Grantham Research Institute on Climate Change and the Environment

Centre for Climate Change Economics and Policy

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January 2023

Centre for Climate Change Economics and Policy Working Paper No. 413
ISSN 2515-5709 (Online)

Grantham Research Institute on Climate Change and the Environment Working Paper No. 388
ISSN 2515-5717 (Online)

Economic and Social Research Council

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Suggested citation:
Andres P (2023) *Industrial policy and global public goods provision: rethinking the environmental trade agreement*. Centre for Climate Change Economics and Policy Working Paper 413/Grantham Research Institute on Climate Change and the Environment Working Paper 388. London: London School of Economics and Political Science

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

Pia Andres†

January 9, 2023

Abstract

Countries around the world increase the downstream cost of low carbon technologies using anti-dumping duties and local content requirements, while simultaneously blaming inadequate efforts to address climate change on the economic cost of doing so. This paper presents a 2-country, 2-period strategic model of trade in a clean technology in the presence of differential country-level production costs and imperfect competition. If the difference in production cost is large enough and learning-by-doing allows the laggard country to catch up, then in the absence of production subsidies remaining in autarky during Stage 1 of the game can be welfare-improving for both countries. This result is strengthened when both countries use consumer subsidies. When countries choose their policy mixes, the Nash Equilibrium involves both trade and production subsidies on the part of the laggard country. The analysis suggests that an environmental trade agreement is most likely to be beneficial if production subsidies for clean technology are explicitly permitted.

*I thank Scott Barrett, Peter Burr, Simon Dietz, Eugenie Dugoua, Ben Filewood, Roger Fouquet, Mads Greaker, Bård Harstad, David Hémous, Katinka Holtsmark, Antony Millner, Giorgio Presidente, and Misato Sato for their thoughtful comments at various stages of this paper's development, as well as the participants of the seminars and workshops where this paper was presented and discussed. All remaining errors are mine. I acknowledge financial and administrative support from the Fulbright Commission in Belgium, the Grantham Research Institute on Climate Change and the Environment, and the Economic and Social Research Council through the Centre for Climate Change Economics and Policy.

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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 (cf. 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? 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 et al. 1982; Melitz 2005; Young 1991). Here, 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.

China's entry into the solar photovoltaics (hereafter PV) market, which was enabled by aggressive 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 decade (cf. 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? In this paper, I present a stylized model highlighting conditions under which this may be the case. I then add the use of consumer or producer 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

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).

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).

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 (cf. Brito et al. 1991; Fisman et al. 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 public goods provision are inefficiently low even without the global public goods aspect 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 public goods provision in Stage 2. The frontier country loses the rents it could otherwise extract from the laggard country, which may yet make infant industry maturation a net reduction in welfare for the frontier 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 public goods provision. The model suggests that when consumer subsidies are available as a policy tool, temporary autarky is beneficial for any distance to frontier, as competition from the laggard country in Stage 1 no longer provides benefits in terms of constraining the frontier monopolist (for the frontier country this is once again counterbalanced by the loss in rents). Producer subsidies exacerbate free rider problems and are generally undesirable as the main climate policy. Under trade they allow the laggard country to free ride on the frontier country's subsidies, as

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

only the frontier firm is active, and make autarky the preferred choice from the perspective of public goods provision.

If countries are free to choose their policy mix then the laggard country will choose a producer subsidy which is sufficiently high to enforce marginal cost pricing, but which leaves the frontier firm to supply the whole market. Both countries subsidize consumers to the point of internalizing the domestic part of the public good. 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 (cf. Chang 2003; Krueger et al. 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 (cf. Krueger et al. 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 consumer surplus in both the high and the frontier country, 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' incentives with respect to trade 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 et al. 2013; Droege et al. 2016). The Asia-Pacific Economic Cooperation (APEC) countries reached an environmental trade agreement in 2012 (Jacob et al. 2017; Steenblik 2005; Vossenaar 2016), while negotiations for a World Trade Organization (WTO)-wide agreement are ongoing (De Melo et al. 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 (cf. De Melo et al. 2022).

This paper suggests that while a trade agreement may be beneficial for climate action and global welfare, producer subsidies should be allowed where they may level the competitive playing field, and more generally whenever countries choose to use them. 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 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 4 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 introduces consumer and producer subsidies and analyzes how this changes the dynamics of the game, both separately and when countries are free to choose their subsidy mixes. Section 6 discusses the evolution of the solar PV sector as a real-world example of the dynamics the model seeks to highlight. Section 7 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 et al. 2004; Melitz 2003). A larger potential market might further increase incentives to innovate

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 et al. 2017; Meckling et al. 2018; Wu et al. 2013). Estimates of the cost of US protective tariffs downstream, both in the solar PV sector and more broadly, include Houde et al. 2022 and Fajgelbaum et al. 2020.

(Aghion et al. 2018; Grossman et al. 1990) and raise the potential for knowledge spillovers and technology diffusion (Grossman et al. 1990; Keller 2004), by making technology more widely and cheaply available (Carbaugh et al. 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 (cf. 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 et al. 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 et al. 1982). Empirical evidence on the justifications for and effectiveness of infant industry protection are mixed: Krueger et al. 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 (cf. 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 et al. 2022). In contrast, this paper explores the implications of infant industry dynamics for consumer surplus and public goods provision 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 et al. 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 et al. 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 (cf. Beccherle et al. 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 et al. 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 et al. 2022; Hagen et al. 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.[6]

3 The Model

Assume that a climate friendly technology has been developed. Using this technology instead of fossil fuels reduces climate damages and thus negative externalities. I abstract from the use of fossil energy and model the technology as generating positive global externalities. Two countries are facing climate change. Each country has a domestic industry able to produce some quantity q of the technology at constant marginal cost c if it has experience producing it in the previous period, and dc otherwise, where $d > 1$. This is captured by

$$c_{i,t}(q_{i,t}) = \begin{cases} cq_{i,t} \;\; if\, q_{i,t-1} > 0 \\ dcq_{i,t} if\, q_{i,t-1} = 0 \end{cases} \tag{1}$$

The game has two stages, both of which are identical. For simplicity, assume there is no discount factor. To aid readability, time subscripts will be dropped wherever possible.

Downstream Consumer Recall that consuming the technology generates both private and public benefits. In each stage of the game, the representative consumer in country i chooses how much r_i to consume in order to maximize utility $U(r_i, Y)$ subject to prices and budget constraints, without taking into account the positive externalities generated. We can think of this as a consumer setting the marginal private benefit from consuming a cleaner technology (such as the utility gained from electricity) equal to the price, without taking into account that

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 implications of upstream versus downstream subsidies identified in this paper contrast with those found by Fischer et al. 2017, whose set up differs from that presented here in several respects. Fischer et al. 2017 model pollution taxes as the baseline environmental policy and include subsidies as an additional policy to address leakage, which is unilaterally set in the region in which pollution taxes are higher. This paper abstracts from the polluting sector and models the benefits of clean technology as a public good, making subsidies the only environmental policy. Bertrand competition implies that prices always equal the laggard firm's constant marginal cost and are not affected by demand. Finally, I consider the Nash equilibrium in subsidies, creating incentives for each country to free-ride on the other's upstream subsidies, which due to rent dissipation under Bertrand competition yield no additional benefits via increased market share.

using a dirtier technology (such as coal) instead would cause climate damages borne by all. Consumers in country j similarly choose r_j. Assuming that utility from the technology and the numeraire good Y are additive, in each stage the consumer solves

$$\max_{\{r_i\}} U_i(r_i, Y_i) = u(r_i) + Y_i \tag{2}$$

subject to the budget constraint[7]

$$Pr_i + Y_i = M_i \tag{3}$$

This yields the demand function

$$P = \frac{\delta u_i}{\delta r_i} \tag{4}$$

I assume that utility is continuously increasing in r_i, concave and twice differentiable – hence $\frac{\delta u}{\delta r_i} > 0$ and $\frac{\delta^2 u}{\delta r_i} < 0$. Utility and demand in country j are symmetric. The positive externality from consumption, which I will refer to as the global public good, is a linear function of $r_i + r_j = R$.

Firms Each country has a representative firm which maximizes profits during each stage of the game. Under autarky, firm i maximizes

$$\max_{\{q_i\}} \Pi_i = P(q_i)q_i - cq_i \tag{5}$$

I assume that country j is a laggard who has not produced the technology in period 0, such that

$$\max_{\{q_j\}} \Pi_j = P(q_j)q_j - dcq_j \tag{6}$$

Under trade, price is instead a function of $r_i + r_j = R$.[8]

Both Cournot and Bertrand competition are highly stylized models of oligopolistic competition. Here, Bertrand competition simplifies the analysis without sacrificing any central insights the paper seeks to provide.[9] Firms therefore play a Bertrand game in which the low cost firm i

7. Note that by assumption, there is no income effect affecting the demand for the good. While this is not a realistic assumption, it is a helpful simplification which allows us to focus on the implications of countries' differential production costs for potential gains from trade for the particular market under consideration, while abstracting from other country-level differences or macroeconomic considerations.

