}E_F\right].
\end{aligned} \tag{60}$$

If $k > \frac{2}{5}$, then the above equation is positive. If $k < \frac{2}{5}$, taking $E_H < (1+2k)E_F$ into the above equation gives

$$(MB_H + MB_F) - (\widehat{MB}_H + \widehat{MB}_F) > \frac{(1-k)(2+9k+11k^2-8k^3)}{4k^2(2-k)} E_F > 0. \tag{61}$$

Therefore, $MB_H + MB_F > \widehat{MB}_H + \widehat{MB}_F$ always holds.

The difference in the global levels of emission permits at equilibria under BAU and ITMO is given by

$$\begin{aligned} &(E_H^* + E_F^*) - (\hat{E}_H^* + \hat{E}_F^*) \\ =& \frac{2a(1-k)\left[1-k+2k^2+(6k^3-k^2+6k-3)k\delta\right]}{[2+(3k^2-2k+3)\delta][1-k+2k^2+4k^2\delta]}. \end{aligned} \tag{62}$$

The term $6k^3 - k^2 + 6k - 3$ is increasing in k monotonically. When this term is positive, $(E_H^* + E_F^*) > (\hat{E}_H^* + \hat{E}_F^*)$ holds. If this term is negative, we have

$$\begin{aligned} &(E_H^* + E_F^*) - (\hat{E}_H^* + \hat{E}_F^*) \\ >& \frac{2a(1-k)\left[1-k+2k^2+(6k^3-k^2+6k-3)\frac{1}{4(1-k)}\right]}{[2+(3k^2-2k+3)\delta][1-k+2k^2+4k^2\delta]} \\ =& \frac{a(-2k^3+11k^2-2k+1)}{2[2+(3k^2-2k+3)\delta][1-k+2k^2+4k^2\delta]} \\ >& 0. \end{aligned} \tag{63}$$

The last inequality holds because $-2k^3 + 11k^2 - 2k + 1 = 2k^2(1-k) + (9k^2 - 2k + 1) > 0$. Therefore, GTT and ITMO always decrease global emissions.

Appendix D: Cooperative choices of emission permits

In this appendix, we investigate how Home and Foreign decide on their levels of emission permits cooperatively to maximize their joint welfare $W_H + W_F$. We assume that the two countries agree on a rule for sharing the total cooperative reward such as a side payment mechanism, ensuring that both of them could gain from cooperation. In the BAU case, because Home firms possess a greener technology than Foreign firms, they can produce more with any given level of emission permits. Therefore, it is optimal for Foreign not to issue any permit ($E_F^{*coop} = 0$), while Home chooses $E_H^{*coop} = \frac{2ka}{1+4k^2\delta}$.

Under GTT and ITMO, with equation (30), the first order condition for each country's welfare maximization problem is given by

$$\frac{\partial(\widehat{W}_H + \widehat{W}_F)}{\partial E_i} = 0; \implies 2\hat{p}_i \frac{\partial \hat{X}_i}{\partial E_i} = \hat{D}'_H + \hat{D}'_F, \quad i \in \{H, F\}. \tag{64}$$

This yields the global level of permits at equilibrium: $\hat{E}_H^{*coop} + \hat{E}_F^{*coop} = \frac{2ka}{1+4k^2\delta}$. In the cooperative game, the global level of permit at equilibrium is the same under BAU and ITMO. This is because all the goods are produced using the greener technology in both cases.

