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Industrial Policy and Global Public Goods Provision: Rethinking the Environmental Trade Agreement*

Pia Andres†

September 19, 2024

Abstract

Countries around the world use anti-dumping duties, local content requirements and other protectionist measures to promote their low carbon industries, thereby inflating downstream costs. At the same time, they ascribe insufficient climate action to the economic burden of mitigation efforts. This paper examines the trade-off between temporarily forgoing gains from trade by protecting an infant industry and increasing future gains through fiercer global competition later on. I introduce a strategic model featuring two countries, two time periods, and trade in a clean technology in a set up with differential production costs and imperfect competition. The findings suggest that when initial differences in production cost surpass a critical threshold, and learning-by-doing facilitates catch-up for the laggard, opting for autarky during Stage 1 can enhance overall welfare for both countries. This result is strengthened when both countries use consumer subsidies. Furthermore, when both consumer and producer subsidies are available, the Subgame Perfect Nash Equilibrium involves both trade and production subsidies on the part of the laggard country and the same welfare payoffs as perfect competition. The analysis suggests that an environmental trade agreement is most likely to be beneficial if production subsidies for clean technology are permitted.

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1 INTRODUCTION

Climate change has been an item on the agenda of global diplomacy and politics for decades. Policy action at the level of nation states, however, has to date remained woefully insufficient to achieve stated aims to reduce greenhouse gas emissions and avoid catastrophic warming. The reason for this is, according to much of the economics literature, the cost of reducing emissions – and the fact that due to the global nature of climate change, each country has an incentive to free-ride on others' efforts (Barrett 1994a, 2005; Finus 2008). One might therefore expect that reductions in the cost of technological solutions would be universally welcomed. And yet, policy support for renewable energy, which is a key component of a climate-compatible global production system, has frequently been accompanied by or met with trade barriers, which are associated with increased user costs.[1] Such decisions are taken in the interest of each country's domestic industry producing renewable energy technology.

Are there conditions under which this might prove beneficial to climate action? Fischer (2017) shows how domestic incentives to expand global market share in a green industry can balance out environmental externalities in a framework in which two producer countries use upstream subsidies and compete for a third market. Here, I consider instead the intertemporal trade-off between foregoing gains from trade early on in order to realize greater gains later, by allowing an infant industry to mature. The literature on industrial policy and infant industry maturation tends to focus on the effectiveness of industrial policy and the cost-benefit trade-off at the level of the country promoting its infant industry (e.g. Krueger and Tuncer 1982; Melitz 2005; Young 1991). In contrast, I analyze the global as well as the local welfare implications of allowing an infant industry to mature in the context of a product with positive consumption externalities. The analysis suggests that such externalities could make infant industry maturation beneficial for both the initially laggard and the initially frontier country. Conversely, in the absence of positive consumption externalities, the frontier country prefers to extract rents from the laggard country's consumers. However, the laggard country, acting strategically, may still opt to protect its infant industry.

China's entry into the solar photovoltaics (hereafter PV) market, which was enabled by targeted industrial policy, considerably increased competition in this market[2] and is widely credited to have contributed to the dramatic declines in the cost of solar PV energy over the past

1. For example, China required 40% of wind turbines and blades to be manufactured locally for projects to be eligible for public tenders as early as 1997. Between 2011 and 2017, India imposed a 60% local content requirement on tenders for solar photovoltaics (PV), and 30% for concentrated solar power. France's feed-in tariff for solar PV between 2002 and 2012 came with a 60% local content requirement (Scheifele et al. 2022). More recent examples include domestic content requirements in the US Inflation Reduction Act, as well as the EU's Net Zero Industry Act which includes the explicit aim that 'by 2030, the manufacturing capacity in the Union of [strategic net-zero technologies] approaches or reaches at least 40% of the Union's annual deployment needs' (European Commission 2023).

2. In 2008, the 10 largest solar PV equipment manufacturers accounted for almost 90% of global market share, operating in just four countries (Germany, the US, Switzerland and Japan). By 2021, the top ten manufacturers' share had dropped by half due to new firm entry. Today, all top ten equipment manufacturers are in China and claim over 45% of the global market share (IEA 2022).

decade (Carvalho et al. 2017; Dent 2018; Nemet 2019). This raises the following question: if industrial policy – possibly including temporary protectionist measures – is necessary to allow a potential supplier country of clean technology to realize its potential and increase competition in the future, can the long-term global benefits of doing so outweigh the short-term cost of protection? I present a stylized model highlighting conditions under which this may be the case. I then add the use of quantity subsidies, and show how this alters the trade-offs considered. The key insight is that allowing the initially laggard country to more effectively compete with the frontier country can be beneficial for the global economy, and allowing for the use of producer subsidies can accomplish this goal while avoiding the temporary cost of protectionism.

I model the production and consumption of an environmentally beneficial product in a 2-country, 2-stage game with imperfect competition, differences in initial production cost, and learning-by-doing. Each country has a representative firm which can produce a technology capable of generating private as well as public benefits. We can think of this as a renewable energy technology which benefits consumers directly by supplying energy, as well as reducing negative externalities which would result if fossil fuels were used instead. While the paper is motivated by the global challenge of addressing climate change, the model is potentially relevant to any game in which consuming a technology carries benefits to other consumers at home and abroad. Other examples include the use of vaccines, which also generate both private and public benefits (Brito et al. 1991; Fisman and Laupland 2009; Francis 1997).

I start with the assumption that there are no subsidies and governments can choose only whether to trade or not. Firms play a Bertrand game if countries engage in trade, and act as local monopolists otherwise. If the laggard (high cost) firm is active during Stage 1, it 'catches up' with the frontier (low cost) firm by Stage 2. If countries trade, then the laggard firm remains inactive and the frontier country extracts rents from the laggard country's consumers. Under both trade and autarky and in the absence of other policy action, consumption and positive externalities are inefficiently low even without the additional factor of transboundary (global) positive externalities. This is due to imperfect competition.[3]

If the laggard firm catches up, Bertrand competition leads to marginal cost pricing in Stage 2. The model shows how for a sufficiently large difference in initial marginal cost, and in the absence of other policy tools, autarky in Stage 1 can benefit both countries through increased consumer surplus and positive externalities in Stage 2. The frontier country loses the rents it could otherwise extract from the laggard country.

In the presence of market failures, such as those arising from the positive externality and imperfectly competitive market structure considered here, a social planner will usually wish to intervene beyond the decision of whether or not to trade. Indeed, various subsidies, preferential loans and other incentives implemented by policy-makers around the world have been decisive in scaling up the deployment of renewable energy technologies. I therefore analyze how quantity subsidies affect the dynamics of trade and positive externalities. The model suggests that

3. Arguably a reasonable assumption for a new industry, see e.g. Fischer (2017) and Fischer et al. (2018)

when consumer subsidies are available as a policy tool, autarky in Stage 1 is always beneficial for the laggard and globally, as competition from the laggard country in Stage 1 no longer provides benefits in terms of constraining the frontier monopolist.

If countries can choose both upstream (producer) and downstream (consumer) subsidies then the laggard country will choose a producer subsidy which is sufficiently high to force the frontier firm to set price equal to marginal cost, but which leaves it to supply the whole market. Both countries subsidize consumers to the point of internalizing the domestic part of the positive externality. The outcome is equivalent to the non-cooperative equilibrium obtained under perfect competition. While the first best is not attainable, the 'second best' policy mix which achieves an outcome equivalent to a game with perfect competition thus requires that countries are able to choose a mix of consumer and producer subsidies.

The paper connects the literature on industrial policy and infant industry protection (e.g. Chang 2003; Krueger and Tuncer 1982; Melitz 2005; Young 1991) to that highlighting increased competition as a cause of gains from trade (Krugman 1979; Markusen 1981) by modelling learning-by-doing in an initially laggard industry as a pre-condition to enable competition later on. It also builds on the literature on international collective action problems related to climate change and the environment (see e.g. Barrett 1994a, 2005; Finus 2008; Harstad 2016). The positive global externality arising from consumption of the good implies that the benefits of an infant industry catching up may be global, rather than being limited to the initially laggard country. In contrast, in the absence of positive externalities the advanced country always prefers to retain its ability to extract rents, despite associated losses in consumer surplus.

Previous work on the infant industry argument has emphasized the need for the cost of temporary protection to be outweighed by the benefits of domestic production in a higher value-added industry later (Krueger and Tuncer 1982); for example, because learning-by-doing exhibits spillovers across goods (Young 1991) or domestic and foreign goods are imperfectly substitutable (Melitz 2005). This paper highlights an additional channel through which infant industry protection may be warranted. I model the maturation of an infant industry as a precondition for allowing gains from trade via increased competition (Krugman 1979; Markusen 1981) to increase in the future.

The model allows me to identify conditions for infant industry protection to improve welfare in the initially laggard country, as well as in the frontier country and globally, even while abstracting from any macroeconomic spillovers or growth effects. I also highlight how the frontier country can, under trade, extract rents from the laggard country, offsetting any losses in consumer surplus from imperfect competition. Finally, introducing a global positive consumption externality implies that infant industry protection can be welfare improving not only for the initially laggard country, but also for the frontier country. The larger the public benefit from consumption becomes relative to the private benefit, the closer countries' interests should align.

Efforts to liberalize trade in 'green' technologies – including, but not limited to, those with the potential to reduce greenhouse gas emissions – have been underway for years. In the 2001 Doha declarations ministers stated their commitment to negotiations on reducing or eliminating tariff and non-tariff barriers to environmental goods and services (Balineau and De Melo 2013; Droege et al. 2016). The Asia-Pacific Economic Cooperation (APEC) countries reached an environmental trade agreement in 2012 (Jacob and Møller 2017; Steenblik 2005; Vossenaar 2016), while negotiations for a World Trade Organization (WTO)-wide agreement are ongoing (De Melo and Solleder 2020; Monkelbaan 2017). The theoretical rationale for liberalizing trade in clean technologies is clear: doing so is expected to facilitate diffusion of such technologies, thereby increasing their deployment, and enabling greater climate change mitigation and other environmentally beneficial outcomes at a lower cost. In practice, however, countries' attitudes towards these technologies have frequently proven to be mercantilist in nature (De Melo and Solleder 2022).

This paper suggests that while a trade agreement may be beneficial for climate action and global welfare, producer subsidies may be key to realizing gains from trade. It further provides intuition for why countries which provide consumer subsidies for renewables often use local content requirements, as well as why early mover countries such as the US or Germany tend to oppose producer subsidies in other countries – even at the expense of their own consumers.[4]

The remainder of the paper proceeds as follows. Section 2 summarizes the literatures on trade and international public good games which the paper builds on. Section 3 discusses the evolution of the solar PV sector as a real-world example of the dynamics the model seeks to highlight. Section 4 introduces the key tenets of the model and the benchmark 'first best' cooperative outcome, comparing it to a status quo under which countries are in autarky and do not subsidize the technology in any way. Section 5.1 analyzes the welfare implications of trade when no other climate policy is available, and identifies the conditions under which autarky may be individually or jointly preferable to trade. Section 5.2 introduces quantity subsidies and analyzes how this changes the dynamics of the game. Section 6 concludes.

2 Related Literature

Gains From Trade and Infant Industries The trade literature identifies many mechanisms through which gains from trade may materialize. These include the efficiency gains of each country specializing where it has a comparative advantage (Ricardo 1891); increased competition and increasing returns to scale in a larger market (Krugman 1979); and a redistribution of market share towards the most productive firms and the exit of the least productive (Baldwin and Gu 2004; Melitz 2003). A larger potential market might further increase incentives to inno-

4. The expansion of low-cost solar panel manufacturing in China was met with anti-dumping duties by both the United States and the European Union (Hughes and Meckling 2017; Meckling and Hughes 2018; Wu and Salzman 2013). Estimates of the cost of US protective tariffs downstream, both in the solar PV sector and more broadly, include Houde and Wang (2022) and Fajgelbaum et al. (2020).

vate (Aghion et al. 2018; Grossman and Helpman 1990) and raise the potential for knowledge spillovers and technology diffusion (Grossman and Helpman 1990; Keller 2004), by making technology more widely and cheaply available (Carbaugh and St Brown 2012; ICTSD 2011).

If comparative advantage and industrial structure are taken as fixed, the benefits of liberalizing trade are clear and highly intuitive. However, patterns of comparative advantage are not solely determined by fundamental endowments (Hausmann et al. 2007). In highly complex modern industries in particular, competitiveness is developed over time. Many scholars argue that industries need temporary protection from import competition in order to develop and become competitive (Chang 2003; Hanlon 2017; Juhász 2018). This is known as the 'infant industry argument'. Infant industry protection is usually seen as a strategy for developing countries, but can also play a role in building productive capabilities in developed economies, especially if the industry in question is underdeveloped in a particular country (Andreoni and Chang 2016).

Theoretical models suggest that temporary protection can be beneficial when entry barriers and dynamic learning effects are high (Irwin 2000; Melitz 2005; Young 1991). The temporary costs of protecting the infant industry must be outweighed by the benefits of domestic production in a higher value-added industry later on (Krueger and Tuncer 1982). Empirical evidence on the justifications for and effectiveness of infant industry protection is mixed: Krueger and Tuncer (1982) show that protected industries in Turkey over the period 1963-1976 did not experience faster cost declines than others, and argue that infant industry protection could therefore not be a valid argument for the use of tariffs. Conversely, Hanlon (2017) argues that competition from Britain hindered North American shipbuilders' ability to transition from wood to metal shipbuilding in the late 19th century, while Juhász (2018) shows that the blockade of British imports during the Napoleonic wars enabled more protected French regions to more rapidly transition to mechanized cotton spinning.