8. However, since both consumers have the same demand function this makes no difference to the slope of market demand.

9. Under Cournot competition, the maturation of an infant industry would still increase competition and reduce prices, but the global market would only approach the competitive equilibrium once a sufficiently large number of firms (clearly exceeding the two firms considered here) enters. The key dynamics illustrated in this paper would likely still hold, but presenting them would require a more complex model with a more sophisticated learning curve. Moreover, given the context which motivates this paper, in which Chinese entrants into the solar PV market

supplies the whole market at $P = dc - \varepsilon$. Note that this requires that d is sufficiently small for dc to be below the monopoly price. Also implicit in the analysis is the assumption that

$$\frac{\delta u_i}{\delta r_i}(0) > dc \tag{7}$$

which is a requirement for consumption to take place in both countries under all scenarios considered, including in the absence of trade or subsidies.

Government The government takes into account cumulative welfare over both stages of the game. It chooses subsidies s and whether or not to engage in trade, taking into account consumer surplus CS, firm profits Π, the benefit generated by consuming the technology which is assumed to be linear, and the actions of the other government. Prices are assumed to be set based on supply, demand and market power. Trade requires both countries' agreement, such that it is sufficient for one country to prefer autarky to prevent trade.[10] Both governments are assumed to have identical objective functions, maximizing cumulative national welfare which equals

$$\Sigma_{t=1}^{2} W_{i,t} = \Sigma_{t=1}^{2} CS_{i,t}(s_{i,t}, s_{j,t}) + \Pi_{i,t}(s_{i,t}, s_{j,t}) + \frac{b}{2} R_t(s_{i,t}, s_{j,t}) - cost(s_{i,t}) \tag{8}$$

where in each stage t of the game, the private (national) benefit from global consumption of R_t is $B_{i,t} = \frac{b}{2} R_t$ and the global benefit from global consumption of R_t is $B_t = bR_t$. The overall cost to country i of subsidizing is $cost(s_i)$. $W_{i,t}$ denotes overall welfare in country i in stage t of the game.

3.1 First Best

The global optimum requires that global marginal benefits from consuming the technology equal the lowest attainable marginal cost. Thus,

$$\frac{\delta u}{\delta r_i} + b = c \tag{9}$$

in each stage of the game. A number of subsidy mixes could in principle achieve this outcome, each of which has different distributional implications. If both countries use consumer subsidies, then since $P = dc$ as a result of Bertrand competition, the market outcome (with a downstream quantity subsidy) will be

sold their products on the world market at considerably lower prices than those previously available from western incumbents (for more detail, see section 6), I argue that Bertrand competition is a reasonable modelling choice.

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.

$$\frac{\delta u}{\delta r_i} + s = dc \tag{10}$$

and the optimal subsidy satisfies

$$s = c(d-1) + b \tag{11}$$

If the subsidy is shared equally in the form of a consumer subsidy, then the low cost country extracts rents from the high cost country amounting to $c(d-1)r_j$. This is not an equilibrium, as in both stages of the game the high cost country will wish to set marginal local benefit equal to marginal local cost. Since in country j the latter remains equal to $P = dc$, this optimization problem yields $s_j = \frac{b}{2}$. A producer subsidy borne by the low cost country implies that the low cost country subsidizes the high cost county with br_j, thus bearing the full cost of public goods provision. While the low cost country will wish to subsidize foreign consumers to the extent that this increases local public goods provision, it will not account for increases in foreign consumer surplus or foreign public goods provision (see Appendix B.2). Neither option can thus constitute a Nash equilibrium. Alternatively, a producer subsidy amounting to $c(d-1)-\varepsilon$ set by the high cost country could enforce marginal cost pricing by the low cost firm, while a consumer subsidy of b could be shared between both countries. Can this more equitable solution be a stable equilibrium?

In Stage 2, each country will have the same welfare which equals

$$W_i = u(r_i) + br_i - cr_i + \frac{b}{2}r_i + \frac{b}{2}r_j - br_i \tag{12}$$

Each country will have an incentive to unilaterally deviate and set the subsidy equal to $\frac{b}{2}$, since individual country welfare is optimized if the marginal cost of consumption equals its marginal (domestic) benefit, which is at $\frac{\delta u}{\delta r_i} + \frac{b}{2} = c$. Since countries foresee a deviation in Stage 2, cooperation cannot be sustained in Stage 1 either.

3.2 Business As Usual

Suppose that under business-as-usual, countries are in autarky and no climate or industrial policy is used. Each firm acts as a monopolist, such that in both Stage 1 and Stage 2, in country i,

$$\begin{aligned} \frac{\delta P}{\delta q_i} q_i + P(q_i) &= c \\ \rightarrow \frac{\delta^2 u}{\delta r_i} r_i + \frac{\delta u}{\delta r_i} &= c \end{aligned} \tag{13}$$

Since $\frac{\delta^2 u}{\delta r_i} < 0$ this outcome is clearly inferior from the consumer's point of view than a competitive equilibrium, where $\frac{\delta u}{\delta r_i} = c$.[11] In country j,

$$\begin{aligned} \frac{\delta P}{\delta q_j} q_j + P(q_j) = & \quad dc \\ \rightarrow \frac{\delta^2 u}{\delta r_j} r_j + \frac{\delta u}{\delta r_j} = & \quad dc \end{aligned} \tag{14}$$

in Stage 1. In Stage 2, country j has caught up with country i, and both firms set prices as in equation 13.

While we saw in section 3.1 that the global optimum may not be attainable, the status quo can be improved upon using a set of policies. In the following, I will analyze equilibrium outcomes and pay-offs under different trade and subsidy regimes, evaluate what kind of 'game' countries will choose to opt into if given the option, and propose a 'second best' policy mix which allows for the outcome which is closest to the first best.

4 Trade and Autarky Without Subsidies

Can a trade agreement constitute an improvement over business-as-usual? In principle, trade allows both countries to benefit from the more advanced industry's lower marginal cost. Under perfect competition, this is usually a straightforward welfare improvement (see Appendix C). However, in practice an emerging new industry is unlikely to be competitive, especially one which depends on government support for its viability. Section 6 argues that in case of solar panels, a few powerful players were highly dominant until China's entry into the global market. The analysis therefore assumes that firms are imperfectly competitive, and that entry from the initially high-cost country is required to challenge the monopoly power of the technological leader. I will use backward induction to analyze whether countries will find it beneficial to trade in each stage.

In Stage 2, the low cost firm will set $P = dc - \varepsilon$ if the high cost firm still has marginal cost dc, and supply the whole market. If the high cost firm has caught up, both firms share the market at $P = c$. Assuming once again that d is sufficiently low for dc to be below the monopoly price, it is trivial to show that consumer surplus, consumption, and the public good are all higher under trade in either case.

Suppose the high cost country has not caught up. Then, $\frac{\delta u_i}{\delta r_i} = \frac{\delta u_j}{\delta r_j} = dc$. Moreover, the high cost country extracts rent from the high cost country amounting to $c(d-1)r_j$.

Conversely, if the high cost country has caught up, $\frac{\delta u_i}{\delta r_i} = \frac{\delta u_j}{\delta r_j} = c$. Since $c < dc$, prices are lower, consumption, consumer surplus and the public good are higher, and the deadweight loss of monopoly has been eliminated. However, the low cost country is no longer able to extract rent from the high cost country, implying that it is ambiguous under which scenario its domestic

11. $c - \frac{\delta^2 u}{\delta r_i} r_i > c$. Under monopoly, prices are higher and consumption, consumer surplus and public goods provision lower.

welfare is higher. In either case, however, neither country wishes to be in autarky in Stage 2.

In Stage 1, both countries face the same contemporaneous trade-off: welfare is higher under trade than autarky. However, recall that equation 1 implies that the high cost firm will have the same marginal cost as the low cost firm in Stage 2 if it is active in Stage 1. If countries trade, the low cost firm supplies the whole market during both periods. If they remain in autarky, the high cost country – and possibly the low cost country, too – trade off welfare losses in Stage 1 for welfare gains in Stage 2.

At this point, it is useful to parameterize the model. Suppose the utility function is of the form

$$u(r_i) = ar_i - \frac{r_i^2}{2} \tag{15}$$

yielding the following demand and inverse demand functions

$$\begin{aligned} P = & \quad a - r_i \\ r_i = & \quad a - P \end{aligned} \tag{16}$$

The assumption that dc is below the low cost firm's monopoly price becomes

$$\frac{a+c}{2c} > d \tag{17}$$

Appendix A derives individual payoffs and welfare implications for both countries under Stage 1 autarky and Stage 1 trade for the utility function specified in equation 15. It leads us to

Proposition 1. *If the high cost firm's distance to frontier is sufficiently large, and if protection from trade allows it to catch up, then temporary autarky can increase overall public goods provision for both countries.*

Proof: Result 1, Appendix A.

Corollary 1. *If the high cost firm's distance to frontier is sufficiently large, and if protection from trade allows it to catch up, then temporary autarky can increase overall consumer surplus for the high cost country.*

Proof: Result 2, Appendix A.

Corollary 2. *If the high cost firm's distance to frontier is sufficiently large, and if protection from trade allows it to catch up, then temporary autarky can increase overall consumer surplus for the low cost country.*

Proof: Result 3, Appendix A.[12]

12. Note that corollaries 1 and 2 imply that even in the absence of a public good, it may be welfare-improving to temporarily refrain from trade to allow an infant industry to catch up. While this is not a new insight from the perspective of the country where the infant industry is located, see e.g. Melitz 2005; Young 1991, corollary 2 further implies that consumers in the initially frontier country may also benefit.