Next, we compare global emissions at the cooperative and non-cooperative equilibria. Under BAU, not surprisingly, the global level of emission permits at the cooperative equilibrium is lower than that at the non-cooperative equilibrium. However, under GTT and ITMO, the global level of emission permits can be higher or lower in the cooperative game than in the non-cooperative game. To see this, we again compare the sums of the two countries' marginal benefits and damage in the two settings:

$$\text{Non-cooperation:} \quad \hat{p}_H \frac{\partial \hat{x}_{HH}}{\partial E_H} + \hat{p}_F \frac{\partial \hat{x}_{HF}}{\partial E_H} + \hat{p}_H \frac{\partial \hat{x}_{FH}}{\partial E_F} + \hat{p}_F \frac{\partial \hat{x}_{FF}}{\partial E_F} = \hat{D}'_H + \hat{D}'_F; \tag{65}$$

$$\text{Cooperation:} \quad \hat{p}_H \frac{\partial \hat{X}_H}{\partial E_H} + \hat{p}_F \frac{\partial \hat{X}_F}{\partial E_H} + \hat{p}_H \frac{\partial \hat{X}_H}{\partial E_F} + \hat{p}_F \frac{\partial \hat{X}_F}{\partial E_F} = 2(\hat{D}'_H + \hat{D}'_F). \tag{66}$$

Compared with the non-cooperative setting, the sum of marginal damage doubles under cooperative setting, because each country takes into account how its issuance of emission permits affects the other country's environment in this case. How the global level of permits changes depends on whether the sum of marginal benefits doubles. The sum of marginal benefits in the cooperative setting is irrelevant to the quantity of ITMO and is equal to $\frac{2}{k}\hat{p}_H$. The sum of marginal benefits in the non-cooperative setting is given by

$$\hat{p}_H \frac{\partial(E_H + \Phi)/k}{\partial E_H} + \hat{p}_F \frac{\partial(E_F - \Phi)/k}{\partial E_F} = \hat{p}_H \left(\frac{1}{k} + \frac{1}{k}\frac{\partial \Phi}{\partial E_H}\right) + \hat{p}_F \left(\frac{1}{k} - \frac{1}{k}\frac{\partial \Phi}{\partial E_F}\right), \tag{67}$$

which is dependent on how the levels of E_H and E_F affect the quantity of ITMO. A larger quantity of ITMO is beneficial to Home but harmful to Foreign. Therefore, Home has an incentive to issue more permits for more ITMO, while Foreign has an incentive to issue fewer permits to cut down ITMO. The latter effect always dominates the former effect, as $\frac{\partial \Phi}{\partial E_H} - \frac{\partial \Phi}{\partial E_F} = -(1-k)(1+2k) < 0$ always holds for $0 < k < 1$. When $k > \frac{1}{2}$, GTT does not lead to a large quantity of ITMO. Foreign's incentive to decrease emission permits is weak. Therefore, in the non-cooperative setting, the sum of marginal benefits is relatively large and the level of global permits is relatively high. Compared with this, the sum of marginal benefits in the cooperative setting increases less than double and the global level of permits becomes lower. In this case, the ranking of global emissions is

$$\widehat{E}_H^{*coop} + \widehat{E}_F^{*coop} = E_H^{*coop} + E_F^{*coop} < \widehat{E}_H^{*} + \widehat{E}_F^{*} < E_H^{*} + E_F^{*}. \tag{68}$$

However, when $k < \frac{1}{2}$, Foreign's incentive to issue fewer permits is strong, leading to a small sum of marginal benefits and a lower level of global permits in the non-cooperative setting. As a result, the sum of marginal benefits increases more than double in the cooperative setting and the global level of permits becomes higher. In this case, the ranking of global emissions is

$$\widehat{E}_H^{*} + \widehat{E}_F^{*} < \widehat{E}_H^{*coop} + \widehat{E}_F^{*coop} = E_H^{*coop} + E_F^{*coop} < E_H^{*} + E_F^{*}. \tag{69}$$

Finally, we compare global welfare under BAU and ITMO in both non-cooperative and cooperative equilibria.[26] Under both BAU and ITMO, global welfare at the cooperative equilibrium reaches its maximal welfare level and is higher than that at the non-cooperative equilibrium, because the two countries cooperate to maximize their joint welfare in the cooperative game.