Overall, more competition through trade may not necessarily be beneficial during the early stage of developing a new industry. This may provide some justification for the use of instruments such as local content requirements (Johnson 2016). The returns from infant industry protection are usually modelled as greater future growth via the reallocation of output to more rapidly growing industry; inter-industry spillovers enabling learning-by-doing (Young 1991); the result of imperfect substitutability between domestic and foreign goods (Melitz 2005); or protection against a sudden demand-shock favouring a foreign-produced good with non-linearly increasing production cost (Traiberman and Rotemberg 2022). In contrast, this paper explores the implications of infant industry dynamics for consumer surplus and positive externalities under trade and autarky, and in particular the potential global benefits of temporarily protecting an infant industry through its impact on competition later on. I thereby identify an additional mechanism through which infant industry protection may be beneficial, and explicitly model the rents which the initially frontier country can extract from the initially laggard country under imperfect competition in the absence of any policy supporting the infant industry.

The paper does not explicitly model the source of these dynamics, nor does it consider other, more long-term, implications of competition and market size beyond prices and quantities, such as innovation or learning by the frontier industry.

Climate Change and International Cooperation Climate change is an inherently global problem, which must nevertheless be addressed within the current framework of individual nation-states. Action on climate change and other transboundary environmental problems involves strategic interaction between individual countries, which makes game theory an attractive tool of analysis. In the absence of a supra-national authority which could force countries to act to achieve the global social optimum, incentives to free ride on others' efforts abound, making it extremely difficult for international cooperation to be achieved.

A broad literature has therefore used game theory to formally analyze the mechanisms at play in international climate negotiations. Due to the absence of an authority which could hold countries to a binding agreement, non-cooperative game theory is usually thought most relevant (Barrett 2005; Finus 2008). This literature typically attempts to provide insights on how treaties may improve on the status quo, using two benchmark cases: no agreement with each country only taking into account its own environmental damages and ignoring the transboundary externalities caused by its emissions; and the global 'first-best' or fully cooperative outcome, which would be obtained if a benevolent social planner could set global policy (e.g. Barrett 1994a; Battaglini and Harstad 2016; Harstad 2012).

Technology as a potential channel for enhancing international cooperation has also been explored. Barrett (2006) discusses if and how a system of two treaties promoting R&D and adoption of a resulting breakthrough technology could enhance cooperation. He argues that the R&D and technology approach faces the same challenges as the Kyoto approach, with the exception of breakthrough technologies with increasing returns to scale. Building on Barrett (2006), Hoel and De Zeeuw (2010) show that when R&D costs affect adoption costs, a large stable coalition is possible and can improve welfare. Harstad (2016), however, points out that in a dynamic setting, green investment may be negatively affected by the hold-up problem identified in earlier literature (Beccherle and Tirole 2011): incentives to invest in green technology may be reduced if countries expect this will force them to agree to abate more in future negotiations, which is especially damaging in the presence of technological spillovers. Conversely, Battaglini and Harstad (2016) present a dynamic model with incomplete contracts, in which the non-contractibility of investments in green technology can help leverage the hold-up problem when agreement duration is endogenous: in their model, a short-term agreement with low investment is used as a credible threat against free-riding, bringing about a longer-term, more comprehensive agreement.

This paper also relates to a growing body of literature exploring international environmental or climate cooperation in the presence of international trade. Research in this area typically explores the issue of pollution leakage and the potential for border adjustments (e.g. Barrett

1994b; Grubb et al. 2022; Richter et al. 2021); the potential use of trade policy to incentivize cooperation, also referred to as 'issue linkage' (e.g. Barrett 1997; Barrett and Dannenberg 2022; Hagen and Schneider 2021; Nordhaus 2015); or both (e.g. Helm et al. 2012). The paper departs from most existing research on trade and the environment in that it considers trade in pollution-reducing, rather than polluting, products.[5] Existing work in this vein includes Fischer et al. (2017), who compare the relative merits of up- and downstream subsidies when regions set different emission taxes and upstream producers engage in Cournot competition, selling abatement technology to downstream polluting firms in both regions. They find greater emission reductions under upstream subsidies, as a downstream subsidy increases the global price of abatement technology, leading the other region to use less of it. Fischer (2017), building on Spencer and Brander (1983) and Brander and Spencer (1985), shows that when producing countries of an environmental technology have domestic political incentives to increase production, and environmental benefits are large relative to such political distortions, restrictions on upstream subsidies can reduce global welfare.

3 Motivation: Solar Photovoltaics

Renewable energy technologies, once considered too expensive to be economically viable, have seen dramatic declines in cost over the past few decades, becoming competitive with traditional fossil fuels in many contexts. The two great success stories are electricity production using wind and solar power. Since the first commercial use of solar PV in 1958, its cost decreased by more than three orders of magnitude (Way et al. 2022). The price of solar panels fell by 75% between 2010 and 2015 (Gerarden 2023).

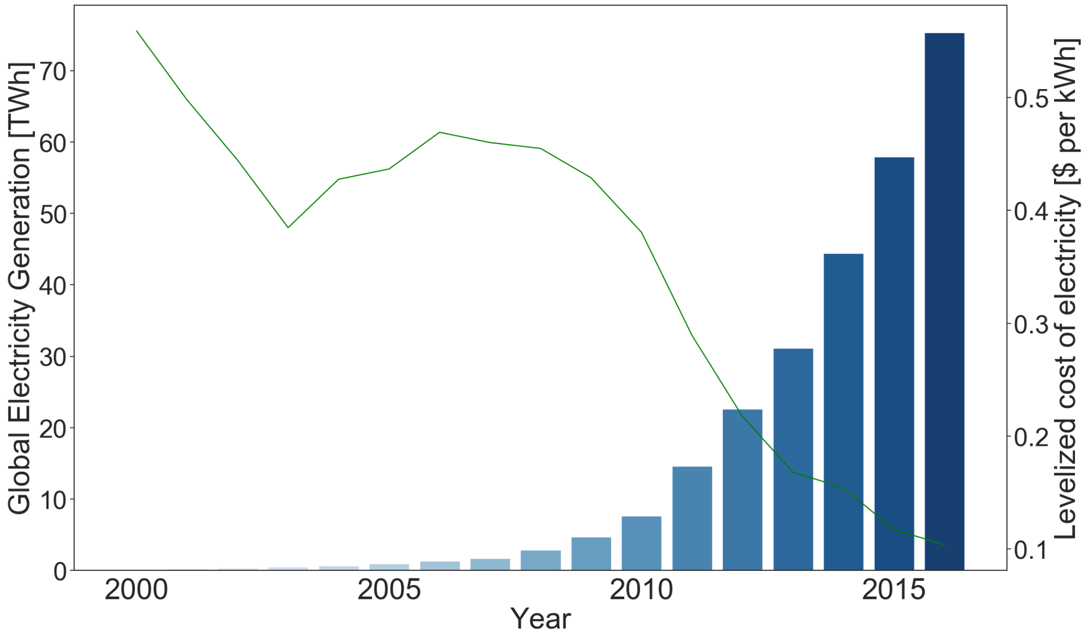
While about half of these cost declines can be attributed to reductions in material costs, economies of scale, and efficiency-increasing innovation (Nemet 2006), increased competition is thought to be another key driver (Carvalho et al. 2017; Dent 2018; Nemet 2006).

Figure 1 shows the levelized cost of electricity[6] in solar PV, as well as global electricity generation from solar, over the period 2000-2016. During this time, the levelized cost of electricity declined from over 0.5 to 0.1 USD per kWh, while global electricity generation increased from virtually nothing to more then 70 TWh per year. Technology innovation support and demand creation through government subsidies around the world, as well as the expansion of Chinese manufacturing – characterized by both supply- and demand-side industrial policy (Chen 2015) – are likely to have played a significant role.[7] Early government policies supporting solar PV

5. In reality, of course, the production process itself of so-called 'clean technology' is rarely carbon-neutral. However, for the purposes of this analysis I will focus on the mitigation potential of a clean technology and its resultant positive externalities.

6. The price per unit of electricity which would be required in order for a project to break even over its lifetime

7. In the context of the model presented in this paper, measures targeting the supply side (such as R&D support or export subsidies) will be conceptualized as 'producer subsidies', while demand-creation policies (such as feed-in tariffs or other deployment programmes) are conceptualized as 'consumer subsidies'.



Note: The green line plots the Levelized Cost of Electricity from solar PV in $ per kWh between 2000 and 2016. The blue bars show global electricity generation from solar PV in TWh over the same period. We see cost declining from over 0.5 to 0.1 $ per kWh, while deployment rose from close to zero to over 70 TWh. Source: Author's calculations based on Way et al. (2022) and Dudley et al. (2018).

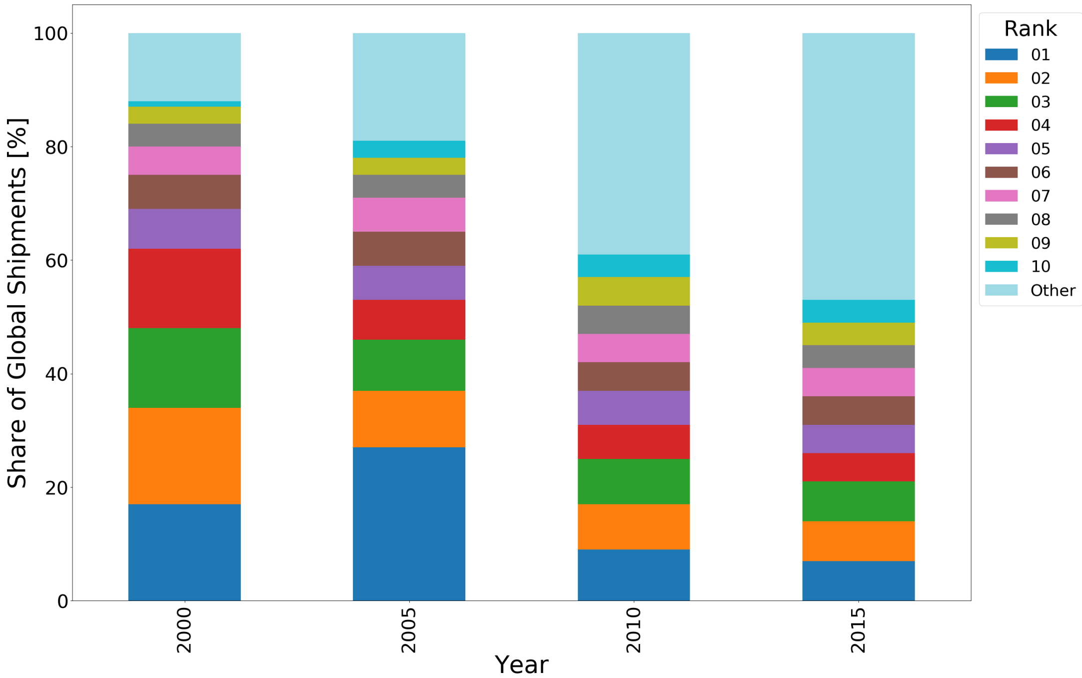
FIGURE 1
Solar PV Cost and Deployment, 2000-2016

include, for example, government R&D support and the founding of the Solar Energy Research Institute in the US in 1974 and the 1990 '1000 Roof' solar deployment program, as well as the 1991 solar feed-in tariff, in Germany (Hansen et al. 2018).

Figure 2 illustrates how the share of the top 10 firms in terms of global solar PV shipments declined from 88% in 2000 to 53% in 2015[8] – a period which experienced significant firm entry, in particular by Chinese firms. The Chinese government supported its solar PV industry using a mix of upstream subsidies, including discounts on raw materials, electricity and funding, export subsidies, and technological, infrastructure and personnel support (Chen 2015); and demand-creation measures such as feed-in tariffs and free grid connection services for distributed solar by China's largest state-owned utility (Zhang and He 2013). Chinese solar panel manufacturers reached more than 50% of global revenue share by 2012 (Chen 2015).

In 2012 and 2013, the US and the EU respectively imposed anti-dumping duties on Chinese solar panels, arguing that the latter were unfairly subsidized (Hughes and Meckling 2017; Meckling and Hughes 2018) and thereby retaliating against subsidies which reduced the cost of a low-carbon energy technology for their own utilities and consumers. The model presented below provides intuition for why the loss in profits earned by domestic producers may have outweighed the benefits to consumers and the climate from the perspective of western govern-

8. Note that the data on market concentration displayed in this section was sourced from industry blogs, as it was not possible to obtain data going back further than 2015 and covering more than the top 5 players from more formal data providers.



Note: The figure shows the share of the top 10 producers in global shipments of solar PV generation capacity for the years 2000 (when the top 10 captured 88% of global market share), 2005, 2010, and 2015 (when the share of the top 10 had declined to 53%). Source: Author's calculations based on Mints (2016) and Renewable Energy World (2014).

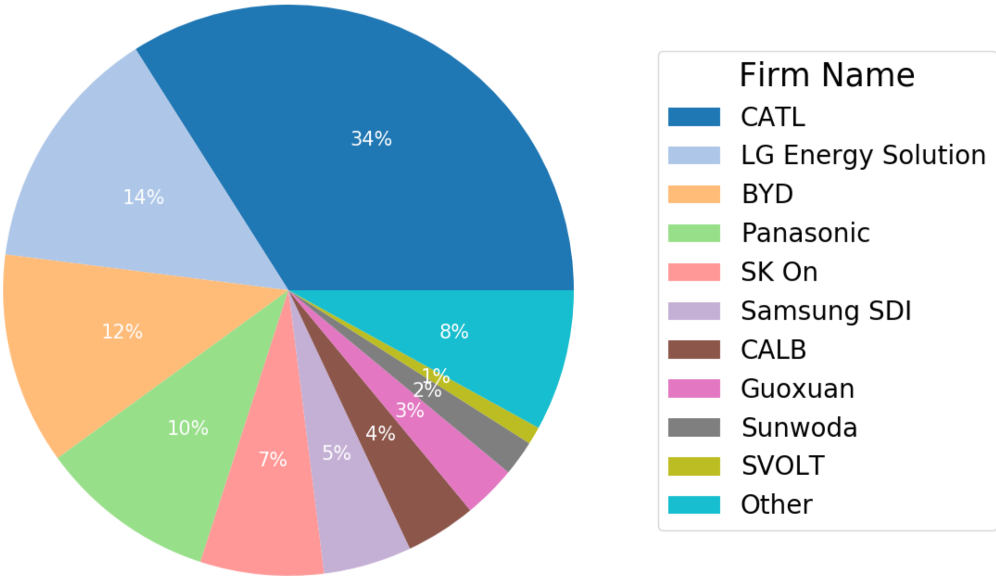
FIGURE 2
Market Concentration Over Time (Solar PV)

ments.