Remark 1. *If public goods provision is higher under temporary autarky than under free trade, then consumer surplus in both countries is also higher under temporary autarky. The reverse is not the case. Further, the high cost country makes a greater temporary sacrifice in terms of consumer surplus by choosing autarky.*

Figure 1a plots the ratio of each country's overall (period 1 plus period 2) consumer surplus, as well as overall consumption and thus public goods provision, under trade versus autarky for different values of d and b when $a = 2c$.

Proposition 2. *If the high cost firm is close enough to the technology frontier to present sufficient competitive pressure under trade, then the low cost firm's profits are higher under temporary protection than free trade. However, there are no values of d under which both consumer surplus and public goods provision and profits in the low cost country are higher under protection.*

Proof: Result 4, Appendix A.

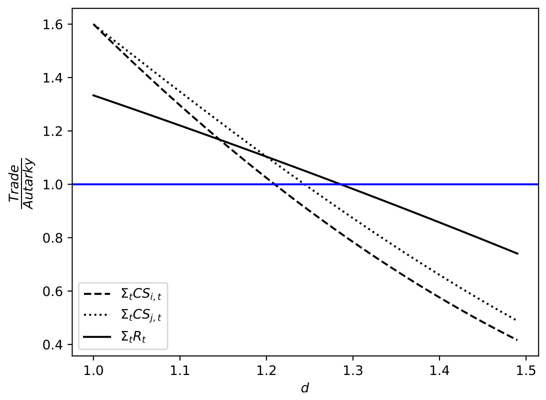
Figure 1b plots the ratio of profits made by firm i under trade over those made under temporary autarky, illustrating result 4. Figure 1c plots the ratios of country welfare. It shows that for $b = 0$, losses in rents and period 1 consumer surplus outweigh any period 2 gains in consumer surplus from the infant industry catching up for the low cost country, while the threshold for infant industry protection being beneficial is much lower for the high cost country. The greater the positive externality b, the more closely aligned countries' preferences for trade or temporary autarky become. Finally, Figure 1d plots the ratios of global welfare for different values of b, showing that in the absence of a public good, global welfare implications more closely resemble the low cost country's welfare and make free trade the preferred choice. When a positive externality is present, infant industry protection becomes welfare improving globally for sufficiently high values of d.

5 Trade and Autarky With Subsidies

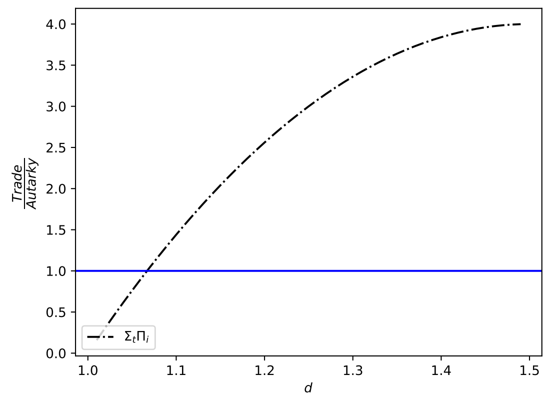
The previous section has examined the conditions under which countries will find it beneficial to move from autarky to trade from period 1, assuming that no other policy levers are available. However, given the presence of two market failures (the positive consumption externality and imperfect competition), governments may wish to employ corrective measures, such as subsidies.

In principle, the government can subsidize either production or consumption of the technology. An upstream subsidy shifts the firm's profit

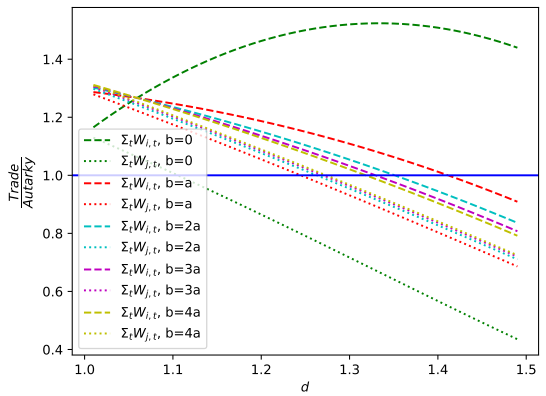
$$\Pi_i = (P(q_i) + s_i^{producer})q_i - cq_i \tag{18}$$



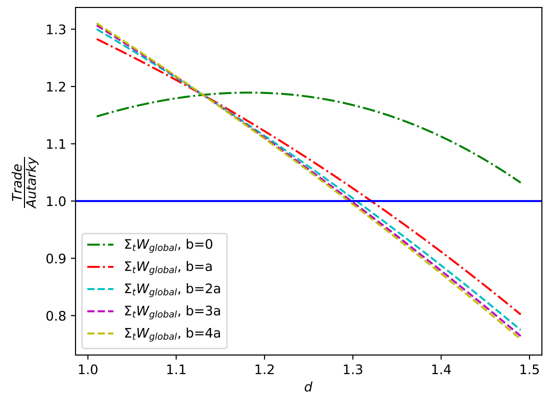
(a) Consumer Surplus and Overall Consumption



(b) Profit by firm i



(c) Country Welfare



(d) Global Welfare

Note: The figures above plot the ratios of overall (sum of period 1 and period 2) consumer surplus, consumption of the good, firm i's profit, country welfare, and global welfare for different values of d under trade as compared to autarky 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 atuarky in period 1.
The figures illustrate the opposing effects of trade on profit and consumer surplus: the further country j is from the technological frontier, the more trade reduces overall consumer surplus, and the more it increases firm i's profits (firm j's profits are not plotted as the ratio is always 0). Figures 1c and 1d highlight the significance of the positive externality $b * R$ in the model: for $b = 0$, trade is always welfare improving for the low-cost country, as well as globally, for any value of d which is greater than 1 and satisfies equation 17. However, for 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 individual countries' preferences should resemble each other.

FIGURE 1
Consumer Surplus, Consumption, Profit and Welfare Under Trade Relative to Autarky

while a downstream subsidy shifts the consumer's utility from consuming the technology (and thus demand)

$$U_i(r_i) = u(r_i) - (P - s_i^{consumer})r_i \tag{19}$$

Under autarky, it makes no difference which subsidy is used. Under trade, this may no longer be the case.[13]

5.1 Consumer Subsidies

In each stage, under autarky each government will subsidize in order to eliminate the dead-weight loss from the monopoly and internalize the domestic part of the climate externality. Consider a downstream subsidy in country i. A quantity subsidy s shifts consumer demand such that

$$\frac{\delta u}{\delta r_i} + s_i^{consumer} = P \tag{20}$$

The monopolist maximizes

$$\begin{aligned} \Pi_i = (\frac{\delta u}{\delta r_i} + s_i^{consumer})r_i - cr_i \\ \rightarrow \frac{\delta^2 u}{\delta r_i} r_i + \frac{\delta u}{\delta r_i} + s_i^{consumer} = c \end{aligned} \tag{21}$$

The government will wish to subsidize such that $\frac{\delta u}{\delta r_i} + \frac{b}{2} = c$. With $u(r_i) = ar_i - \frac{r_i^2}{2}$, we get

$$s_i = a + b - c; r_i = a - c + \frac{b}{2} \tag{22}$$

Proof: Appendix B.1. The high cost country solves an equivalent problem, substituting dc for c.

Under trade, the low cost firm once again supplies the world market at $P = dc$. The low cost country's government will once again want to set a subsidy such that $\frac{\delta u}{\delta r_i} + \frac{b}{2} = c$. Since $\frac{\delta u}{\delta r_i} = P - s_i^{consumer} = dc - s_i^{consumer}$, $c - \frac{b}{2} = dc - s_i^{consumer}$ and we obtain

$$s_i^{consumer} = c(1-d) + \frac{b}{2} \tag{23}$$

The high cost firm is inactive and makes no profit, implying that prices and marginal costs of consumption in the high cost country are equal at dc. The high cost country thus sets a subsidy such that $\frac{\delta u}{\delta r_j} + \frac{b}{2} = dc$, which given that $\frac{\delta u}{\delta r_j} = P - s_j^{consumer} = dc - s_j^{consumer}$, implies

13. Fischer et al. 2017 highlight 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.

$$s_j^{consumer} = \frac{b}{2} \tag{24}$$

The low cost country extracts rent amounting to

$$Rent_i = c(1-d)r_j \tag{25}$$

Proposition 3. *Under Bertrand competition and with downstream subsidies, the low cost country chooses a subsidy which internalizes the domestic part of the public good and eliminates the domestic loss in consumer surplus from the monopoly, which is proportionate to the rent which the low cost firm extracts due to the high cost firm's distance to frontier. On net, the low cost country thus extracts rent from the high cost country's consumers. The high cost country, whose firm is inactive, sets a subsidy which only internalizes the domestic externality. Quantities, consumer surplus and public goods provision are the same under trade as under autarky.*

Proof: Result 5, Appendix B.1.

Given Result 5 and equation 1, it is trivial to show that autarky in Stage 1 leads to higher public goods provision and higher welfare in the high cost country in Stage 2 for all parameter values.[14] The low cost country may yet prefer free trade if the rents it can thereby collect from the high cost country outweigh the loss in public goods provision.

Proposition 4. *Under Bertrand competition and downstream subsidies, Stage 1 autarky leads to an increase in public goods provision and consumer surplus over both periods for both countries. This is a pareto improvement from the low cost country's perspective if these gains are not outweighed by the loss in rents collected from the high cost country.*

This implies that when infant industry protection allows an initially uncompetitive industry to catch up, *and* the new technology is at a stage where competitive pressures on first mover industries are low, then protection is always preferable from the point of view of the country where the infant industry is located; it increases climate action globally; and it may be a pareto improvement in some instances.