At the cooperative equilibrium, global welfare is identical under BAU and ITMO, as the global level of permits remains the same across these two policy regimes. In the non-cooperative game, GTT and ITMO enhance global welfare, as shown in Proposition 3. The ranking of global welfare at equilibrium in the four scenarios is

$$\widehat{W}_H^{*coop} + \widehat{W}_F^{*coop} = W_H^{*coop} + W_F^{*coop} > \widehat{W}_H^{*} + \widehat{W}_F^{*} > W_H^{*} + W_F^{*}. \tag{70}$$

Proof of Proposition 5

In this subsection, we demonstrate that in the BAU case, the cooperative levels of global emissions are lower than the non-cooperative levels.

$$\begin{aligned} & (E_H^{*coop} + E_F^{*coop}) - (E_H^{*} + E_F^{*}) \\ = & \frac{2ka}{1+4k^2\delta} - \frac{2a(1+k)}{2+(3k^2-2k+3)\delta} \\ = & \frac{2a[k-1+k(-k^2-6k+3)\delta]}{(1+4k^2\delta)[2+(3k^2-2k+3)\delta]}. \end{aligned} \tag{71}$$

[26] The welfare effects of GTT and ITMO on individual countries are not analytically tractable and are expected to be ambiguous, as in the case with exogenous emission permits.

If $-k^2-6k+3 \leq 0$, the above equation is always negative. If $-k^2-6k+3 > 0$, recalling $\delta < \frac{1}{4k(1-k)}$, we have

$$
\begin{aligned}
& (E_H^{*coop} + E_F^{*coop}) - (E_H^* + E_F^*) \\
< & \frac{2a\left[k-1+(-k^2-6k+3)\frac{1}{4(1-k)}\right]}{(1+4k^2\delta)[2+(3k^2-2k+3)\delta]} \\
< & \frac{a(-5k^2+2k-1)}{2(1-k)(1+4k^2\delta)[2+(3k^2-2k+3)\delta]} \\
< & \ 0.
\end{aligned}
\tag{72}
$$

The last inequality holds because $-5k^2+2k-1 < 0$ always holds. Therefore, we obtain $E_H^{*coop} + E_F^{*coop} < E_H^* + E_F^*$ under BAU.

Under BAU and ITMO, the difference between cooperative and non-cooperative levels of global emissions is

$$
\begin{aligned}
& (\hat{E}_H^{*coop} + \hat{E}_F^{*coop}) - (\hat{E}_H^* + \hat{E}_F^*) \\
= & \frac{2ka}{1+4k^2\delta} - \frac{2ak(1-k+2k^2)}{1-k+2k^2+4k^2\delta} \\
= & \frac{8k^4 a\delta(1-2k)}{(1+4k^2\delta)[1-k+2k^2+4k^2\delta]},
\end{aligned}
\tag{73}
$$

which is positive for $0 < k < \frac{1}{2}$ and negative for $\frac{1}{2} < k < 1$.

Appendix E: Proof of Proposition 3

In this section, we mainly demonstrate that under non-cooperative choices of permits, GTT and ITMO improve global welfare at equilibrium, compared with the BAU case.

Case one: $\frac{1}{2} < k < 1$

As shown in Appendix D, when $\frac{1}{2} < k < 1$ and under GTT and ITMO, the global level of permits at the non-cooperative equilibrium is higher than that at the cooperative equilibrium. Specifically, we have

$$
\widehat{E}_H^{*coop} + \widehat{E}_F^{*coop} = E_H^{*coop} + E_F^{*coop} < \widehat{E}_H^* + \widehat{E}_F^* < E_H^* + E_F^*. \tag{74}
$$

In the non-cooperative BAU case, Foreign produces with the dirty technology. If, hypothetically, Foreign instead used the clean technology while the permit levels E_H^* and E_F^* remained unchanged, global welfare would increase due to higher consumption. We denote this hypothetical global welfare as $(W_H^* + W_F^*)^{hypo}$, where $(W_H^* + W_F^*)^{hypo} > W_H^* + W_F^*$. Note that when both countries produce with the clean technology, the function of global welfare becomes the same as that of the non-cooperative ITMO case and the two cooperative cases. For global emission levels higher than $\widehat{E}_H^{*coop} + \widehat{E}_F^{*coop}$ and $E_H^{*coop} + E_F^{*coop}$, global welfare decreases as global emission levels increase further. Thus, from equation (74), we conclude:

$$\widehat{W}_H^* + \widehat{W}_F^* > (W_H^* + W_F^*)^{hypo} > W_H^* + W_F^*. \tag{75}$$

This scenario is illustrated in Figure A.1.