Looking forward, technologies which need to decline in cost in order to be economical include carbon capture and storage, green hydrogen, and energy storage. Lithium ion batteries, for example, are currently the most expensive part of electric vehicles, with a heavily concentrated global market. Figure 3 plots global market shares in EV batteries in 2022, showing that the top 10 producers currently capture 92% of global market share. Firm entry and competition may be key to driving down cost.

However, it is important to note that competition is only one of many reasons why the solar sector has evolved as it has. Moreover, the ability of Chinese manufacturers to sell at lower prices is likely to be at least in part due to domestic production conditions, rather than rent-seeking by western manufacturers.[9] Finally, the relationship between firm entry and technological maturity is surely bi-directional. While this section has sought to add intuition and real-world context to the theoretical model presented below, it should be interpreted with caution.

9. One seemingly obvious advantage are lower labor costs. However, Chen (2015) argues that labor costs account for only 10% of the cost of solar panel manufacturing, due to the industry's highly capital intensive nature.



Note: The figure shows the global market share of the top 10 firms in EV batteries in 2022. The market is highly concentrated, with the top 10 producers capturing 92% of the global market. Source: Author's calculations based on E-Vehicle Info (2022).

FIGURE 3
Market Concentration in 2022 (EV Batteries)

4 Model and Preliminaries

I analyze the strategic interactions between two countries, denoted as $i \in \{F, L\}$, over two time periods $t \in \{1, 2\}$. The model is a sequential game, wherein in each period, both countries simultaneously set policy. Both countries face the challenge of climate change and consider supporting the adoption of a climate-friendly technology that mitigates climate damages and negative externalities associated with fossil fuels. This technology is modeled to generate positive global externalities.

The strategic agents in this game are the governments of the two countries, responsible for trade policy and subsidies with the aim of maximizing domestic welfare over both periods. For simplicity, I assume there is no discount factor. Each government's welfare function encompasses consumer surplus ($CS_{i,t}$), industry profits ($\Pi_{i,t}$), and positive externalities ($B_{i,t}$) from global technology consumption.

Both governments are assumed to have complete information.

Government Policy To define the action set, it is useful to distinguish between the policy decisions each government can take.

First, in both periods government i chooses whether to trade or not to trade: $T_i = (\tau_{i,1}, \tau_{i,2})$.

$$T_i = \{(\tau_{i,1}, \tau_{i,2}) | (\tau_{i,1}, \tau_{i,2} \in \{0,1\})\}$$

, where $\tau_{i,t} = 0$ means autarky in period t and $\tau_{i,t} = 1$ means trade in period t.

Trade requires mutual agreement, such that it is sufficient for one country to prefer autarky to prevent trade.[10] This implies that countries' decisions with respect to trade map to trade policy outcomes as follows: $A_t = min(\tau_{F,t}, \tau_{L,t})$, where $A_t = 0$ indicates that countries are in autarky in period t, and $A_t = 1$ indicates that they are trading (i.e. there is a trade agreement) in period t. Let the sequence of trade policy outcomes[11] be denoted $A = \{A_1, A_2\}$.

Second, in each period t, governments also set the level of consumer subsidies $s_{i,t}^{cons} \geq 0$ and producer subsidies $s_{i,t}^{prod} \geq 0$. The set of subsidy policy decisions across both periods is

$$S_i = \{(s_{i,1}^{cons}, s_{i,1}^{prod}, s_{i,2}^{cons}, s_{i,2}^{prod}) | (s_{i,1}^{cons}, s_{i,1}^{prod}, s_{i,2}^{cons}, s_{i,2}^{prod} \in \mathbb{R}^+)\}$$

An element $s_i \in S_i$ is therefore 4-dimensional vector with the levels of subsidies for country i in both periods.

The full action set of government i is

$$P_i = T_i \times S_i$$

I assume that the subsidies employed are quantity subsidies, such that the overall cost of a consumer subsidy is $s_{i,t}^{cons} r_{i,t}$, where $r_{i,t}$ represents the quantity demanded by consumers in country i and period t, and that of a producer subsidy is $s_{i,t}^{prod} q_{i,t}$, where $q_{i,t}$ is the quantity produced by the domestic industry in period t. The government's best response will be that which maximizes

$$\begin{aligned} &\Sigma_{t=1}^{2} W_{i,t}(\tau_i, s_i, \tau_{-i}, s_{-i}) = \\ &\Sigma_{t=1}^{2} CS_{i,t}(\tau_i, s_i, \tau_{-i}, s_{-i}) + \Pi_{i,t}(\tau_i, s_i, \tau_{-i}, s_{-i}) + B_{i,t}(\tau_i, s_i, \tau_{-i}, s_{-i}) \\ &- s_{i,t}^{cons} r_{i,t}(\tau_i, s_i, \tau_{-i}, s_{-i}) - s_{i,t}^{prod} q_{i,t}(\tau_i, s_i, \tau_{-i}, s_{-i}) \end{aligned} \tag{1}$$

.

Consumer Demand and Externalities In each country and at each stage,[12] private sector demand for the technology is characterized by a linear relationship,[13] where p_i is the domestic price of the technology, and a is the demand curve intercept:

10. In practice, of course, trade policy tends to focus either on import or export barriers. Strategic sectors might be protected from import competition, while key inputs into such sectors might be subject to export restrictions. However, trade barriers do tend to be reciprocal where possible, and free trade agreements require mutual cooperation. I therefore consider this a reasonable simplification.

11. hereafter referred to as a 'trade policy sequence'

12. Time subscripts are dropped where possible to to aid readability.

13. Similarly to Fischer (2017) and Fischer et al. (2018).

$$r_i = \quad a - (p_i - s_i^{cons}) \tag{2}$$

implying that consumer surplus is

$$CS_i = \frac{a - (p_i - s_i^{cons})}{2} r_i = \frac{(a - (p_i - s_i^{cons}))^2}{2} = \frac{r_i^2}{2}$$

I assume that the clean technology replaces a dirty one, thereby avoiding negative externalities from pollution. For ease of exposition, I model this as a public benefit. The positive externality ($B_{i,t}$) from consumption in country i is a linear function[14] of global consumption:

$$B_{i,t} = \frac{b}{2}(r_{F,t} + r_{L,t})$$

The global positive externality is the sum of both countries' externalities, i.e.

$$B_t = b(r_{F,t} + r_{L,t})$$

Production and Market Structure Each country possesses a domestic industry capable of producing any quantity of the technology. The quantity produced in country i is denoted q_i. The cost of production depends on previous experience, with constant marginal cost c if experience exists and dc otherwise, where $d > 1$.

I assume that at the beginning of Stage 1, industry F is at the technology frontier with marginal production cost c, while industry L is lagging behind with marginal production cost dc. The process of the laggard country moving from marginal production cost dc in Stage 1 to marginal production cost c in Stage 2 will hereafter be referred to as 'catching up'. This process is captured by

$$c_{L,2}(q_{L,2}) = \begin{cases} cq_{L,2} & \text{if } q_{L,1} > 0 \\ dcq_{L,2} & \text{if } q_{L,1} = 0 \end{cases} \tag{3}$$

Markets are imperfectly competitive, with each country's domestic industry acting as a monopolist under autarky and a Bertrand duopolist under trade. I assume that the leading firm's monopoly price[15] exceeds the marginal cost of the lagging firm, such that trade puts competitive pressure on both firms under all scenarios. This implies that

$$\frac{a + c}{2} > dc \tag{4}$$

.

Firms are assumed to be myopic and only take into account the information available in the

14. Linear climate damage functions are used in much of the literature on international climate cooperation, e.g. Battaglini and Harstad (2016) and Holtsmark and Midttømme (2021).
15. Firm F's monopoly price is given by Equation 6.

current period.

Market Equilibrium Under autarky, firm i solves

$$\max_{\{p_i\}} \Pi_i = p_i q_i(p_i) + s_i^{prod} q_i(p_i) - c_i(q_i(p_i)) \tag{5}$$

Under trade, both consumers face the same prices – therefore, the firm with the lower price captures the whole market. Firm F's individual demand curve is given by

$$q_F(p_F, p_L) = \begin{cases} 2a - 2p_F + s_F^{cons} + s_L^{cons} & \text{if } p_F < p_L \\ a - p_F + \frac{s_F^{cons} + s_L^{cons}}{2} & \text{if } p_F = p_L \\ 0 & \text{if } p_F > p_L \end{cases}$$

while firm L's demand curve is given by

$$q_L(p_F, p_L) = \begin{cases} 0 & \text{if } p_F < p_L \\ a - p_L + \frac{s_F^{cons} + s_L^{cons}}{2} & \text{if } p_F = p_L \\ 2a - 2p_L + s_F^{cons} + s_L^{cons} & \text{if } p_F > p_L \end{cases}$$

. Let the competitive price faced by the consumer be denoted p. In the absence of producer subsidies, this leads to $p = c$ if the industry is levelled, and $p = dc - \varepsilon$ if it is unlevelled, where ε is an infinitesimal positive number. When producer subsidies are positive they modify firms' marginal costs accordingly.

I further assume that $a > dc$, which ensures consumption in all scenarios.

First Best A benevolent social planner seeking to maximize the sum of both countries' welfare over both periods would set global marginal benefits from consuming the technology, both private and public, equal to marginal cost c.[16] This yields

$$a + b - c = r_i$$

in each stage of the game. Proof: Appendix A.

Business As Usual Under autarky and without subsidies, each firm acts as a monopolist, leading to suboptimal outcomes due to monopoly losses, missed trade gains, and uninternalized externalities.

In both Stage 1 and Stage 2, in country F, the representative firm solves

$$\max_{\{p_F\}} [\Pi_F = \quad (a - p_F)p_F - (a - p_F)c]$$

16. Because the frontier country's marginal cost is lower, it is more efficient for the frontier country to supply the whole market in this scenario.

yielding

$$p_{F,1} = p_{F,2} = \frac{a+c}{2}; r_{F,1} = r_{F,2} = \frac{a-c}{2} \tag{6}$$

In country L,

$$p_{L,1} = \frac{a+dc}{2}; p_{L,2} = \frac{a+c}{2}; r_{L,1} = \frac{a-dc}{2}; r_{L,2} = \frac{a-c}{2}$$

Proof: Appendix A.

Subgame Perfect Nash Equilibrium I analyze governments' strategies over trade policy and subsidies. The following analysis will use backward induction to identify Subgame Perfect Nash Equilibria in pure strategies.

5 Analysis & Results

In the following, I identify Subgame Perfect Nash Equlibria in pure strategies for different versions of the game and examine their welfare implications. I start by analyzing the case in which countries have the option to trade, but do not use any additional policy to correct market failures. I then move on to a scenario in which countries can additionally use quantity subsidies to support the clean technology.

5.1 Equilibrium and Welfare without Subsidies

Could a trade agreement on its own (absent other policy to internalize externalities or correct monopoly losses) constitute an improvement over business-as-usual? Proposition 1 discusses countries' welfare payoffs under different trade policy strategies and highlights how these depend on the distance to frontier d. Proposition 2 characterizes the pareto optimal Subgame Perfect Nash Equilibrium, and Proposition 3 highlights the global welfare implications of different trade policy sequences.

Proposition 1. *Suppose that no subsidies can be employed, and the government's action set is restricted to T_i. Let T_i^* denote country i's trade policy choice in both periods under its best response. Then,*

i $\Sigma_{t=1}^{2} W_{L,t}((\tau_{L,1},1),T_F^*)) > \Sigma_{t=1}^{2} W_{L,t}((\tau_{L,1},0),T_F^*))$

ii $\Sigma_{t=1}^{2} W_{F,t}((\tau_{F,1},1),T_L^*)) > \Sigma_{t=1}^{2} W_{F,t}((\tau_{F,1},0),T_L^*))$

iii *There exists a threshold $\omega = f(a,c,b)$ such that*

- *For $d > \omega$:* $\Sigma_{t=1}^{2} W_{L,t}((0,1),T_F^*)) \geq \Sigma_{t=1}^{2} W_{L,t}((1,1),T_F^*))$

- *For $d < \omega$:* $\Sigma_{t=1}^{2} W_{L,t}((0,1),T_F^*)) < \Sigma_{t=1}^{2} W_{L,t}((1,1),T_F^*))$

iv *There exists a threshold $\gamma = g(a,c,b)$ such that*

- *For $d > \gamma$ and $b > a-c$:* $\Sigma_{t=1}^{2} W_{F,t}((0,1),T_L^*)) \geq \Sigma_{t=1}^{2} W_{F,t}((1,1),T_L^*))$
- *For $d < \gamma$ or $b < a-c$:* $\Sigma_{t=1}^{2} W_{F,t}((0,1),T_L^*)) \leq \Sigma_{t=1}^{2} W_{F,t}((1,1),T_L^*))$

v *For any a,c,b which are consistent with the assumptions of the model, $\omega < \gamma$.*

Proof: Welfare payoffs under trade and autarky and the implied thresholds ω and γ are derived in Appendix B.

Proposition 1, parts (i) and (ii) state that both countries are better off if they trade in Stage 2. In Stage 2, if the laggard firm has not caught up with the frontier firm, the frontier firm will dominate the market with a price $p = dc - \varepsilon$. However, if the laggard firm catches up, both firms share the market at a price $p = c$. In either case, trade leads to higher consumer surplus, consumption, and positive externalities compared to autarky.[17] Because trade requires mutual agreement, there are other Nash Equilibria in which there is no trade. Therefore, this implies that trade is a weakly dominant strategy for both countries in Stage 2.