5.2 Producer Subsidies

Under autarky, it makes no difference whether countries set an upstream or downstream subsidy. Equilibrium outcomes at any stage of the game under autarky are therefore identical to those derived in section 5.1. Under trade, producer subsidies affect the prices faced by both countries' consumers, as well as the market share of the domestic firm. In Stage 1, the industry is unlevelled. In Stage 2, it may be levelled (if the low cost country caught up, either by

14. The Stage 1 outcome from the perspective of the high cost country is identical under trade or autarky. In Stage 2, if countries were previously in autarky, both firms produce at marginal cost c, leading to higher consumption and higher public goods provision in the high cost country in Stage 2.

remaining in autarky or by trading with a sufficient production subsidy) or unlevelled (if countries trade in Stage 1 and the low cost firm supplies the whole market, or the high cost country subsidized its firm sufficiently to price the low cost firm out of the market).

Levelled Industry Suppose we start with a level playing field in Stage 2, such that both firms have constant marginal cost equal to c. If both firms share the market, then price equals $c - s_i = c - s_j$ and each government solves

$$\max_{\{s_i\}} W_i(s_i, s_j) = \max_{\{s_i\}} CS(s_i, s_j) + \Pi(s_i, s_j) + \frac{b}{2} R(s_i, s_j) - s_i \frac{R(s_i, s_j)}{2} \tag{26}$$

Note that under Bertrand competition and marginal cost pricing, profits equal 0 and the government weighs consumer surplus and public goods provision against the cost of the subsidy. The first order condition yields $s_i = s_j = b$ – the global optimum. Is this a Nash Equilibrium? Appendix B.2 shows that it is not. Under Bertrand competition and producer subsidies, no rents can be extracted from the importing country to compensate for the cost of the subsidy. Each country will therefore wish to reduce subsidies, thereby shifting the burden of public goods provision onto the other country, up until the point at which the subsidy is optimal even if the country is the sole supplier and subsidizer of the technology.

Proposition 5. *In a levelled industry, if countries trade they will set identical producer subsidies. Because a producer subsidy subsidizes consumer surplus and the public good in the other country as well as domestically, and no rents can be extracted, neither country has an incentive to price the other out of the market. Producer subsidies, consumption and public goods provision are lower under producer than under consumer subsidies.*

Proof: Result 6, Appendix B.2.

Unlevelled Industry Suppose country i has marginal cost c and country j has marginal cost dc. Market sharing requires a subsidy on the part of country j which it will not be prepared to support, unless it does not expect to pay it. Proof: Appendix B.2. The low cost firm therefore supplies the whole market, while the high cost government sets a producer subsidy which enforces marginal cost pricing, but does not lead to actual production in the high cost country.

Since the low cost government subsidizes both markets, while both countries receive the same consumer surplus and public goods provision, the high cost country's welfare is higher in this scenario.[15] What does this imply for Stage 1?

Subgame Perfect Nash Equilibrium Since it is not desirable to be in the position of the low cost country in Stage 2, if countries trade then the high cost country will not be prepared to

15. Note that I am abstracting from other potential benefits of economic activity, such as employment. Moreover, the very stylized nature of Bertrand competition and associated profit dissipation is a key assumption here.

subsidize consumption enough to participate in global trade.[16] It is therefore in the low cost country's interest not to trade in Stage 1, if the benefits of not having to subsidize the high cost country in Stage 2 outweigh the costs of lower public goods provision in Stage 1. Moreover, it is not obvious that public goods provision is greater under trade. This would require that $\frac{2}{3}(2a-2c+b) > 2a-c(1+d)+b$, which holds only for very large values of d.[17]

Furthermore, after Stage 1 autarky it is in both countries' interests to remain in autarky in Stage 2, since public goods provision is higher under autarky than trade for $d = 1$. Overall, upstream subsidies to provide the public good are not desirable, as they increase opportunities to free-ride and reduce subsidies and consumption in equilibrium as compared to downstream subsidies. If downstream subsidies are available, neither country will choose upstream subsidies to support the public good.

Proposition 6. *Results 6 and 7 imply that regardless of whether the industry is levelled or not, producer subsidies result in lower quantities and public goods provision than consumer subsidies, as they incentivize free riding. In an unlevelled industry, only the low cost firm is active, and the low cost country bears the full cost of public goods provision.*

Temporary Production Subsidy Can an upstream subsidy ever be welfare improving? The low cost country will never choose a production over a consumption subsidy if given the choice, as much of the subsidy would 'leak out' or 'spill over' to the other country. Paragraph B.2 considers the case in which countries trade and the high cost country subsidizes its industry during Stage 1 in order to catch up with the low cost industry. A temporary production subsidy is preferable to autarky if the gains in consumer surplus and the public good outweigh the cost of the subsidy.

Proposition 7. *In a 2-stage game with learning according to equation 1, the high cost country always prefers trade with a temporary production subsidy to trade without it. Whether a production subsidy is preferred to autarky depends on whether the associated gains in consumer surplus and the public good outweigh the cost of the subsidy.*

However, if the high cost country can choose its subsidy mix in both periods, then under Bertrand competition it will find it preferable not to actually catch up, but to set a subsidy which enforces marginal cost pricing on the part of the low cost firm.

5.3 Equilibrium Policy Mix

If both countries choose their subsidy mix in both periods, then under trade, the high cost country will set an upstream subsidy which enforces marginal cost pricing, ie $s_j^{producer} = c(d-$

16. Table 3 shows the pay-off matrix for the low cost country.
17. So large that it would not be consistent with our previous condition that $dc < \frac{a+c}{2}$, and is consistent with $a > dc$ only for values of a so large that $a-c > b$.

$1) - \varepsilon$, while both countries will set a downstream subsidy which equals $s_i^{consumer} = s_j^{consumer} = \frac{b}{2}$. The low cost firm supplies the world market at $P = c$, with $r_i = r_j = a - c$. Welfare in each country during each stage of the game equals

$$W_i = W_j = \frac{(a-c)^2}{2} + b(a-c) \tag{27}$$

This is the Subgame Perfect Nash Equilibrium of this game.

To see this, note that the high cost country cannot improve its welfare by deviating from this position. If it sets a higher upstream subsidy, both firms will either share the market, which reduces W_j by $c(d-1)r_j$, or the high cost firm supplies the whole market, which reduces W_j by $c(d-1)R$. Given the price regime and trade conditions, $\frac{b}{2}$ is the optimal consumer subsidy. While public goods provision would increase if the subsidy was higher, each country considers only the marginal benefit to its own population, which equals $\frac{b}{2}$. Further, since the high cost country does not actually incur the upstream subsidy, it has no incentive to move to autarky, as this would increase production costs and reduce consumer surplus and public goods provision.

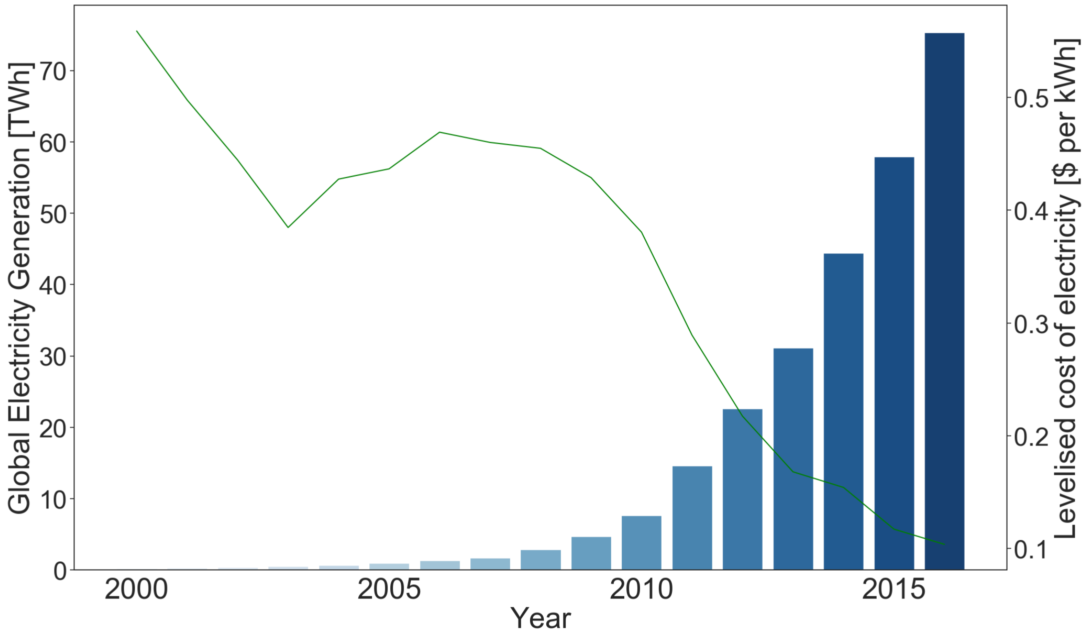
The low cost country cannot improve welfare by changing the subsidy regime either, for the same reasons. When production subsidies are available, it is unable to extract rent from the high cost country in either period. In autarky, the low cost country would set a subsidy which eliminates the deadweight loss from the monopoly and internalizes the domestic part of the public good, leading to the same domestic outcome as that which is obtained when $s_j^{producer} = c(d-1) - \varepsilon$ and $s_i^{consumer} = s_j^{consumer} = \frac{b}{2}$. Autarky would reduce welfare in the low cost country by lowering public goods provision in the high cost country.