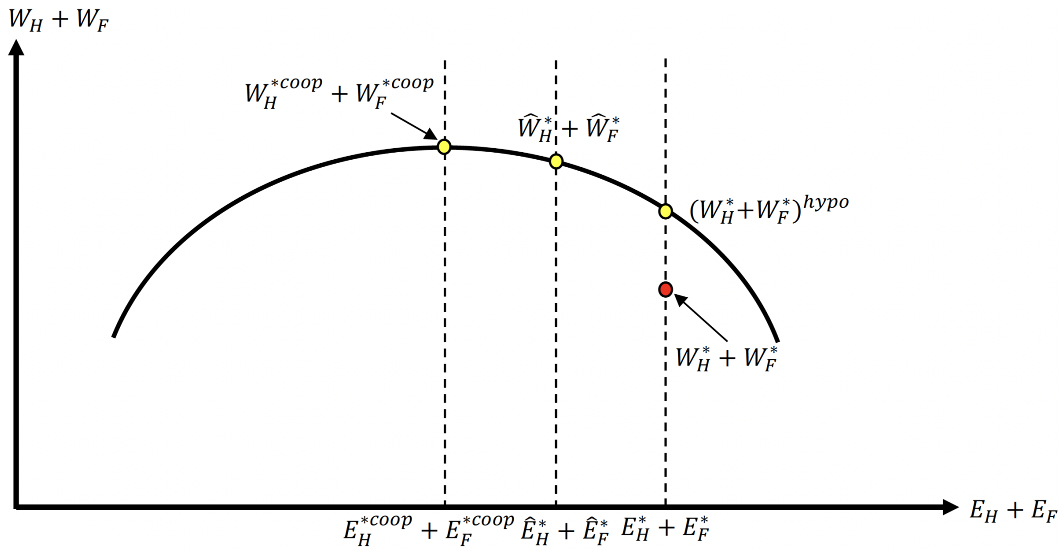

Figure A.1: Comparison of global welfare with $\frac{1}{2} < k < 1$.

Case two: $0 < k < \frac{1}{2}$

As shown in Appendix D, when $0 < k < \frac{1}{2}$ and under GTT and ITMO, the global level of permits at the non-cooperative equilibrium is lower than that at the cooperative equilibrium. In this case, we have

$$\widehat{E}_H^* + \widehat{E}_F^* < \widehat{E}_H^{*coop} + \widehat{E}_F^{*coop} = E_H^{*coop} + E_F^{*coop} < E_H^* + E_F^*. \tag{76}$$

Unlike the first case, we cannot compare $\widehat{W}_H^* + \widehat{W}_F^*$ and $W_H^* + W_F^*$ directly, because $\widehat{E}_H^* + \widehat{E}_F^*$ is located on the left of $E_H^{*coop} + E_F^{*coop}$ in Figure A.1.

Note that at the non-cooperative equilibrium, the total consumption of goods in each country is given by

$$X_H^* = X_F^* = \frac{2a[1 + (1-k)^2\delta]}{2 + (3k^2 - 2k + 3)\delta}; \tag{77}$$

$$\widehat{X}_H^* = \widehat{X}_F^* = \frac{(1-k+2k^2)a}{1-k+2k^2+4k^2\delta}. \tag{78}$$