If the laggard country has not caught up, the frontier firm extracts rent from the laggard country amounting to $c(d-1)r_L$. Conversely, if it has caught up, prices are lower, consumption, consumer surplus, and positive externalities are higher, and the deadweight loss of monopoly is eliminated. In order for the laggard country to catch up, countries must remain in autarky in Stage 1.

Proposition 1, part (iii) states that whether the laggard country's welfare over both periods is greater under trade in both periods or autarky in Stage 1, trade in Stage 2, depends on the value of d. As in Stage 2, in Stage 1 welfare is higher under trade than autarky. However, remaining in autarky allows the laggard country to catch up. If countries trade in Stage 1, then the frontier firm supplies the market in both periods. If they remain in autarky in Stage 1, the laggard country trades off welfare losses in Stage 1 for gains in Stage 2. Whether welfare gains in Stage 2 outweigh welfare losses in Stage 1 of remaining in autarky to catch up with the frontier country depends on whether d exceeds some threshold ω.

While the frontier country extracts rents from the laggard country in an unlevelled industry with trade, it also enjoys higher consumer surplus and positive externalities in Stage 2 if the laggard country has caught up. Proposition 1, part (iv) states that the frontier country's best response is also dependent on the value of d, as well as the level of the positive externality b. If d exceeds a threshold γ and there are positive externalities $b > a-c$, the frontier country's welfare payoff is also higher under the trade policy sequence $A = \{0,1\}$ than under $A = \{1,1\}$.

17. This is not the case when subsidies can be employed to correct for monopoly losses and positive externalities. However, when there are no subsidies, given stated assumptions trade always leads to competitive benefits for both countries.

Intuitively, while the intertemporal trade-off for the laggard country depends only on the relative levels of consumer surplus and positive externalities under different trade policy sequences, the frontier country additionally takes into account the rents it can extract from the laggard in an unlevelled industry under trade. In the absence of positive externalities, these rents ensure that the benefits from trading in the first stage (comprising higher consumer surplus in Stage 1, as well as rents collected in both stages) always outweigh the gains in consumer surplus in Stage 2 if the laggard has caught up. However, positive externalities from consumption present an additional gain from fiercer competition in Stage 2, resulting in the conditions presented in (iv).

Part (v) states that the threshold ω is smaller than γ, meaning that there are values of d for which the laggard country's pay-off is higher under $A = \{0,1\}$, while that of the frontier country would be higher under $A = \{1,1\}$.

Following from Proposition 1, we can characterize the pareto-optimal SPNE in pure strategies as follows:

Proposition 2. *If no subsidies can be employed, and the government's action set is restricted to T_i, then*

i There exists a pareto-optimal Subgame Perfect Nash Equilibrium in which the outcome is characterized by

- *Autarky in Stage 1, Trade in Stage 2 if $d > \omega$*
- *Trade in Stage 1, Trade in Stage 2 if $d < \omega$*

ii If $d > \gamma > \omega$ and $b > a - c$ or $d < \omega < \gamma$, this SPNE is pareto superior to any other trade policy sequence, including other Nash Equilibria as well as non-equilibria.

iii If $\omega < d < \gamma$ or $d > \gamma$ and $b < a - c$, the SPNE is pareto optimal, but the frontier country would enjoy a higher welfare payoff under trade in both Stage 1 and Stage 2.

Given that trade requires mutual agreement, it is sufficient for one country to prefer autarky over trade in order to prevent trade. Proposition 2, part (i) therefore describes the equilibrium as determined by the value of d in relation to ω as defined in Proposition 1: the pareto optimal Subgame Perfect Nash Equilibrium involves autarky in Stage 1, trade in Stage 2 if $d > \omega$, and trade in both periods if $d < \omega$.

Proposition 2, part (ii) states that if $d > \gamma$ (as defined in Proposition 1) and $b > a - c$ or if $d < \omega$, the policy outcomes defining the SPNE are associated with the highest possible welfare payoff for both the laggard and the frontier country, and are therefore pareto superior to all other possible outcomes (including both equilibria and non-equilibria). Part (iii) states that if one of these conditions does not hold, the equilibrium is pareto optimal, but it is not the only pareto optimal allocation: the frontier country would enjoy a higher welfare payoff under a different outcome which is, however, not an equilibrium.

As per the reasoning presented above and the welfare payoffs derived in Appendix B, if countries trade in Stage 2, neither country can increase its welfare by moving to autarky. In Stage 1, if $d > \omega$, cumulative welfare over both periods in the laggard country is higher by remaining in autarky, and moving to trade will therefore not constitute a welfare improvement. Since trade requires mutual agreement, the frontier country cannot unilaterally bring about trade, even if this would be welfare-improving. Moreover, if $d < \omega$, moving to autarky would be welfare-reducing for both countries, making the mutual decision to trade an equilibrium.

Other Equilibria The Subgame Perfect Nash Equilibrium in pure strategies as outlined in Proposition 2 is pareto optimal, but not unique. Due to the assumption that trade requires mutual agreement, opting for trade affects payoffs only if the other country also opts for trade, while opting for autarky affects payoffs only if the other country does not. This implies that there are additional Subgame Perfect Nash Equilibria which deviate from the equilibrium outlined in Proposition 2, for example because both countries have opted for autarky in Stage 1 despite $d < \omega$ or both countries have opted for autarky in Stage 2. These equilibria are pareto inferior.

Having analyzed each individual country's welfare payoffs under different trade policy outcomes and characterized the pareto optimal SPNE, I now turn to global welfare.

Proposition 3. *If the government's action set is restricted to T_i, there exists a threshold $\theta = k(a,c,b)$ such that*

- *For $d > \theta$ and $b > \frac{a-c}{24}$:*

$$\Sigma_{t=1}^{2} W_{F,t}((0,1),(\tau_{L,1},1)) + W_{L,t}((\tau_{L,1},1),(0,1)) =$$
$$\Sigma_{t=1}^{2} W_{F,t}((\tau_{F,1},1),(0,1)) + W_{L,t}((0,1),(\tau_{F,1},1)) > \Sigma_{t=1}^{2} W_{F,t}((1,1),(1,1)) + W_{L,t}((1,1),(1,1))$$

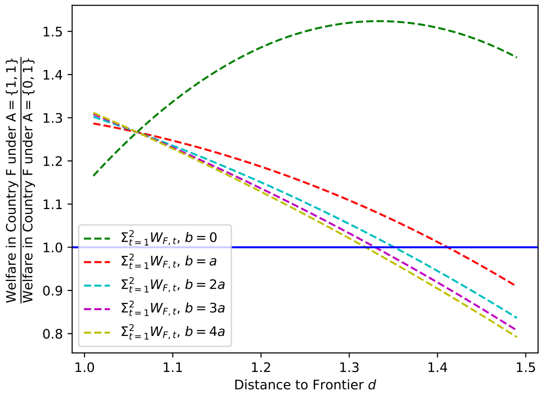
- *For $d < \theta$ or $b < \frac{a-c}{24}$:*

$$\Sigma_{t=1}^{2} W_{F,t}((0,1),(\tau_{L,1},1)) + W_{L,t}((\tau_{L,1},1),(0,1)) =$$
$$\Sigma_{t=1}^{2} W_{F,t}((\tau_{F,1},1),(0,1)) + W_{L,t}((0,1),(\tau_{F,1},1)) < \Sigma_{t=1}^{2} W_{F,t}((1,1),(1,1)) + W_{L,t}((1,1),(1,1))$$

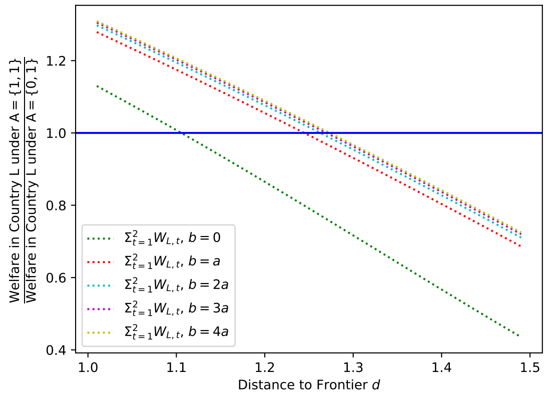
Proof: θ is derived in Appendix B.

Proposition 3 states that the presence of positive externalities implies that the policy sequence $A = \{0,1\}$ is associated with greater global welfare than $A = \{1,1\}$ if d exceeds a particular threshold. For any a,c,b which are consistent with the assumptions of the model, $\omega < \theta < \gamma$.

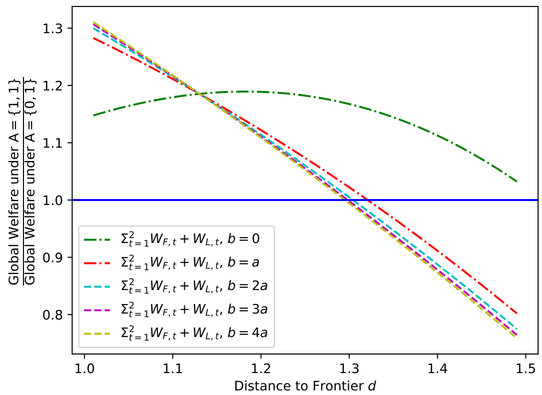
Appendix B derives welfare payoffs for both countries for all possible strategy profiles.



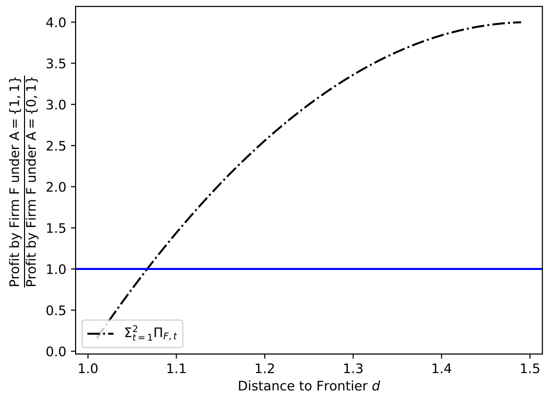
(a) Frontier Country Welfare



(b) Laggard Country Welfare



(c) Global Welfare



(d) Profit by firm F

Note: The figures above plot the ratios of overall (sum of Stage 1 and Stage 2) country welfare, global welfare, and firm F's profit for different values of d under $A = \{1,1\}$ as compared to $A = \{0,1\}$ when $a = 2c$. Figures 5, 6 and 7 (Appendix) show the same plots for different ratios of a to c. Where the ratio falls below 1, the outcome in question is improved by remaining in autarky in Stage 1.
The figures illustrate the opposing effects of trade on profit and welfare: the further country L is from the technological frontier, the more $A = \{1,1\}$ reduces overall welfare as compared to $A = \{0,1\}$, and the more it increases firm F's profits (firm L's profits are not plotted as the ratio is always 0). Figures 4a and 4c highlight the significance of the positive externality $b(r_F + r_L)$ in the model: for $b = 0$, $A = \{1,1\}$ is always welfare improving for the frontier country, as well as globally, for any value of d which is greater than 1 and satisfies Equation 4. However, for sufficiently large positive values of b, trading in both periods can become welfare reducing beyond certain thresholds of d for both countries. Moreover, the greater b becomes relative to a, the more the ratio of individual countries' welfare payoffs should resemble each other.

FIGURE 4
Welfare and Profit Under Trade Relative to Autarky

Figure 4a plots the ratio of the frontier country's, Figure 4b the laggard country's overall (Stage 1 plus Stage 2) welfare under the policy sequence $A = \{1,1\}$ versus $A = \{0,1\}$ for different values of d and b when $a = 2c$. The figures show that for $b = 0$, losses in rents and Stage 1 externalities and consumer surplus outweigh any Stage 2 gains in externalities and consumer surplus from the laggard industry catching up for the frontier country, while ω is much lower than it is at higher values of b. The greater the positive externality b, the more closely aligned countries' preferences for trade or autarky in Stage 1 become: ω and λ converge as b increases. Finally, Figure 4c plots the ratios of global welfare for different values of b, showing that in the absence of positive externalities, global welfare implications more closely resemble the frontier country's welfare and make free trade the preferred choice. When a positive externality is present, remaining in autarky in Stage 1 to allow the laggard country to catch up becomes welfare improving globally for sufficiently high values of d.

Finally, Figure 4d plots the ratio of profits earned by firm F in the scenario $A = \{1,1\}$ compared to $A = \{0,1\}$.

5.2 Optimal Subsidy Mix Under Trade

In the presence of market failures such as consumption externalities and imperfect competition, a policy maker may want to intervene beyond the decision whether or not to trade. In this section, I therefore consider the use of quantity subsidies.

An upstream (producer) subsidy shifts the firm's profit, as in Equation 5, while a downstream (consumer) subsidy shifts the demand curve, as shown in Equation 2. Under autarky, either subsidy affects quantitites and welfare in the same way. Under trade, the subsidy mix matters.[18]

Let s_i^* denote country i's optimal subsidy mix, with s_i^{prod*} and s_i^{cons*} denoting the optimal producer and consumer subsidy.

Proposition 4. *Suppose both countries can choose a mix of consumer and producer subsidies. In Stage 1, the laggard firm produces at constant marginal cost dc, while the frontier firm produces at constant marginal cost c. Then there exists a pareto-optimal SPNE in pure strategies such that*

i Countries trade in both periods: $T_L^* = T_F^* = (1,1)$.

ii In each period, the laggard country sets its producer subsidy at $s_L^{prod*} = c(d-1) - \varepsilon$.

iii The frontier country does not use producer subsidies: $s_F^{prod*} = 0$

iv In each period, both countries set consumer subsidies $s_F^{cons*} = s_L^{cons*} = \frac{b}{2}$.