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. On the other hand, if producer subsidies are not available, trade may be welfare reducing, as sections 4, 5.1 and 5.2 have shown.

6 Case Study: 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 2017).

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).



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 2
Solar PV Cost and Deployment, 2000-2016

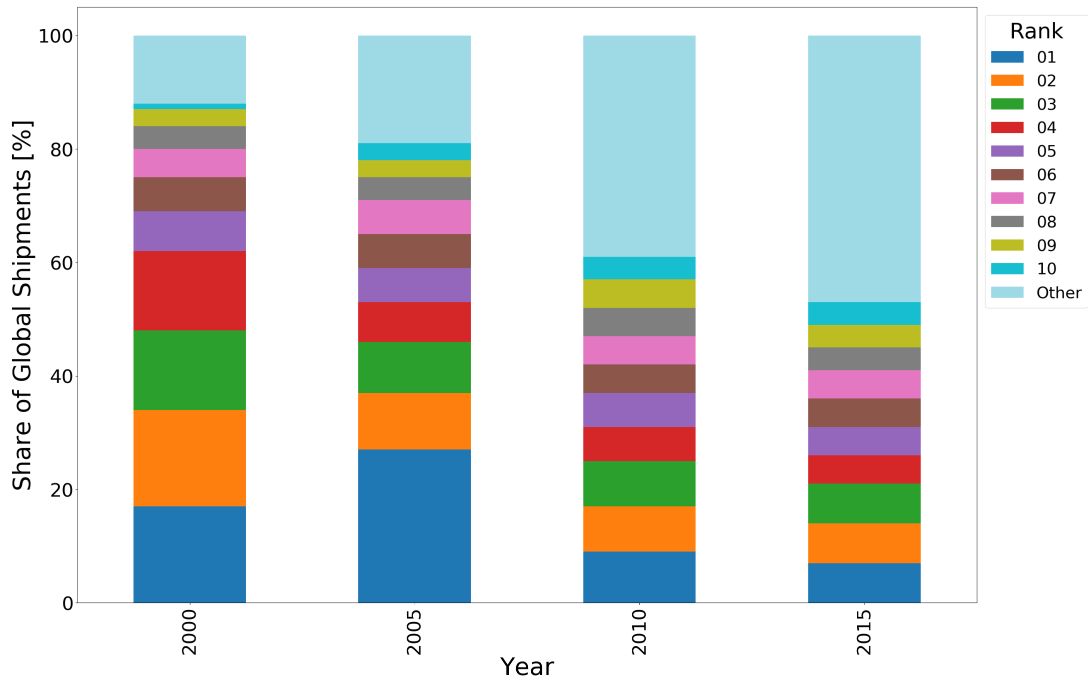
Figure 2 shows the levelized cost of electricity[18] in solar PV, as well as global electricity generation from solar, over the period 2000-2016. During this time, the levelized cost of electricity declined from over 0.5 to 0.1 USD per kWh, while global electricity generation increased from virtually 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 (cf. Chen 2015) – are likely to have played a significant role.[19] Early government policies supporting solar PV 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 3 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[20] – a period which experienced significant firm entry, in particular by Chinese firms. The Chinese government supported its solar PV

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

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

20. 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; Renewable Energy World 2014.

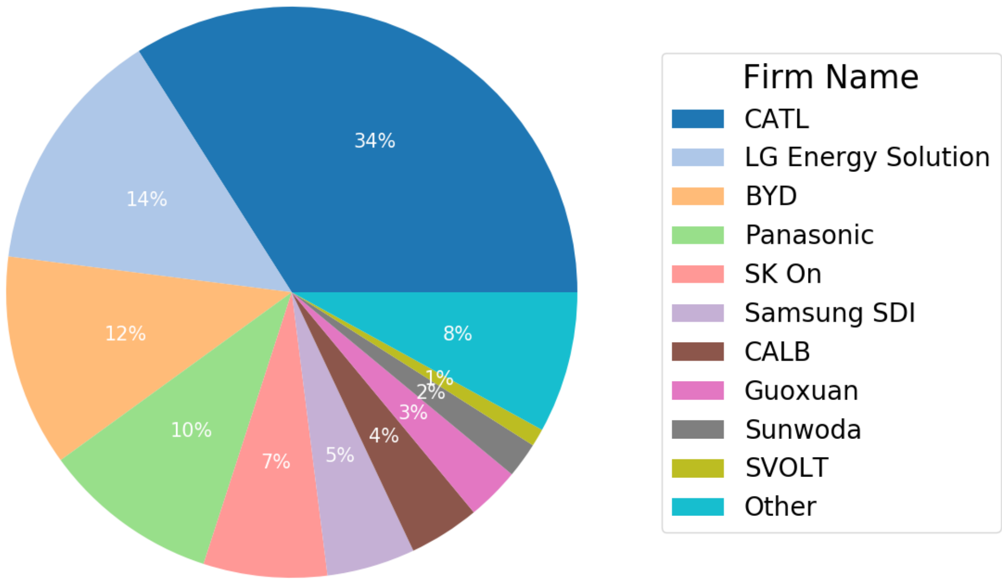
FIGURE 3
Market Concentration Over Time (Solar PV)

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 et al. 2013). Chinese solar panel manufacturers reached more than 50% of global revenue share by 2012 (Chen 2015).

In 2012, the US and the EU both imposed anti-dumping duties on Chinese solar panels, arguing that the latter were unfairly subsidized (Hughes et al. 2017; Meckling et al. 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 here 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 governments.

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 4 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.[21] 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 findings, it should be interpreted with caution.



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 4
Market Concentration in 2022 (EV Batteries)

7 Conclusion: Implications for Trade Policy

This paper has used a simple, two-country model of trade in a technology with positive externalities to highlight how in the absence of subsidies, temporary autarky to allow an infant industry to catch up may increase consumer surplus and public goods provision and be welfare improving for the high cost country, as well as potentially the low cost country, if the high cost country's distance to frontier is sufficiently large. This is driven by the losses otherwise incurred due to imperfect competition. The low cost country may prefer that the high cost country does not catch up, if the rents it thereby extracts outweigh gains in public goods provision and consumer surplus.

21. 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.

When both countries use consumer subsidies which correct monopoly losses as well as internalizing the domestic public good, public goods provision and consumer surplus under temporary autarky are higher for any distance to frontier – whether the low cost country also prefers autarky depends on whether this outweighs the loss in rent extracted. When both countries use producer subsidies, autarky in both periods is preferable to the low cost country, because producer subsidies in a set-up with Bertrand competition and profit dissipation exacerbate free riding on the other country's subsidies, leading to lower public goods provision and lower welfare for the supplier country.

When countries are free to choose their subsidy mix, the high cost country can subsidize its domestic industry to enforce marginal cost pricing under trade. This is the Sub-Game Perfect Nash Equilibrium of this game. The low cost country may find that producer subsidies lower its domestic welfare due to the loss in rents extracted from the high cost country. Put differently: allowing the laggard country to more effectively compete with the frontier country through upstream subsidies[22] can increase consumer surplus and public goods provision globally. However, it is at odds with any mercantilist ambitions to extract rents which the initially frontier country may harbor.

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,[23] 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. 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 Adjustment Mechanism in the European Union (Grubb et al. 2022). More broadly, encouraging the use of producer support over protectionist measures accompanying demand-side policies could reduce the costs of protectionism and may prove more effective than simply challenging local content requirements or discriminatory public procurement.

There are a number of important limitations. First, Bertrand competition abstracts from some of the potential benefits of having a competitive industry in a level playing field, due to rent dissipation. Further work on the trade-offs between trade and autarky may investigate how Cournot competition might lead to different outcomes by providing stronger incentives to compete for market share. However, with a large number of entrants following the maturation of infant industries I would argue that it is reasonable to assume profit dissipation.

22. And for some parameter values, even infant industry protection, which is more costly for both countries.

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

Moreover, I use a very simple model of learning in which the laggard country catches up immediately if it is active, and 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 innovation. Finally, the paper only considers infant industry protection and the competitive implications of a level versus an un-level playing field. Future work could look at the implications of 'racing' to be the frontier country and extract rents in the first place, which may provide a channel through which to address the global collective action problem presented by climate change.

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Appendix

A Trade and Autarky Without Subsidies

TABLE 1
Outcome Matrix for Country i

Stage 1 Strategy	Stage 1 Outcome, country i	Stage 2 Outcome, country i
Autarky	$P_i = \frac{a+c}{2}; r_i = \frac{a-c}{2}; R = a - \frac{c(1+d)}{2}$ $W_i = \frac{3}{8}(a-c)^2 + \frac{b}{2}(a - \frac{c(1+d)}{2})$ $CS_i = \frac{(a-c)^2}{8}; \Pi_i = \frac{(a-c)^2}{4}$	$P_i = c; r_i = a-c; R = 2(a-c)$ $W_i = \frac{(a-c)^2}{2} + b(a-c)$ $CS_i = \frac{(a-c)^2}{2}; \Pi_i = 0$
Trade	$P_i = dc; r_i = a-dc; R = 2(a-dc)$ $W_i = (a-dc)\left(\frac{a-dc}{2} + 2c(d-1) + b\right)$ $CS_i = \frac{(a-dc)^2}{2}; \Pi_i = 2c(a-dc)(d-1)$	$P_i = dc; r_i = a-dc; R = 2(a-dc)$ $W_i = (a-dc)\left(\frac{a-dc}{2} + 2c(d-1) + b\right)$ $CS_i = \frac{(a-dc)^2}{2}; \Pi_i = 2c(a-dc)(d-1)$

Note: The Table shows prices, quantities, profits, consumer surplus, overall public goods provision and welfare for the low cost country in both Stages of the game, depending on whether countries are in autarky or engage in trade during Stage 1.