The difference in total consumption in a country between BAU and ITMO is

$$\begin{aligned} X_H^* - \widehat{X}_H^* &= \frac{a\delta(1-k)\left[8k^2(1-k)\delta + 2k^3 + 5k^2 - 2k - 1\right]}{[2+(3k^2-2k+3)\delta][1-k+2k^2+4k^2\delta]} \\ &< \frac{a\delta(1-k)\left[2k^3+5k^2-1\right]}{[2+(3k^2-2k+3)\delta][1-k+2k^2+4k^2\delta]}. \end{aligned} \tag{79}$$

The inequality holds because $0 < \delta < \frac{1}{4k(1-k)}$. Note that $2k^3 + 5k^2 - 1 < 0$ holds for $0 < k \leq 0.4$. Therefore, for $0 < k < 0.4$, we have $X_H^* < \widehat{X}_H^*$, implying that GTT and ITMO increase total consumption of goods and consumer surplus in both countries. Since GTT and ITMO also decrease environmental damage from global emissions, they enhance global welfare for $0 < k \leq 0.4$.

Next, we show that when $0.4 < k < 0.5$, GTT and ITMO also enhance global welfare. Recall that in this case, $\widehat{E}_H^* + \widehat{E}_F^*$ is located on the left of $E_H^{*coop} + E_F^{*coop}$ in Figure A.1. A sufficient (though not necessary) condition for $\widehat{W}_H^* + \widehat{W}_F^* > W_H^* + W_F^*$ is: $(\widehat{E}_H^* + \widehat{E}_F^*) + (E_H^* + E_F^*) > 2(E_H^{*coop} + E_F^{*coop})$. We demonstrate that this condition holds for $0.4 < k < 0.5$.

Using the results above, we have

$$\begin{aligned} &2(E_H^{*coop} + E_F^{*coop}) - (\widehat{E}_H^* + \widehat{E}_F^*) - (E_H^* + E_F^*) \\ =\ &\frac{2a\left[4k^3(-6k^4+7k^3-9k^2-3k+3)\delta^2 + k(1-3k)(6k^3+3k^2-4k+3)\delta - (1-k)(1-k+2k^2)\right]}{(1+4k^2\delta)[2+(3k^2-2k+3)\delta][1-k+2k^2+4k^2\delta]} \end{aligned} \tag{80}$$

$k(1-3k)(6k^3+3k^2-4k+3)\delta < 0$ always holds for $0.4 < k < 0.5$. The term $-6k^4+7k^3-9k^2-3k+3$ is decreasing in k for $0.4 < k < 0.5$, implying that $-6k^4+7k^3-9k^2-3k+3 < 0.6544 < 0.7$. With $0 < \delta < \frac{1}{4k(1-k)}$, we can obtain

$$\begin{aligned} &4k^3(-6k^4+7k^3-9k^2-3k+3)\delta^2 + k(1-3k)(6k^3+3k^2-4k+3)\delta - (1-k)(1-k+2k^2) \\ <\ &2.8k^3\delta^2 - (1-k)(1-k+2k^2) \\ <\ &\frac{2.8k}{16(1-k)^2} - (1-k)(1-k+2k^2) \\ =\ &\frac{2.8k - 16(1-k)^3(1-k+2k^2)}{16(1-k)^2} \\ <\ &\frac{2.8 \times 0.5 - 16 \times 0.5^3 \times (1-0.4+2\times 0.4^2)}{16(1-k)^2} \\ =\ &-\frac{0.44}{16(1-k)^2} \end{aligned}$$

$$< 0. \tag{81}$$

Therefore, $2(E_H^{*coop} + E_F^{*coop}) - (\widehat{E}_H^* + \widehat{E}_F^*) - (E_H^* + E_F^*) < 0$ for $0.4 < k < 0.5$, which implies that $\widehat{W}_H^* + \widehat{W}_F^* > W_H^* + W_F^*$.

To conclude, $\widehat{W}_H^* + \widehat{W}_F^* > W_H^* + W_F^*$ always holds. That is, at the non-cooperative equilibrium, GTT and ITMO always enhance global welfare, compared with the BAU case.

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