Proposition 4, part (i) is based on the observation that if both countries have the flexibility to choose their subsidy mix, the weakly dominant strategy for both is to trade in both periods.[19] Part (ii) states that the laggard country opts for a producer subsidy that enforces marginal cost pricing and prevents the frontier firm from extracting rents:

18. Fischer (2017) highlights how under imperfect competition, an upstream subsidy will enhance the domestic firm's market share, while a downstream subsidy benefits both domestic and foreign firms. Under Cournot competition, a downstream subsidy also tends to increase prices globally, which is not the case here.

19. When both producer and consumer subsidies are available, neither country benefits from allowing the laggard country to catch up. The inter-temporal trade-off therefore becomes irrelevant.

$$s_L^{prod*} = c(d-1) - \varepsilon$$

Part (iv) states that simultaneously, both countries implement a consumer subsidy equal to

$$s_F^{cons*} = s_L^{cons*} = \frac{b}{2}$$

, thereby internalizing domestic positive externalities.

As a result, the frontier firm supplies the global market at a price of $p = c$, with demand (r_F and r_L) equal to $a - c$. The outcome is equivalent to perfect competition. Welfare in each country during each stage of the game can be expressed as:

$$W_F = W_L = \frac{(a-c)^2}{2} + b(a-c)$$

This configuration represents a Subgame Perfect Nash Equilibrium in this model. The equilibrium is pareto-optimal, but not unique. Optimal subsidies and the resulting quantities and welfare payoffs are derived in Appendix D.

The laggard country has no incentive to deviate from this equilibrium. Moving to autarky would increase production costs and reduce consumer surplus and positive externalities. Setting a higher upstream subsidy results in either market sharing or the laggard firm monopolizing the market, both of which similarly reduce its welfare. Reducing the subsidy would allow the frontier firm to extract rent from its consumers and increase prices while reducing consumer surplus and positive externalities.

Likewise, the frontier country finds no welfare-improving deviations. In autarky, the frontier country would set a subsidy which eliminates the deadweight loss from the monopoly and internalizes domestic positive externalities, leading to the same domestic outcome as that which is obtained when countries trade and $s_L^{prod*} = c(d-1) - \varepsilon$ and $s_F^{cons*} = s_L^{cons*} = \frac{b}{2}$. Autarky would reduce welfare in the frontier country by lowering positive externalities from consumption in the laggard country.

Finally, given the price regime and trade conditions, $\frac{b}{2}$ is the optimal consumer subsidy. While positive externalities would increase if the subsidy was higher, each country considers only the marginal benefit to its own population, which equals $\frac{b}{2}$.

The policy mix countries will choose if they are able to trade and use a combination of producer and consumer subsidies thus delivers the highest cumulative welfare, given the first best is not available. It cannot correct the market failure resulting from the climate externality. However, it yields an outcome equivalent to perfect competition.

Other Equilibria The Subgame Perfect Nash Equilibrium in pure strategies as outlined above is pareto optimal, but not unique. Because trade requires mutual agreement, neither country can unilaterally decide to bring about trade. If one country opts to remain in autarky then the other country is indifferent between trade and autarky, making trade a weakly dominant strategy. This implies that there are additional Subgame Perfect Nash Equilibria in which countries trade only in one period, but not the other, or remain in autarky throughout both periods. In any given stage of the game, such an equilibrium could come about because both countries have opted for autarky. The optimal subsidy for each country becomes that which eliminates the deadweight loss from monopoly and internalizes domestic positive externalities. However, both countries are worse off under autarky relative to trade, rendering these other equilibria pareto inferior. For optimal subsidies, quantities and welfare under autarky, see Appendix C.

Equilibrium and Welfare without Producer Subsidies In practice, countries have often relied on downstream subsidies to support green industries. This may be due to political acceptability considerations, fiscal constraints, or the dubious status of upstream subsidies under World Trade Organization rules. This section therefore analyzes equilibrium policy and welfare when only consumer subsidies are available.

Proposition 5. *Suppose countries can only use consumer subsidies, and all other assumptions remain unchanged. Then,*

i $\Sigma_{t=1}^{2} W_{L,t}((0,1), s_L^*, T_F^*, s_F^*)) = \Sigma_{t=1}^{2} W_{L,t}((0,0), s_L^*, T_F^*, s_F^*) > \Sigma_{t=1}^{2} W_{L,t}((1,\tau_{L,2}), s_L^*, T_F^*, s_F^*))$. *There are thus two weakly dominant strategies for the laggard country. One strategy involves autarky in both stages, while the other involves autarky in the first and trade in the second stage.*

ii *There are eight SPNE in pure strategies. In all of them, the strategy profiles imply autarky in the first stage.*

iii *For all equilibria, in Stage 1:* $s_{F,1}^{cons*} = a+b-c$, $s_{L,1}^{cons*} = a+b-dc$

iv *For all equilibria, in Stage 2, both firms produce at constant marginal cost c.*

v *For the set of SPNE in which countries trade in the second stage, in Stage 2:* $s_{F,2}^{cons*} = s_{L,2}^{cons*} = \frac{b}{2}$

vi *For the set of SPNE in which countries are in autarky in the second stage, in Stage 2:* $s_{F,2}^{cons*} = s_{L,2}^{cons*} = a+b-c$

Proof: Appendix D.1.

Proposition 5, part (i) states that the laggard country's overall welfare payoff is higher if countries remain in autarky in Stage 1 than if they trade in Stage 1. Whether countries trade in Stage 2, having remained in autarky in Stage 1, is irrelevant to either country's welfare. Under autarky each government will subsidize in order to eliminate the deadweight loss from the monopoly and internalize the domestic part of the climate externality.

As a result, there are no competitive benefits from trade, and quantities consumed in both countries in any given stage are the same under trade as under autarky. However, remaining in autarky in Stage 1 implies equalized marginal costs in Stage 2, which reduces prices, increases consumer surplus and positive externalities, and eliminates the possibility of rent extraction by the frontier country. The laggard country's (weakly)[20] dominant strategy is therefore to remain in autarky in Stage 1. There is no equlibrium involving trade in Stage 1. In Stage 2, both countries are indifferent between trade and autarky as quantities consumed and welfare payoffs are identical under both scenarios. There are thus eight Subgame Perfect Nash Equilibria in pure strategies, as stated in Proposition 5, part (ii).

Each SPNE involves autarky in Stage 1, with the consumer subsidies given in Proposition 5, part (iii). As a result, the laggard firm catches up and also produces at marginal cost c in Stage 2, as stated in part (iv).

Part (v) states optimal consumer subsidies in Stage 2 of those SPNE which involve trade in the second stage, while part (vi) states optimal consumer subsidies in Stage 2 of the SPNE which involve autarky in the second stage.

To see why these are the only pure strategy Nash Equilibria, suppose countries opted for trade in Stage 1. As shown in Table 3, Appendix D.1, the laggard's welfare in Stage 1 remains the same, while the frontier country's welfare in Stage 1 increases by $c(d-1)r_L$. In Stage 2, following autarky, the laggard is indifferent between trade and autarky. However, its welfare would be higher, had it remained in autarky in Stage 1 and caught up to the technology frontier. Anticipating this, the laggard could increase its Stage 2 welfare by moving to autarky in Stage 1, without sacrificing any Stage 1 welfare. Thus, the laggard's best response if the frontier country opts for trade in Stage 1 is to opt for autarky. Given the laggard's best response, the frontier is indifferent between trade and autarky.

6 Discussion & Conclusion

Government support for climate change mitigation technologies often goes hand in hand with efforts to promote domestic production, such as in the US Inflation Reduction Act and the EU's Net Zero Industry Act. Meanwhile, foreign subsidies for such technologies have in the past been met with trade restrictions such as anti-dumping measures, as for example in the US- and EU-China solar trade wars in 2012 and 2013. While restrictions on trade increase the cost of deploying green technologies, thereby potentially slowing down climate change mitigation efforts, attempts to reach an environmental trade agreement at the WTO have thus far been unsuccessful.

Promoting domestic green industries could be deemed desirable for many reasons. Underlying factors and objectives could include local job creation and the interests of industry lobby

20. Because trade requires mutual agreement, such that the laggard country would be indifferent between trade and autarky if the frontier country had opted for autarky.

groups, as well as the resilience of domestic supply chains in a key sector such as energy, particularly in the context of a volatile geopolitical environment. Fischer (2017) shows how in the presence of environmental externalities, these individual country objectives can lead to an upstream subsidy race correcting environmental externalities in a framework building on Spencer and Brander (1983) and Brander and Spencer (1985), where two producing countries compete for a third country export market.

This paper has focused on the implications of environmental externalities in the presence of an infant industry and imperfect competition. In the absence of policy tools such as subsidies to correct for market failures, temporarily protecting an infant industry can be beneficial for the protecting country in the long run. In contrast to other work on infant industries, which typically emphasizes intersectoral spillovers and other growth-promoting factors rendering a sector strategically important, these benefits arise because allowing the infant industry to mature increases global competition later on. This prevents rent extraction by the country which was originally at the technology frontier. Moreover, when there are sufficiently large positive externalities from the technology (such as, in this case, avoided climate damages), allowing an infant industry to catch up improves not only the welfare of the initially laggard country, but also global welfare, and sometimes even the welfare of the frontier country.

In contrast, when countries are able to use both up- and downstream subsidies, the laggard can avoid rent extraction by the frontier country and global gains from trade are maximized. Infant industry protection is no longer necessary in this framework and the short-term costs associated with it can be avoided. However, when only downstream subsidies are available, gains from trade disappear. Then, both the laggard country's welfare as well as global welfare are unambiguously higher when the infant industry is allowed to catch up. The frontier country is worse off than under free trade, as it loses the ability to extract rents from the laggard.

The model provides intuition for why it may be optimal that (a) countries supporting clean technology often use trade barriers such as local content requirements, to the extent to which those actually work,[21] and (b) early movers in the global market often oppose production subsidies, as was apparent in the EU and US-China solar trade wars, for example.[22] The results imply that an environmental trade agreement may be desirable from a climate point of view only when production subsidies are available. Global trade law does not currently make allowances for the potential global benefits of producer subsidies for products with positive externalities, which renders such subsidies susceptible to challenge, as exemplified in the US- and EU-China solar trade wars. This relates to the broader challenge of reviewing WTO rules to ensure they are compatible with climate goals, especially given stated plans to introduce a Carbon Border

21. Recent empirical evidence, however, suggests that local content requirements alone are not sufficient to develop an infant industry, see Scheifele et al. (2022).

22. The inspiration for this paper comes from China's entry into the solar PV market, supported by industrial policy, and the resulting increase in competition and reduction in prices. By now, however, China has come to dominate the market for solar PV as well as other clean technologies. One might therefore argue that at this point in time, China has become the frontier country and countries which used to be early movers are lagging behind.

Adjustment Mechanism in the European Union (Grubb et al. 2022).

More broadly, the framework presented here demonstrates that when there are positive externalities, industrial policy can benefit not only the country undertaking it, but also the rest of the world. This is relevant to any technology with positive consumption externalities in addition to those with environmental benefits.

The model presented is very parsimonious and includes a number of limiting assumptions. First, the only mechanism through which an active domestic industry is beneficial for the laggard country is by catching up the technology frontier and thereby avoiding rent extraction by the other country. Once the laggard has caught up, Bertrand competition implies profit dissipation for both countries. The model abstracts from any other potential benefits of having an active domestic industry, such as job creation or inter-sectoral spillovers.

While there may be some differences in quality, the products motivating the paper – such as solar panels, batteries or vaccines – are homogenous enough for price competition to be a reasonable assumption. The 'catching up' process can be conceptualized as implicitly being driven by entry costs or dynamic economies of scale, and, while highly simplified, is sufficient to illustrate the mechanism this paper has sought to highlight. However, other factors such as capacity constraints on the one hand, economies of scale on the other, are not explicitly considered here and might more appropriately be modelled using Cournot competition.

In a Cournot model, both firms would produce positive quantities even in an unlevelled industry, implying that results would depend on the properties of the learning curve. Here, the learning process is modelled in a very simplistic way: if the laggard country is active, it catches up; otherwise the industry remains unlevelled. The frontier country does not learn. Future work could consider a more sophisticated learning curve, as well as dynamics of innovation in level versus uneven global supplier markets. The merits of infant industry protection would then depend on the relative rates of learning, as well as degree to which current market share and competition incentivize learning and innovation.

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Appendix

A Model Preliminaries

First Best Note that because production costs are lower in the frontier country, welfare would be higher if all production took place there, provided other market failures such as those arising from imperfect competition can be corrected.

In each stage, a benevolent social planner maximizes global welfare by setting the marginal benefit of consumption equal to the marginal cost.

From the demand curve we deduce that the marginal private benefit from consumption (given by the marginal willingness to pay price p_i, $p_i = a - r_i$) is equal to $a - r_i$ in each country $i \in \{F, L\}$. The global public benefit from consumption is equal to $B = b(r_F + r_L)$, implying that the marginal public benefit from each additional unit consumed is b. Finally, the marginal cost of production in the frontier country is c. Thus, the social planner sets

$$a - r_i + b = c$$

such that

$$r_F = r_L = a + b - c$$

However, due to misalignment of countries' incentives this outcome cannot be sustained as an equilibrium. Neither country has an incentive to pay the subsidies required to achieve the first best outcome, because the marginal public benefit from consumption in each country is only $\frac{b}{2}$.

Business as Usual Let a business-as-usual scenario be one where countries are in autarky and no subsidies are employed. Then, in the frontier country the monopolist sets prices or quantities to solve

$$\begin{aligned}\max_{\{p_F\}} \Pi_F = r_F(p_F - c) =& (a - p_F)(p_F - c) \\ =& ap_F - p_F^2 - ac + p_F c\end{aligned}$$

The first order condition is:

$$\frac{\delta \Pi_F}{\delta p_F} = a + c - 2p_F = 0$$

It is satisfied at

$$p_F = \frac{a+c}{2}; r_F = \frac{a-c}{2}$$

The second order condition is always satisfied as

$$\frac{\delta^2 \Pi_F}{\delta p_F} = -2 < 0$$

The monopolist in the laggard country solves an equivalent problem, substituting dc for c in Stage 1. Thus

$$
\begin{aligned}
p_{L,1} = \frac{a+dc}{2}; r_{L,1} = \frac{a-dc}{2} \\
p_{L,2} = \frac{a+c}{2}; r_{L,2} = \frac{a-c}{2}
\end{aligned} \tag{7}
$$

B EQUILIBRIUM WITH NO SUBSIDIES

In a business-as-usual scenario in which countries are in autarky and no subsidies are used, each firm acts as a monopolist, with prices and quantities given by Equation 7.