TABLE 2
Outcome Matrix for Country j

Stage 1 Strategy	Stage 1 Outcome, country j	Stage 2 Outcome, country j
Autarky	$P_j = \frac{a+dc}{2}; r_j = \frac{a-dc}{2}; R = a - \frac{c(1+d)}{2}$ $W_j = \frac{3}{8}(a-dc)^2 + \frac{b}{2}(a - \frac{c(1+d)}{2})$ $CS_j = \frac{(a-dc)^2}{8}; \Pi_j = \frac{(a-dc)^2}{4}$	$P_j = c; r_j = a-c; R = 2(a-c)$ $W_j = \frac{(a-c)^2}{2} + b(a-c)$ $CS_j = \frac{(a-c)^2}{2}; \Pi_j = 0$
Trade	$P_j = dc; r_j = a-dc; R = 2(a-dc)$ $W_j = \frac{(a-dc)^2}{2} + b(a-dc)$ $CS_j = \frac{(a-dc)^2}{2}; \Pi_j = 0$	$P_j = dc; r_j = a-dc; R = 2(a-dc)$ $W_j = \frac{(a-dc)^2}{2} + b(a-dc)$ $CS_j = \frac{(a-dc)^2}{2}; \Pi_j = 0$

Note: The Table shows prices, quantities, profits, consumer surplus, overall public goods provision and welfare for the high cost country in both Stages of the game, depending on whether countries are in autarky or engage in trade during Stage 1.

Tables 1 and 2 provide an overview of prices, quantities, consumer surplus, profits, public good provision and overall welfare in each country, respectively, for both Stages of the game, depending on which strategy is chosen in Stage 1. It is clear that Stage 1 welfare in both countries is greater under trade, while the high cost country's and collective Stage 2 welfare are greater following autarky in Stage 1.[24] Each government must therefore trade off the welfare losses from temporary autarky against the welfare gains derived from the low cost firm's ability to catch up. In the following analysis, I decompose welfare into three parts: consumer surplus; profits; and the public good. I start with overall consumption of the new technology, ie the public good.

In order for $r_i + r_j = R$ to be greater under temporary autarky than under trade, it must be the case that

$$a - \frac{c(1+d)}{2} + 2(a-c) > 4(a-dc) \tag{28}$$

This holds for any $d > \frac{2a}{7c} + \frac{5}{7}$[25] and can be consistent with equation 17 for any $d > 1$ and $c < a$.

Result 1. *If $d > \frac{2a}{7c} + \frac{5}{7}$, then $R_1 + R_2$ is greater under Stage 1 autarky than under Stage 1 trade.*

Turning to consumer surplus, consumer surplus over both periods is greater for country j if

$$\frac{(a-dc)^2}{8} + \frac{(a-c)^2}{2} > (a-dc)^2 \tag{30}$$

This holds for $d > \frac{(\sqrt{7}-2)a+2c}{\sqrt{7}c}$.

Result 2. *If $d > \frac{(\sqrt{7}-2)a+2c}{\sqrt{7}c}$, then $\Sigma(CS_{j,1} + CS_{j,2})$ is greater under Stage 1 autarky than under Stage 1 trade.*

For country i this is the case if

$$\frac{(a-c)^2}{8} + \frac{(a-c)^2}{2} > (a-dc)^2 \tag{31}$$

which holds for $d > \frac{(\sqrt{8}-\sqrt{5})a+\sqrt{5}c}{\sqrt{8}c}$.

Result 3. *If $d > \frac{(\sqrt{8}-\sqrt{5})a+\sqrt{5}c}{\sqrt{8}c}$, then $\Sigma(CS_{i,1} + CS_{i,2})$ is greater under Stage 1 autarky than under Stage 1 trade.*

Note that Result 1 implies that both Results 2 and 3 also hold. The converse is not the case, implying that there are values of d for which one or both countries would choose temporary autarky over trade, even though the latter would be preferable for public goods provision and collective welfare. Further,

24. The low cost country's welfare may be higher or lower in Stage 2 following autarky, depending on whether the increases in consumer surplus and public goods provision are greater or lower than the loss in rents extracted from the high cost country's consumers.

25. This follows from

$$\begin{aligned} a - \frac{c}{2} - \frac{dc}{2} + 2a - 2c &> 4a - 4dc \\ \rightarrow d &> \frac{2a}{7c} + \frac{5}{7} \end{aligned} \tag{29}$$

$$\frac{(\sqrt{7}-2)a+2c}{\sqrt{7}c} > \frac{(\sqrt{8}-\sqrt{5})a+\sqrt{5}c}{\sqrt{8}c} \tag{32}$$

implying that the low cost country enjoys gains in consumer surplus from temporary protection at lower levels of d than the high cost country. Put differently, the high cost country makes a greater temporary sacrifice in terms of consumer surplus by choosing autarky.

The final outcome affected by the choice to engage in trade are profits. Since the high cost firm is inactive under Stage 1 trade, profits in the high cost country will always be greater under autarky. In the low cost country, temporary autarky benefits the producer if

$$\begin{aligned} \frac{(a-c)^2}{4} &> 4c(a-dc)(d-1) \\ \rightarrow \frac{(a-c)^2}{4} - 4c(a-dc)(d-1) &> 0 \end{aligned} \tag{33}$$

Equation 33 holds for any (a) $d > \frac{2a+2c+\sqrt{3}a-\sqrt{3}c}{4c}$ and (b) $d < \frac{2a+2c-\sqrt{3}a+\sqrt{3}c}{4c}$. (a) is not consistent with a $d > 1$ and $a > c$.[26] (b) is consistent with $d > 1$ and $a > c$.[27]

Result 4. *If $d < \frac{2a+2c-\sqrt{3}a+\sqrt{3}c}{4c}$, then the low-cost firm's profits are higher under temporary autarky than under free trade.*

However, result 3 and 4 cannot hold at the same time. Proof:

$$\begin{aligned} \frac{2a+5c}{7c} < d &< \frac{2a+2c-\sqrt{3}a+\sqrt{3}c}{4c} \\ \rightarrow 4(2a+5c) &< 7(2a+2c-\sqrt{3}a+\sqrt{3}c) \\ \rightarrow (8-14+7\sqrt{3})a &< (14-20+7\sqrt{3})c \\ \rightarrow a &< c \end{aligned} \tag{36}$$

is not consistent with $a > c$.

26. This follows from

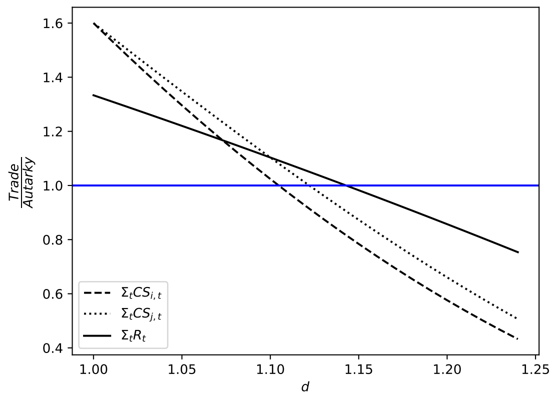
$$\begin{aligned} d > 1 &> \frac{2a+2c+\sqrt{3}a-\sqrt{3}c}{4c} \\ \rightarrow c &> a + \frac{\sqrt{3}}{2}(a-c) \end{aligned} \tag{34}$$

which is not consistent with $a > c$.

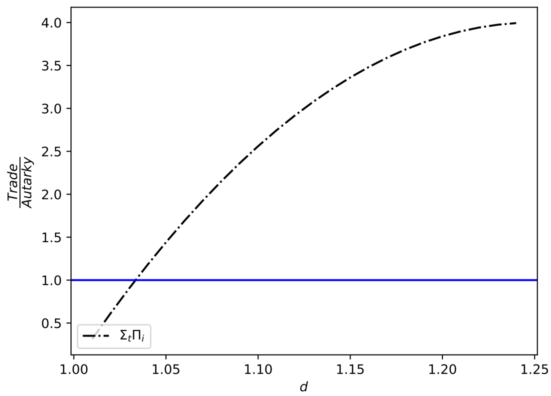
27. Proof:

$$\begin{aligned} 1 < d &< \frac{2a+2c-\sqrt{3}a+\sqrt{3}c}{4c} \\ \rightarrow 4c &< 2a+2c-\sqrt{3}a+\sqrt{3}c \\ \rightarrow (2-\sqrt{3})c &< (2-\sqrt{3})a \end{aligned} \tag{35}$$

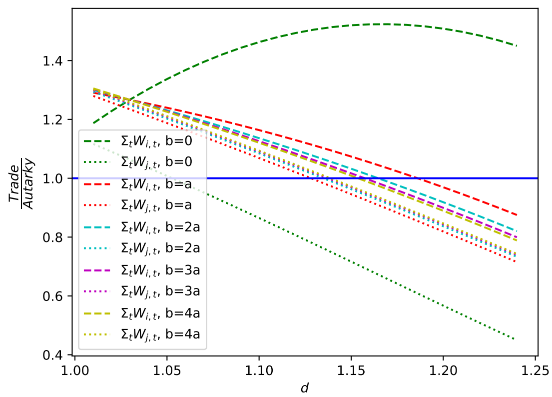
which implies $a > c$.



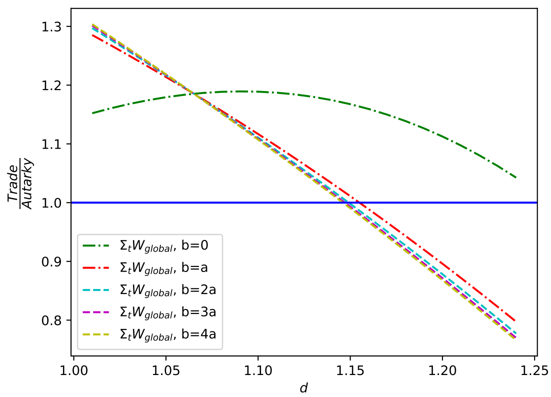
(a) Consumer Surplus and Overall Consumption



(b) Profit by Firm i



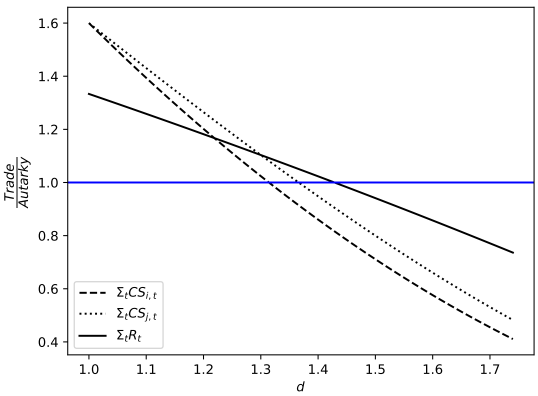
(c) Country Welfare



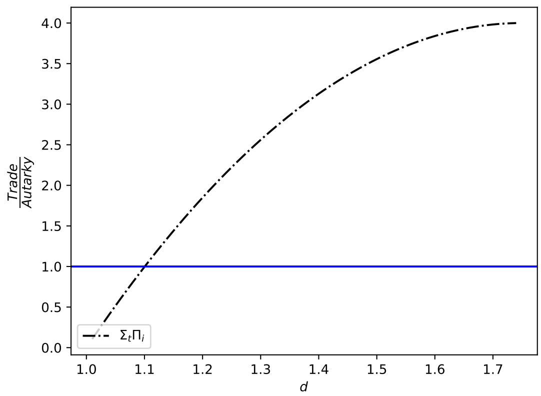
(d) Global Welfare

Note: Like Figure 1, but with $a = 1.5c$.

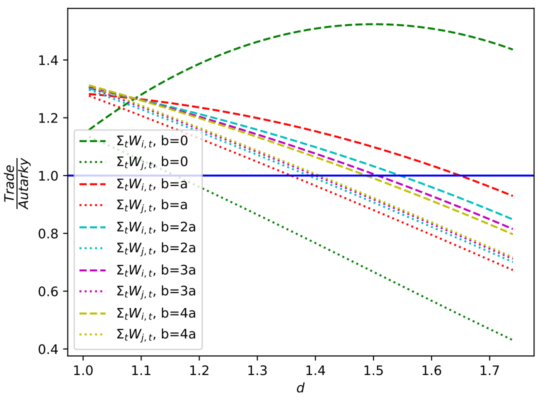
FIGURE 5
Consumer Surplus, Consumption, Profit and Welfare Under Trade Relative to Autarky



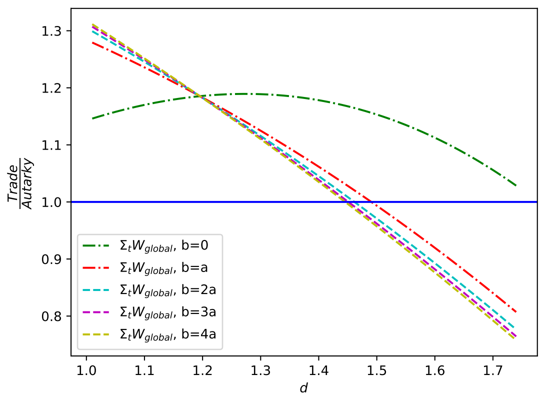
(a) Consumer Surplus and Overall Consumption



(b) Profit by Firm i



(c) Country Welfare

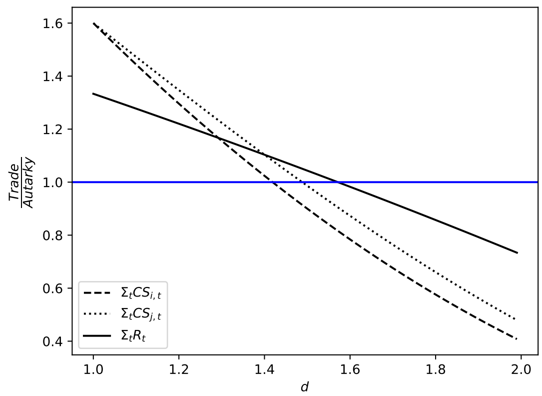


(d) Global Welfare

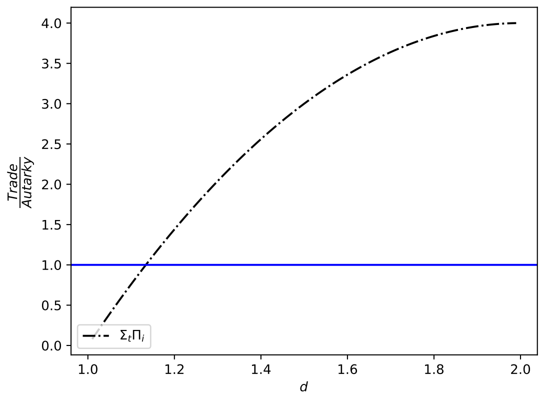
Note: Like Figure 1, but with $a = 2.5c$.

FIGURE 6

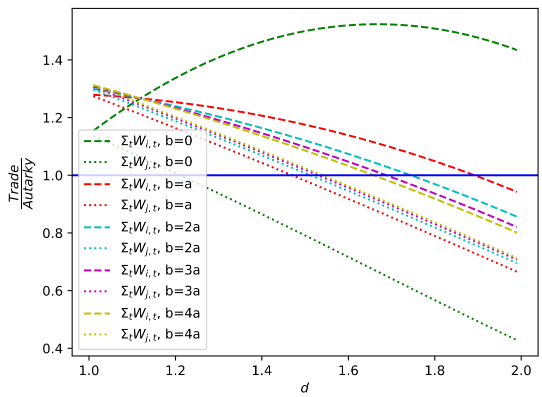
Consumer Surplus, Consumption, Profit and Welfare Under Trade Relative to Autarky



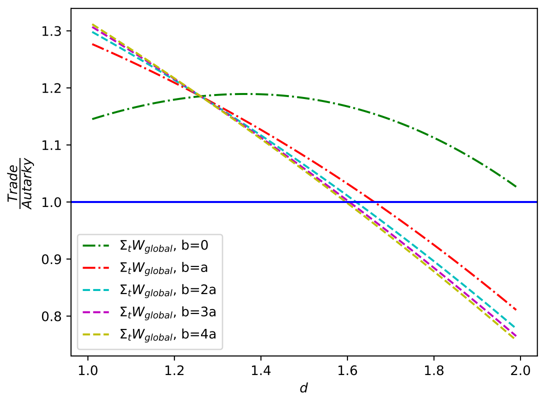
(a) Consumer Surplus and Overall Consumption



(b) Profit by Firm i



(c) Country Welfare



(d) Global Welfare

Note: Like Figure 1, but with $a = 3c$.

FIGURE 7

Consumer Surplus, Consumption, Profit and Welfare Under Trade Relative to Autarky

B TRADE AND AUTARKY WITH SUBSIDIES

B.1 Consumer Subsidies

Under autarky, in any Stage of the game each government will subsidize in order to eliminate the deadweight loss from the monopoly and internalize the domestic part of the climate externality. Consider a downstream subsidy in country i. A quantity subsidy s shifts consumer demand such that

$$r_i = a - P + s_i \tag{37}$$

The monopolist now maximizes

$$\begin{aligned} \Pi_i &= (a - P + s_i)(P - c) \\ \rightarrow P &= \frac{a + s_i + c}{2} \end{aligned} \tag{38}$$

thus

$$r_i = \frac{a + s_i - c}{2} \tag{39}$$

The government thus faces the objective function

$$\begin{aligned} W_i(s) &= ar_i - \frac{r_i^2}{2} - (P - s_i)r_i + Pr_i - cr_i + \frac{b}{2}(r_i + r_j) - s_i r_i \\ &= (a - c + \frac{b}{2})r_i - \frac{r_i^2}{2} + \frac{b}{2}r_j \\ &= (a - c + \frac{b}{2})(\frac{a + s_i - c}{2}) - \frac{(\frac{a+s_i-c}{2})^2}{2} + \frac{b}{2}r_j \end{aligned} \tag{40}$$

From the first order condition we get

$$s_i = a + b - c \tag{41}$$

which yields

$$r_i = a - c + \frac{b}{2} \tag{42}$$

Country j solves a symmetric problem, substituting dc for c. Quantities and welfare are thus the same as under perfect competition - see appendix C.