Let ε be an infinitesimal positive number. Under trade and in the absence of subsidies, the competitive price and resultant quantities are given by $p_1 = p_{F,1} = dc - \varepsilon$, $q_{F,1} = r_{F,1} + r_{L,1}; q_{L,1} = 0$ and $r_{F,1} = r_{L,1} = a - dc$ in Stage 1. In Stage 2,

$$
p_2 = \begin{cases} p_{F,2} = dc - \varepsilon & \text{if } q_{L,1} = 0 \\ p_{F,2} = p_{L,2} = c & \text{if } q_{L,1} > 0 \end{cases}
$$

implying that

$$
\begin{cases} q_{F,2} = r_{F,2} + r_{L,2}; q_{L,2} = 0 & \text{if } q_{L,1} = 0 \\ q_{F,2} = q_{L,2} = \frac{r_{F,2}+r_{L,1}}{2} & \text{if } q_{L,1} > 0 \end{cases}
$$

and

$$
\begin{cases} r_{F,2} = r_{L,2} = a - dc & \text{if } q_{L,1} = 0 \\ r_{F,2} = r_{L,2} = a - c & \text{if } q_{L,1} > 0 \end{cases}
$$

Welfare payoffs for each strategy profile in the game without subsidies are given in Table 1.

In Stage 2, trade is a weakly dominant strategy for both countries. The following analysis will therefore focus on characterizing the Subgame-Perfect Nash Equilibrium in which countries trade in Stage 2, and determine which Stage 1 strategy is welfare maximizing across both periods.

It is clear that Stage 1 welfare in both countries is greater under trade, while the laggard country's and collective Stage 2 welfare are greater following autarky in Stage 1.[23] Each government must therefore trade off the welfare losses from Stage 1 autarky against the welfare gains derived from the frontier firm's ability to catch up.

Proof of Proposition 1 Using the welfare payoffs presented in Table 1, we see that

$$
\Sigma_{t=1}^{2} W_{L,t}((0,1), T_F^*)) > \Sigma_{t=1}^{2} W_{L,t}((1,1), T_F^*))
$$

requires

$$
\frac{3}{8}(a-dc)^2 + \frac{(a-c)^2}{2} + \frac{b}{4}(6a - c(5+d)) > (a-dc)^2 + 2b(a-dc)
$$

which holds for

$$
d > \frac{5a+7b}{5c} - \frac{1}{5}\sqrt{\frac{20a^2+50ab+49b^2-40ac-50bc+20c^2}{c^2}}
$$

23. The frontier country's welfare may be higher or lower in Stage 2 following autarky in Stage 1, depending on whether the increases in consumer surplus and positive externalities are greater or lower than the loss in rents extracted from the laggard country's consumers.

TABLE 1
Payoff Matrix (No Subsidies)

	Laggard: (1, 1)	Laggard: (1, 0)	Laggard: (0, 1)	Laggard: (0, 0)
Frontier: (1, 1)	$\Big(2(a-dc)(\frac{a-dc}{2}+2c(d-1)+b),\ (a-dc)^2+2b(a-dc)\Big)$	$\Big((a-dc)(\frac{a-dc}{2}+2c(d-1)+b)+\frac{3}{8}(a-c)^2+\frac{b}{2}(a-\frac{c(1+d)}{2}),\ \frac{7}{8}(a-dc)^2+\frac{b}{4}(6a-c(1+5d)\Big)$	$\Big(\frac{7}{8}(a-c)^2+\frac{b}{4}(6a-c(5+d)),\ \frac{3}{8}(a-dc)^2+\frac{(a-c)^2}{2}+\frac{b}{4}(6a-c(5+d)\Big)$	$\Big(\frac{3}{4}(a-c)^2+\frac{b}{4}(4a-c(3+d)),\ \frac{3}{8}(a-dc)^2+\frac{3}{8}(a-c)^2+\frac{b}{4}(4a-c(3+d))\Big)$
Frontier: (1, 0)	$\Big((a-dc)(\frac{a-dc}{2}+2c(d-1)+b)+\frac{3}{8}(a-c)^2+\frac{b}{2}(a-\frac{c(1+d)}{2}),\ \frac{7}{8}(a-dc)^2+\frac{b}{4}(6a-c(1+5d)\Big)$	$\Big((a-dc)(\frac{a-dc}{2}+2c(d-1)+b)+\frac{3}{8}(a-c)^2+\frac{b}{2}(a-\frac{c(1+d)}{2}),\ \frac{7}{8}(a-dc)^2+\frac{b}{4}(6a-c(1+5d)\Big)$	$\Big(\frac{3}{4}(a-c)^2+\frac{b}{4}(4a-c(3+d)),\ \frac{3}{8}(a-dc)^2+\frac{3}{8}(a-c)^2+\frac{b}{4}(4a-c(3+d))\Big)$	$\Big(\frac{3}{4}(a-c)^2+\frac{b}{4}(4a-c(3+d)),\ \frac{3}{8}(a-dc)^2+\frac{3}{8}(a-c)^2+\frac{b}{4}(4a-c(3+d))\Big)$
Frontier: (0, 1)	$\Big(\frac{7}{8}(a-c)^2+\frac{b}{4}(6a-c(5+d)),\ \frac{3}{8}(a-dc)^2+\frac{(a-c)^2}{2}+\frac{b}{4}(6a-c(5+d)\Big)$	$\Big(\frac{3}{4}(a-c)^2+\frac{b}{4}(4a-c(3+d)),\ \frac{3}{8}(a-dc)^2+\frac{3}{8}(a-c)^2+\frac{b}{4}(4a-c(3+d))\Big)$	$\Big(\frac{7}{8}(a-c)^2+\frac{b}{4}(6a-c(5+d)),\ \frac{3}{8}(a-dc)^2+\frac{(a-c)^2}{2}+\frac{b}{4}(6a-c(5+d)\Big)$	$\Big(\frac{3}{4}(a-c)^2+\frac{b}{4}(4a-c(3+d)),\ \frac{3}{8}(a-dc)^2+\frac{3}{8}(a-c)^2+\frac{b}{4}(4a-c(3+d))\Big)$
Frontier: (0, 0)	$\Big(\frac{3}{4}(a-c)^2+\frac{b}{4}(4a-c(3+d)),\ \frac{3}{8}(a-dc)^2+\frac{3}{8}(a-c)^2+\frac{b}{4}(4a-c(3+d))\Big)$	$\Big(\frac{3}{4}(a-c)^2+\frac{b}{4}(4a-c(3+d)),\ \frac{3}{8}(a-dc)^2+\frac{3}{8}(a-c)^2+\frac{b}{4}(4a-c(3+d))\Big)$	$\Big(\frac{3}{4}(a-c)^2+\frac{b}{4}(4a-c(3+d)),\ \frac{3}{8}(a-dc)^2+\frac{3}{8}(a-c)^2+\frac{b}{4}(4a-c(3+d))\Big)$	$\Big(\frac{3}{4}(a-c)^2+\frac{b}{4}(4a-c(3+d)),\ \frac{3}{8}(a-dc)^2+\frac{3}{8}(a-c)^2+\frac{b}{4}(4a-c(3+d))\Big)$

. We therefore define the threshold ω as

$$\omega = \frac{5a+7b}{5c} - \frac{1}{5}\sqrt{\frac{20a^2+50ab+49b^2-40ac-50bc+20c^2}{c^2}}$$

.

$$\Sigma_{t=1}^{2} W_{F,t}((0,1),T_L^*)) \geq \Sigma_{t=1}^{2} W_{F,t}((1,1),T_L^*))$$

requires that

$$\frac{3}{8}(a-c)^2 + \frac{b}{2}(\frac{a-dc}{2} + \frac{a-c}{2}) + \frac{(a-c)^2}{2} + b(a-c) > 2\left[(a-dc)\left(\frac{a-dc}{2} + 2c(d-1) + b\right)\right]$$

which holds for

$$d > \frac{8a-7b+16c}{24c} + \frac{1}{24}\sqrt{\frac{88a^2-16ab+49b^2-176ac+16bc+88c^2}{c^2}}$$
$$b > a-c$$

leading us to define γ as

$$\gamma = \frac{8a-7b+16c}{24c} + \frac{1}{24}\sqrt{\frac{88a^2-16ab+49b^2-176ac+16bc+88c^2}{c^2}}$$

.

Proof of Proposition 3 Defining trade policy in terms of outcomes $A = \{A_1, A_2\}$ rather than strategies for ease of exposition,

$$\Sigma_{t=1}^{2} W_{F,t}(\{0,1\}) + W_{L,t}(\{0,1\})) > \Sigma_{t=1}^{2} W_{F,t}(\{1,1\}) + W_{L,t}(\{1,1\})$$

requires that

$$\frac{11}{8}(a-c)^2 + \frac{3}{8}(a-dc)^2 + b\left(3a - \frac{c(5-d)}{2}\right) > 2(a-dc)^2 + 4(a-dc)(c(d-1)+b)$$

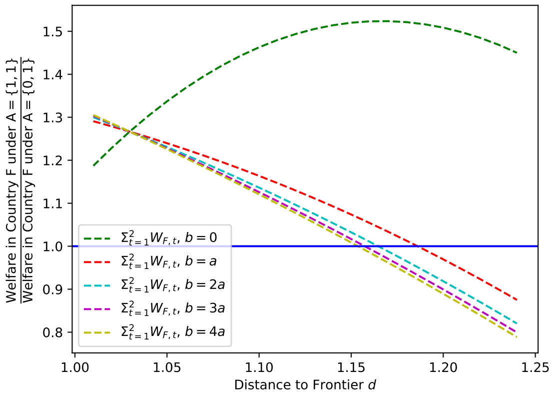
which holds for

$$d > \frac{3a-14b+16c}{19c} + \frac{1}{19}\sqrt{\frac{47a^2+68ab+196b^2-94ac-68bc+47c^2}{c^2}}$$
$$b > \frac{a-c}{24}$$

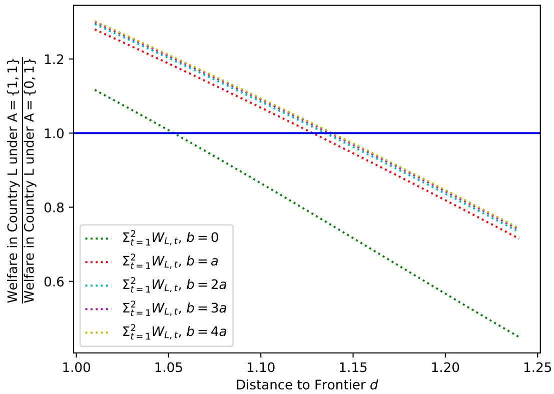
. This leads us to define

$$\theta = \frac{3a-14b+16c}{19c} + \frac{1}{19}\sqrt{\frac{47a^2+68ab+196b^2-94ac-68bc+47c^2}{c^2}}$$

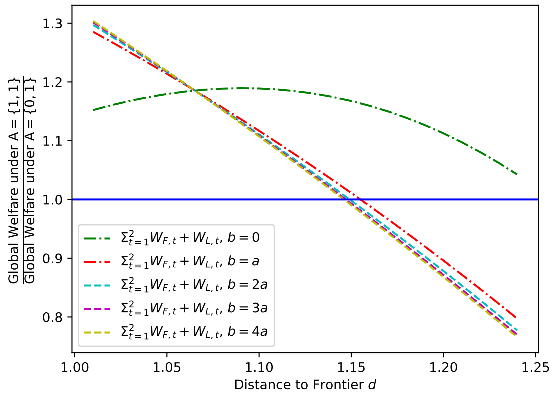
.



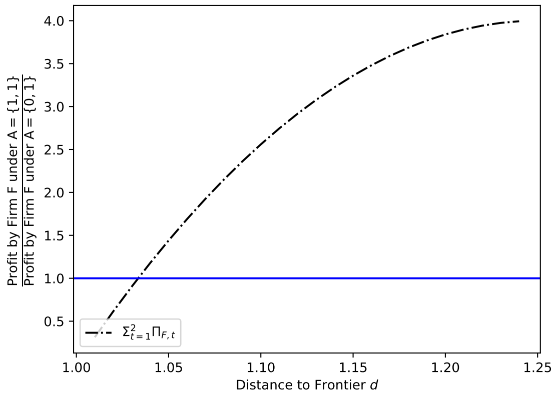
(a) Frontier Country Welfare



(b) Laggard Country Welfare



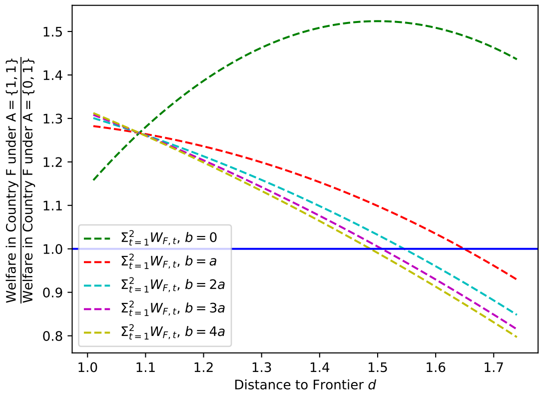
(c) Global Welfare



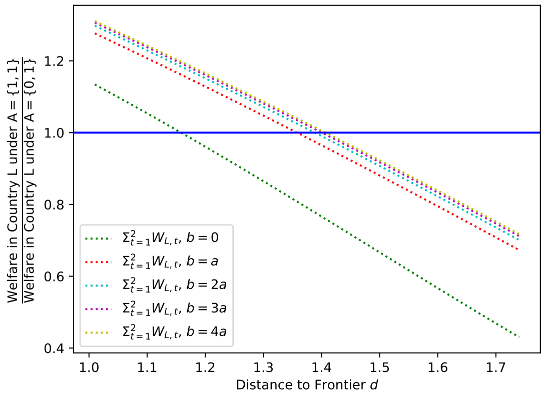
(d) Profit by firm F

Note: Like Figure 4, but with $a = 1.5c$.

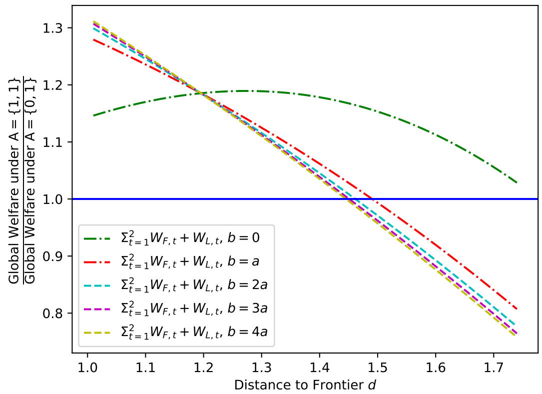
FIGURE 5
Welfare and Profit Under Trade Relative to Autarky



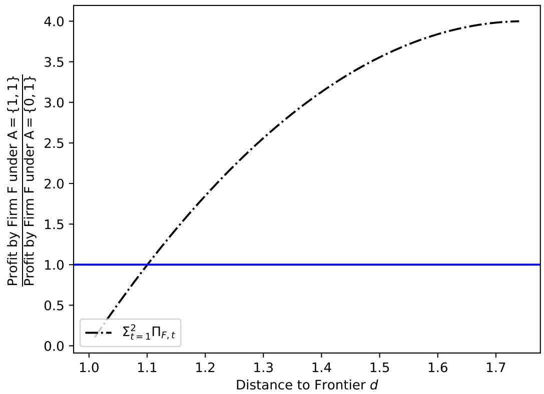
(a) Frontier Country Welfare



(b) Laggard Country Welfare



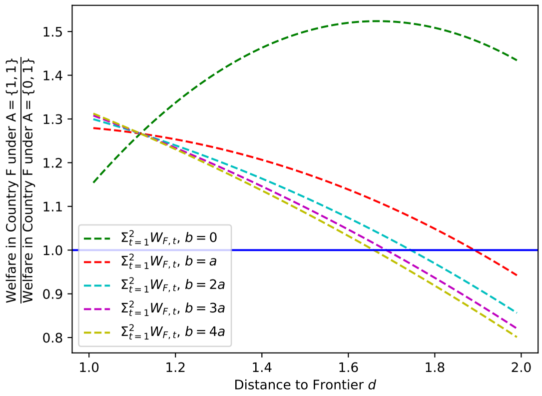
(c) Global Welfare



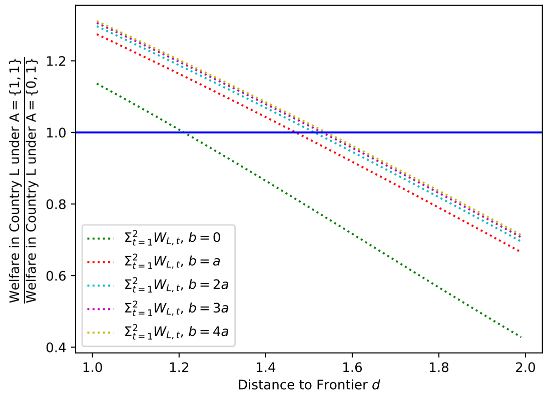
(d) Profit by firm F

Note: Like Figure 4, but with $a = 2.5c$.

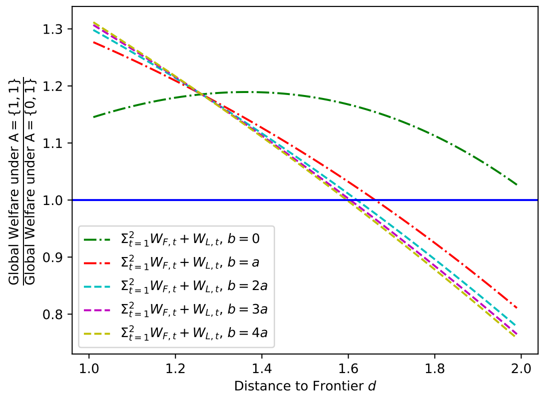
FIGURE 6
Welfare and Profit Under Trade Relative to Autarky



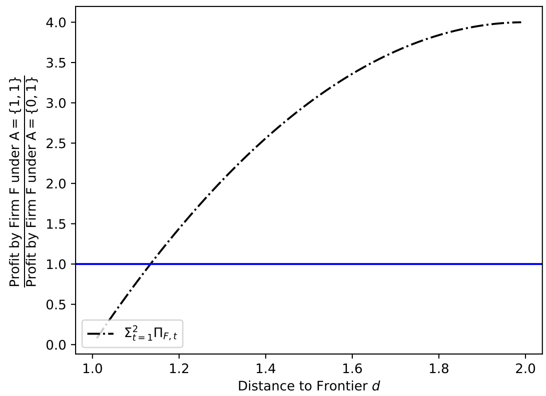
(a) Frontier Country Welfare



(b) Laggard Country Welfare



(c) Global Welfare



(d) Profit by firm F

Note: Like Figure 4, but with $a = 3c$.

FIGURE 7
Welfare and Profit Under Trade Relative to Autarky

C OPTIMAL SUBSIDIES UNDER AUTARKY

In any stage of the game, the optimal subsidy under autarky corrects monopoly losses and internalizes positive externalities which are realized locally. It does not matter whether the government subsidizes the consumer or the producer.[24]

Consider a consumer subsidy in country i. A quantity subsidy s_i^{cons} shifts consumer demand such that

$$r_i = a - p_i + s_i^{cons}$$

The monopolist in the frontier country now maximizes

$$\Pi_F = (a - p_F + s_F^{cons})(p_F - c) \tag{8}$$

24. To see this, consider how a producer subsidy would shift the monopolist's profit maximization problem. Profit in the frontier country would become $\Pi_F = (a - p_F)p_F + (a - p_F)s_F^{prod} - (a - p_F)c$, which is equivalent to Equation 8. The laggard firm's profit maximization function is modified in the same way, substituting dc for c.

such that

$$p_F = \frac{a + s_F^{cons} + c}{2}; r_F = \frac{a + s_F^{cons} - c}{2}$$

The government thus faces the objective function

$$\max_{\{s_F^{cons}\}} W_F(s_F^{cons}) = ar_F - \frac{r_F^2}{2} - (p_F - s_F^{cons})r_F + p_F r_F - cr_F + \frac{b}{2}(r_F + r_L) - s_F^{cons} r_F$$
$$= (a - c + \frac{b}{2})r_F - \frac{r_F^2}{2} + \frac{b}{2}r_L$$
$$= (a - c + \frac{b}{2})(\frac{a + s_F^{cons} - c}{2}) - \frac{(\frac{a + s_F^{cons} - c}{2})^2}{2} + \frac{b}{2}r_L$$

From the first order condition we get the optimal consumer subsidy

$$s_F^{cons*} = a + b - c$$

which yields

$$r_F = a - c + \frac{b}{2}; p_F = a + \frac{b}{2}$$

Unlevelled industry In an unlevelled industry, country L solves a similar problem, substituting dc for c. The optimal consumer subsidy is

$$s_L^{cons*} = a + b - dc$$

leading to quantity and price

$$r_L = a - dc + \frac{b}{2}; p_L = a + \frac{b}{2}$$

Therefore, welfare in the frontier country is

$$W_F = \frac{r_F^2}{2} + r_F(a + \frac{b}{2} - c) + \frac{b}{2}(r_F + r_L) - r_F(a + b - c)$$
$$= \frac{r_F^2}{2} + \frac{b}{2}r_L = \frac{(a - c + \frac{b}{2})^2}{2} + \frac{b}{2}(a - dc + \frac{b}{2})$$

.

Similarly, welfare in the laggard country is

$$W_L = \frac{r_L^2}{2} + \frac{b}{2}r_F = \frac{(a - dc + \frac{b}{2})^2}{2} + \frac{b}{2}(a - c + \frac{b}{2})$$

.

Levelled industry In a levelled industry, subsidies, prices and quantities in the frontier country are the same as in the unlevelled case. In the laggard country,

$$s_L^{cons*} = a + b - c; r_L = a - c + \frac{b}{2}; p_L = a + \frac{b}{2}$$

Therefore, welfare in both countries is

$$W_F = W_L = \frac{(a-c+\frac{b}{2})^2}{2} + \frac{b}{2}(a-c+\frac{b}{2})$$

.

D OPTIMAL SUBSIDIES UNDER TRADE

Unlevelled industry Let ε be an infinitesimal positive number. In each period, the competitive price facing the consumer is defined by

$$p = \begin{cases} p_F = dc - s_L^{prod} - \varepsilon & \text{if } p_F < p_L \\ p_F = p_L = dc - s_L^{prod} = c - s_F^{prod} & \text{if } p_F = p_L \\ p_L = c - s_F^{prod} - \varepsilon & \text{if } p_F > p_L \end{cases}$$

Quantities demanded are

$$\{r_F, r_L\} = \{a - p + s_F^{cons}, a - p + s_L^{cons}\}$$

.

Quantities produced by each firm are given by

$$\{q_F, q_L\} = \begin{cases} \{r_F + r_L, 0\} & \text{if } p_F < p_L \\ \{\frac{(r_F+r_L)}{2}, \frac{(r_F+r_L)}{2}\} & \text{if } p_F = p_L \\ \{0, r_F + r_L\} & \text{if } p_F > p_L \end{cases}$$

Welfare in the frontier country is defined as follows

$$W_F = \begin{cases} \frac{r_F^2}{2} + (p + s_F^{prod} - c)(r_F + r_L) + \frac{b}{2}(r_F + r_L) - s_F^{cons} r_F - s_F^{prod}(r_F + r_L) & \text{if } p_F < p_L \\ \frac{r_F^2}{2} + (p + s_F^{prod} - c)\frac{(r_F+r_L)}{2} + \frac{b}{2}(r_F + r_L) - s_F^{cons} r_F - s_F^{prod}\frac{(r_F+r_L)}{2} & \text{if } p_F = p_L \\ \frac{r_F^2}{2} + \frac{b}{2}(r_F + r_L) - s_F^{cons} r_F & \text{if } p_F > p_L \end{cases}$$

While welfare in the laggard country is

$$W_L = \begin{cases} \frac{r_L^2}{2} + \frac{b}{2}(r_F + r_L) - s_L^{cons} r_L & \text{if } p_F < p_L \\ \frac{r_L^2}{2} + (p + s_L^{prod} - dc)\frac{(r_F+r_L)}{2} + \frac{b}{2}(r_F + r_L) - s_L^{cons} r_L - s_L^{prod}\frac{(r_F+r_L)}{2} & \text{if } p_F = p_L \\ \frac{r_L^2}{2} + (p + s_L^{prod} - dc)(r_F + r_L) + \frac{b}{2}(r_F + r_L) - s_L^{cons} r_L - s_L^{prod}(r_F + r_L) & \text{if } p_F > p_L \end{cases}$$

Optimal subsidies if $p_F < p_L$ First, note that $p_F < p_L$ implies $c - s_F^{prod} < dc - s_L^{prod}$. The first order condition on s_F^{cons} is given by

$$\begin{aligned} \frac{\delta W_F}{\delta s_F^{cons}} &= r_F + (p + s_F^{prod} - c) + \frac{b}{2} - r_F - s_F^{cons} - s_F^{prod} = 0 \\ &= p - c + \frac{b}{2} - s_F^{cons} = 0 \end{aligned}$$

therefore

$$s_F^{cons} = c(d-1) + \frac{b}{2} - s_L^{prod}$$

The second order condition is trivially satisfied with

$$\frac{\delta^2 W_F}{\delta s_F^{cons}} = -1 < 0$$

The first order condition on s_F^{prod} is

$$\frac{\delta W_F}{\delta s_F^{prod}} = (r_F + r_L) - (r_F + r_L) = 0$$

and is satisfied at any value of s_F^{prod}, implying that s_F^{prod} is solely defined by $c - s_F^{prod} < dc - s_L^{prod}$.

Solving for the laggard's optimal subsidies gives

$$\frac{\delta W_L}{\delta s_L^{cons}} = r_L + \frac{b}{2} - s_L^{cons} - r_L = 0$$

therefore

$$s_L^{cons*} = \frac{b}{2}$$

with the second order condition trivially satisfied at

$$\frac{\delta^2 W_L}{\delta s_L^{cons}} = -1 < 0$$

When solving for the optimal level of s_L^{prod},

$$\frac{\delta^2 W_L}{\delta s_L^{prod}} = 1$$

indicates that the laggard's welfare is strictly increasing in s_L^{prod} as long as $c - s_F^{prod} < dc - s_L^{prod}$ is satisfied and all production takes place in the frontier country.

In equilibrium, the frontier country's producer subsidy will therefore equal zero, while $s_L^{prod*} = c(d-1) - \varepsilon$. To see this, consider the case where $s_L^{prod} = c(d-1) - \lambda$, where $\lambda > \varepsilon$ is a non-negligible positive number, and $c - s_F^{prod} < dc - s_L^{prod}$. Welfare in the frontier country is

$$\begin{aligned} W_F &= \frac{r_F^2}{2} + (p + s_F^{prod} - c)(r_F + r_L) + \frac{b}{2}(r_F + r_L) - s_F^{cons} r_F - s_F^{prod}(r_F + r_L) \\ &= \frac{r_F^2}{2} + (p - c)(r_F + r_L) + \frac{b}{2}(r_F + r_L) - s_F^{cons} r_F \\ &= \frac{r_F^2}{2} + (dc - s_L^{prod} - c)(r_F + r_L) + \frac{b}{2}(r_F + r_L) - s_F^{cons} r_F \end{aligned} \tag{9}$$

The second term in the above equation becomes negative, as $dc - c(d-1) - \lambda - c = -\lambda$. This implies that there is a profitable unilateral deviation for the frontier country. By reducing its own production subsidy such that $c - s_F^{prod} = dc - s_L^{prod} + \varepsilon$ it can shift all production to the laggard country and increase its welfare by $\lambda(r_F + r_L)$ while retaining the same level of consumption and positive externalities.

Similarly, if $s_F^{prod} > 0$ there would be a profitable unilateral deviation for the laggard country, which could reduce prices and increase its own welfare by raising s_L^{prod} to $c(d-1)+\lambda$. Finally, if $s_L^{prod} < c(d-1)-\varepsilon$ the frontier country would extracts rents amounting to $(dc - s_L^{prod} - c)r_L > 0$ from the laggard country and consumer surplus and positive externalities would be lower in both countries. This implies a profitable unilateral deviation for the laggard country, which increases s_L^{prod} until all rents have dissipated.

Given $s_F^{prod*} = 0$, $s_L^{prod*} = c(d-1)-\varepsilon$, and $s_F^{cons*} = s_L^{cons*} = \frac{b}{2}$, the price facing the consumer is $p = p_F = c$ and quantities demanded in both countries are $r_F = r_L = a - c + \frac{b}{2}$.

Welfare is equal in both countries:

$$W_F = \frac{r_F^2}{2} + \frac{b}{2}(r_F + r_L) - \frac{b}{2}r_F = \frac{(a-c+\frac{b}{2})^2}{2} + \frac{b}{2}(a-c+\frac{b}{2})$$
$$W_L = \frac{r_L^2}{2} + \frac{b}{2}(r_F + r_L) - \frac{b}{2}r_L = \frac{(a-c+\frac{b}{2})^2}{2} + \frac{b}{2}(a-c+\frac{b}{2})$$

Optimal subsidies if $p_F = p_L$ $\quad p_F = p_L$ implies that $p = c - s_F^{prod} = dc - s_L^{prod}$. Since $p + s_F^{prod} - c = 0$ and $p + s_L^{prod} - dc = 0$, the frontier country maximizes

$$W_F = \frac{r_F^2}{2} + \frac{b}{2}(r_F + r_L) - s_F^{cons} r_F - s_F^{prod}\frac{(r_F + r_L)}{2}$$

where $r_F = a - c + s_F^{prod} + s_F^{cons}$ and $r_L = a - c + s_F^{prod} + s_L^{cons}$.

The laggard country maximizes

$$W_F = \frac{r_L^2}{2} + \frac{b}{2}(r_F + r_L) - s_L^{cons} r_L - s_L^{prod}\frac{(r_F + r_L)}{2}$$

where $r_F = a - dc + s_L^{prod} + s_F^{cons}$ and $r_L = a - dc + s_L^{prod} + s_L^{cons}$.

Taking partial derivatives with respect to s_F^{cons}, s_F^{prod}, s_L^{cons}, and s_L^{prod} yields the first and second order conditions

$$\frac{\delta W_F}{\delta s_F^{prod}} = b - s_F^{prod} - \frac{s_F^{cons} + s_L^{cons}}{2} = 0; \frac{\delta^2 W_F}{\delta s_F^{prod}} = -1$$

$$\frac{\delta W_F}{\delta s_F^{cons}} = \frac{b}{2} - s_F^{cons} - \frac{s_F^{prod}}{2} = 0; \frac{\delta^2 W_F}{\delta s_F^{cons}} = -1$$

$$\frac{\delta W_L}{\delta s_L^{prod}} = b - s_L^{prod} - \frac{s_F^{cons} + s_L^{cons}}{2} = 0; \frac{\delta^2 W_L}{\delta s_F^{prod}} = -1$$

$$\frac{\delta W_L}{\delta s_L^{cons}} = \frac{b}{2} - s_L^{cons} - \frac{s_L^{prod}}{2} = 0; \frac{\delta^2 W_L}{\delta s_L^{cons}} = -1$$

Solving this system of equations yields

$$s_F^{prod} = b, s_L^{prod} = b, s_F^{cons} = 0, s_L^{cons} = 0 \tag{10}$$

Since $dc-b=c-b$ requires that $d=1$, this implies that a market sharing equilibrium is not possible in an unlevelled industry. Moreover, $s_F^{prod}=s_L^{prod}=b$ is not a Nash Equilibrium even when $d=1$, as will be argued in the paragraph below denoted 'Levelled industry'.

Optimal subsidies if $p_F > p_L$ $p_F > p_L$ implies that $c-s_F^{prod} > dc-s_L^{prod}$. The price faced by the consumer is defined by $c-s_F$.

No subsidy mix satisfying this condition can be a Nash equilibrium. To see this, assume that $c-s_F^{prod} > dc-s_L^{prod}$ holds. Suppose that $s_F^{prod}=0$ and $s_L^{prod}=c(d-1)+\varepsilon$. Now, the laggard country's welfare is

$$\begin{aligned}
W_L &= \frac{r_L^2}{2}+(p+s_L^{prod}-dc)(r_F+r_L)+\frac{b}{2}(r_F+r_L)-s_L^{cons}r_L-s_L^{prod}(r_F+r_L)\\
&= \frac{r_L^2}{2}+(p-dc)(r_F+r_L)+\frac{b}{2}(r_F+r_L)-s_L^{cons}r_L\\
&= \frac{r_L^2}{2}+(c-s_F^{prod}-dc)(r_F+r_L)+\frac{b}{2}(r_F+r_L)-s_L^{cons}r_L
\end{aligned}$$

The second term in the above equation is negative as $c-dc<0$ for any $d>1$. Thus, by reducing s_L^{prod} to $c(d-1)-\varepsilon$ the laggard can shift all production to the frontier country and retain the same prices, consumer surplus and positive externalities, while increasing its welfare by $c(d-1)(r_F+r_L)$. The laggard will therefore not be willing to support at producer subsidy greater than $s_L^{prod}=c(d-1)-\varepsilon$.

Levelled industry In a levelled industry, prices, quantities and welfare are defined as in the unlevelled case, where $d=1$. The unique Nash Equilibrium is characterized by $s_F^{prod*}=s_L^{prod*}=0, s_F^{cons*}=s_L^{cons*}=\frac{b}{2}$.

To see this, suppose first that $p_F<p_L$, which requires that $c-s_F^{prod}<c-s_L^{prod}$, thus $s_F^{prod}>s_L^{prod}$. Assume that $s_F^{prod}>s_L^{prod}$ and $s_L^{prod}=\lambda$.

Welfare in the frontier country is given by Equation 9, with $d=1$. The frontier country can profitably deviate by reducing its s_F^{prod} to $\lambda-\varepsilon$ and shifting all production to the other country without lowering consumption and positive externalities in a meaningful way. This increases its welfare by $\lambda(r_F+r_L)$. By the same logic, $s_F^{prod}<s_L^{prod}$ cannot be sustained as a Nash Equilibrium either. Thus, the Nash Equilibrium will involve a market sharing equilibrium, with $s_F^{prod}=s_L^{prod}=s^{prod}$ and $p=p_F=p_L=c-s^{prod}$.

Equation 10 implies that $s^{prod}=b$ and $s_F^{cons}=s_L^{cons}=s^{cons}=\frac{b}{2}-\frac{s^{prod}}{2}=0$. While these subsidies are optimal as long as $s_F^{prod}=s_L^{prod}$, either country can increase its welfare by unilaterally reducing its producer subsidy to $b-\varepsilon$, thereby shifting all production and the burden of subsidizing to the other country. As demonstrated previously, such a move increases the deviating country's welfare by $b\frac{(r_F+r_L)}{2}$ and reduces the other country's welfare by the same amount. The other country can then do the same by reducing its producer subsidy to $b-2\varepsilon$.

In conclusion, profitable deviations are possible for any positive producer subsidy. Thus, $s_F^{prod*}=s_L^{prod*}=0, s_F^{cons*}=s_L^{cons*}=\frac{b}{2}$ in equilibrium. Prices are $p_F=p_L=c$ and quantities $r_F=r_L=a-c+\frac{b}{2}$. Welfare in both countries is $W_F=W_L=\frac{(a-c+\frac{b}{2})^2}{2}+\frac{b}{2}(a-c+\frac{b}{2})$.

Table 2 lays out welfare payoffs for both countries under all trade strategy profiles given the prices, quantities and optimal subsidies derived in this section. Since $dc>c$ by assumption,

TABLE 2
Payoff Matrix (Optimal Subsidies)

	Laggard: (1, 1)	Laggard: (1, 0)	Laggard: (0, 1)	Laggard: (0, 0)
Frontier: (1, 1)	$\left((a-c+\frac{b}{2})^2 + b(a-c+\frac{b}{2}), (a-c+\frac{b}{2})^2 + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$
Frontier: (1, 0)	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$
Frontier: (0, 1)	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$
Frontier: (0, 0)	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$	$\left((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(1+d)+b), \frac{(a-c+\frac{b}{2})^2}{2} + \frac{(a-dc+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\right)$

these payoffs imply that trade is a weakly dominant strategy for both countries in both stages of the game. The pareto-optimal Subgame Perfect Nash Equilibrium is one in which

i Countries trade in both periods.

ii The laggard country sets $s_L^{prod*} = c(d-1)$.

iii Both countries set their consumer subsidies, s_F^{cons*} and s_L^{cons*} equal to $\frac{b}{2}$.

D.1 Equilibrium without Producer Subsidies

Optimal consumer subsidies in autarky are derived in Appendix C.

Under trade, again assuming that dc is below the frontier country's monopoly price, only the frontier firm is active and supplies the market at global price $p = p_F = dc - \varepsilon$. Dropping ε for simplicity, the frontier country's government sets a subsidy to optimize

$$W_F = ar_F - \frac{r_F^2}{2} - (dc - s_F^{cons})r_F + (dc - c)(r_F + r_L) - r_F s_F^{cons} + \frac{b}{2}(r_F + r_L)$$

Given that $r_F = a - dc + s_F^{cons}$ and r_L is not affected by the domestic subsidy, the first order condition implies that

$$s_F^{cons*} = c(d-1) + \frac{b}{2}$$

The laggard country's government solves

$$maxW_L = ar_L - \frac{r_L^2}{2} - dcr_L + \frac{b}{2}(r_F + r_L)$$

yielding

$$s_L^{cons*} = \frac{b}{2}$$

These subsidies lead to quantities

$$r_F = a - c + \frac{b}{2}; r_L = a - dc + \frac{b}{2}$$

and welfare

$$\begin{aligned} W_F &= \frac{r_F^2}{2} + c(d-1)(r_F + r_L) + \frac{b}{2}(r_F + r_L) - (c(d-1) + \frac{b}{2})r_F \\ &= \frac{r_F^2}{2} + (c(d-1) + \frac{b}{2})r_L \\ &= \frac{(a - c + \frac{b}{2})^2}{2} + (c(d-1) + \frac{b}{2})(a - dc + \frac{b}{2}) \end{aligned}$$

$$\begin{aligned} W_L &= \frac{r_L^2}{2} + \frac{b}{2}(r_F + r_L) - \frac{b}{2}r_L \\ &= \frac{r_L^2}{2} + \frac{b}{2}r_F \\ &= \frac{(a - dc + \frac{b}{2})^2}{2} + \frac{b}{2}(a - c + \frac{b}{2}) \end{aligned}$$

The frontier country extracts rent amounting to

$$Rent_F = c(d-1)r_L$$

Table 3 shows the welfare payoff matrix in the version of the game with consumer subsidies only. While country F weakly prefers trade in Stage 2, country L's Stage 2 pay-offs depend solely on the strategy chosen in Stage 1. The laggard country's welfare in Stage 1 is the same whether countries trade or remain in autarky. However, its welfare in Stage 2 – and therefore its cumulative welfare – is higher if countries are in autarky in Stage 1. As trade requires mutual agreement, there is no equilibrium under which countries trade in Stage 1. There are eight SPNE in pure strategies, which are characterized by the following optimal trade decisions:

(1) $T_L^* = (0,1)$ and $T_F^* = (1,1)$

(2) $T_L^* = (0,1)$ and $T_F^* = (0,1)$

(3) $T_L^* = (0,1)$ and $T_F^* = (1,0)$

(4) $T_L^* = (0,1)$ and $T_F^* = (0,0)$

(5) $T_L^* = (0,0)$ and $T_F^* = (1,1)$

(6) $T_L^* = (0,0)$ and $T_F^* = (0,1)$

(7) $T_L^* = (0,0)$ and $T_F^* = (1,0)$

(8) $T_L^* = (0,0)$ and $T_F^* = (0,0)$

TABLE 3
Payoff Matrix (Consumer Subsidies)

	Laggard: (1, 1)	Laggard: (1, 0)	Laggard: (0, 1)	Laggard: (0, 0)
Frontier: (1, 1)	$\Big((a-c+\frac{b}{2})^2 + 2(c(d-1)+\frac{b}{2})(a-dc+\frac{b}{2}),\ (a-dc+\frac{b}{2})^2 + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + (c(d-1)+b)(a-dc+\frac{b}{2}),\ (a-dc+\frac{b}{2})^2 + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$
Frontier: (1, 0)	$\Big((a-c+\frac{b}{2})^2 + (c(d-1)+b)(a-dc+\frac{b}{2}),\ (a-dc+\frac{b}{2})^2 + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + (c(d-1)+b)(a-dc+\frac{b}{2}),\ (a-dc+\frac{b}{2})^2 + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$
Frontier: (0, 1)	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$
Frontier: (0, 0)	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$	$\Big((a-c+\frac{b}{2})^2 + \frac{b}{2}(2a-c(d+1)+b),\ \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{(a-c+\frac{b}{2})^2}{2} + b(a-c+\frac{b}{2})\Big)$