Under trade, again assuming that dc is below the low cost country's monopoly price, only the low cost firm is active and supplies the market at $P = dc$. The low cost country's government sets a subsidy to optimize

$$W_i = ar_i - \frac{r_i^2}{2} - (dc - s_i)r_i + (dc - c)(r_i + r_j) - r_i s_i + \frac{b}{2}(r_i + r_j) \tag{43}$$

Given that only $r_i = a - dc + s_i$ and r_j is not affected by the domestic subsidy, the first order condition implies that

$$s_i = c(d-1) + \frac{b}{2} \tag{44}$$

The high cost country's government solves

$$maxW_j = ar_j - \frac{r_j^2}{2} - dcr_j + \frac{b}{2}(r_i + r_j) \tag{45}$$

yielding

$$s_j = \frac{b}{2} \tag{46}$$

These subsidies lead to quantities

Result 5. $r_i = a - c + \frac{b}{2}; r_j = a - dc + \frac{b}{2}$

B.2 Producer Subsidies

Autarky Under autarky and upstream subsidies, the firm optimizes

$$\begin{aligned} \Pi_i &= Pr_i - cr_i + s_i r_i \\ &= (P - c + s_i)(a - P) \end{aligned} \tag{47}$$

which yields $P = \frac{a+c-s_i}{2}$ and $r = \frac{a-c+s_i}{2}$. The optimal subsidy resulting from the government's maximization problem is $s_i = a + b - c_i$, as it was under downstream subsidies. Government j solves a symmetrical problem. Outcomes are identical to perfect competition and autarky (see appendix C).

Trade – Levelled Industry Suppose government i changes strategy unilaterally and sets $s_i = b + \varepsilon$. It can now capture the whole market. However, since $s_j = b$, profits effectively remain 0. The government's welfare now becomes

$$\begin{aligned} W_i(b+\varepsilon, b) &= CS(b+\varepsilon, b) + \Pi(b+\varepsilon, b) + \frac{b}{2}R(b+\varepsilon, b) - (b+\varepsilon)R(b+\varepsilon, b) \\ &= CS(b+\varepsilon, b) + 0 + \frac{b}{2}R(b+\varepsilon, b) - (b+\varepsilon)R(b+\varepsilon, b) \end{aligned} \tag{48}$$

which reduces welfare by $\frac{R}{2}(b+\varepsilon)$ – the amount by which it subsidizes country j's consumption. This is clearly not a desirable move.

Conversely, suppose government i instead sets $s_i = b - \varepsilon$, such that firm j captures the market. Welfare in country i becomes

$$W_i(b-\varepsilon, b) = CS(b-\varepsilon, b) + \frac{b}{2}R(b-\varepsilon, b) \tag{49}$$

while welfare in country j is

$$W_j(b-\varepsilon, b) = CS(b-\varepsilon, b) + 0 + \frac{b}{2}R(b-\varepsilon, b) - bR(b-\varepsilon, b) \tag{50}$$

$s = b$ is not a sustainable outcome, because each government has an incentive to incrementally reduce subsidies to shift the burden of public goods provision on the other country while maintaining marginal cost pricing. Up to what point? Suppose government i expects all production to take place domestically, while price is determined by the subsidy set by government j. $P = c - s_j$, $r_i = r_j = r = a - c + s_j$. The government's problem becomes

$$\max_{\{s_i\}} W_i(s_i, s_j) = \max_{\{s_i\}} CS(s_i, s_j) + \Pi(s_i, s_j) + \frac{b}{2}R(s_i, s_j) - s_i\frac{R(s_i, s_j)}{2} \tag{51}$$

Setting $u(r_i) = ar_i - \frac{r_i^2}{2}$, we get $s_j = \frac{b+c-a}{3}$. This is the degree to which country i is willing to subsidize country j, and vice versa.

Result 6. *Since it is in country j's interest to maintain marginal cost pricing, the Nash equilibrium in pure strategies is at $s_i = s_j = s = \frac{b+c-a}{3}$ and $P = c - s = \frac{a+2c-b}{3}$ – the same as under perfect competition.*

$$\begin{aligned}\max_{\{s_i\}} W_i(s_i,s_j) &= \max_{\{s_i\}} ar_i - \frac{r_i^2}{2} - Pr + PR - cR + s_iR + \frac{b}{2}R - s_iR \\ &= \max_{\{s_i\}} (a-c+s_j)r - \frac{r^2}{2} + (c-s_j)R - cR + s_iR + \frac{b}{2}R - s_iR\end{aligned} \tag{52}$$

We see all terms containing s_i cancel out. Reframe the problem as

$$\begin{aligned}\max_{\{s_j\}} W_i(s_i,s_j) &= \max_{\{s_j\}} (a-c+s_j)r - \frac{r^2}{2} - s_jR + \frac{b}{2}R \\ &= \max_{\{s_j\}} \frac{(a-c+s_j)^2}{2} + 2(\frac{b}{2} - s_j)(a-c+s_j)\end{aligned} \tag{53}$$

Trade – Unlevelled Industry Market sharing requires that $dc - s_j = c - s_i$, implying that $s_j = dc + s_i - c$.

However, we have already shown that the largest subsidy which country i will support is $s_i = \frac{b+c-a}{3}$, while for country j with cost dc this is now $s_j = \frac{b+dc-a}{3}$. $s_j = dc + s_i - c = dc - c + \frac{b+c-a}{3} = \frac{3dc-2c+b-a}{3} > \frac{b+dc-a}{3}$. Country j will not be prepared to sustain this subsidy, unless it does not actually expect to pay it. The low cost firm will thus supply the entire market, and its government subsidize both countries' consumers via upstream subsidies. The low cost firm sets $P = dc - s_j$ and $r_i = r_j = r = a - dc + s_j$. Government i optimizes the following objective function:

$$W_i = (a - dc + s_j - \frac{r}{2})r + (dc - s_j - c + s_i)R + \frac{b}{2}R - s_iR \tag{54}$$

Any terms containing s_i cancel out, because price is affected only by s_j, not s_i, and only r_js_j spills over to the other country. The optimal level of s_j from the high cost government's perspective is infinite as long as in practice, its firm is inactive. From the perspective of the low cost government, the first order condition yields the optimal subsidy $s_j = \frac{3dc-2c+b-a}{3}$. This is the highest subsidy which the low cost government is prepared to outbid. If the industry is levelled such that $d = 1$, this reduces to $\frac{b+c-a}{3}$ – the same subsidy we found in the previous paragraph.

Result 7. *In the unlevelled industry, government j will therefore set $s_j = \frac{3dc-2c+b-a}{3} - \varepsilon$. Government i will set $s_i = \frac{b+c-a}{3}$ and the low cost firm supplies the whole market at $P = dc - s_j = \frac{a+2c-b}{3} + \varepsilon$.*

Temporary Production Subsidy Suppose the high cost country subsidizes its industry during Stage 1 in order to catch up with the low cost industry. For simplicity, assume this is the only policy instrument used. In order for the high cost firm to compete, $c = dc - s_j \rightarrow s_j = c(d-1)$.

TABLE 3
Outcome Matrix for Country i

Stage 1 Strategy	Stage 1 Outcome, country i	Stage 2 Outcome, country i
Autarky	$s_i = a+b-c; P_i = \frac{2c-b}{2}; r_i = a-c+\frac{b}{2}$ $W_i = \frac{3}{8}(2a-2c+b)^2 + \frac{b}{2}(2a-c(1+d)+b) - (a+b-c)(a-c+\frac{b}{2})$ $CS_i = \frac{(2a-2c+b)^2}{8}; \Pi_i = \frac{(2a-2c+b)^2}{4}; B_i = \frac{b}{2}(2a-c(1+d)+b)$	$s_i = \frac{b+c-a}{3}; P_i = \frac{a+2c-b}{3}; r_i = \frac{2a-2c+b}{3}$ $W_i = \frac{(2a-2c+b)^2}{18} + \frac{b}{3}(2a-2c+b) - \frac{b+c-a}{3}\frac{2a-2c+b}{3}$ $CS_i = \frac{(2a-2c+b)^2}{18}; \Pi_i = 0; B_i = \frac{b}{3}(2a-2c+b)$
Trade	$s_i = \frac{b+c-a}{3}; P_i = \frac{a+2c-b}{3}; r_i = r_i = \frac{2a-2c+b}{3}$ $W_i = \frac{(2a-2c+b)^2}{18} + \frac{b}{3}(2a-2c+b) - 2\frac{b+c-a}{3}\frac{2a-2c+b}{3}$ $CS_i = \frac{(2a-2c+b)^2}{18}; \Pi_i = 0; B_i = \frac{b}{3}(2a-2c+b)$	$s_i = \frac{b+c-a}{3}; P_i = \frac{a+2c-b}{3}; r_i = r_i = \frac{2a-2c+b}{3}$ $W_i = \frac{(2a-2c+b)^2}{18} + \frac{b}{3}(2a-2c+b) - 2\frac{b+c-a}{3}\frac{2a-2c+b}{3}$ $CS_i = \frac{(2a-2c+b)^2}{18}; \Pi_i = 0; B_i = \frac{b}{3}(2a-2c+b)$

Note: The Table shows prices, quantities, profits, consumer surplus, overall public goods provision and welfare for the low cost country in both Stages of the game when both countries are using producer subsidies, depending on whether countries are in autarky or engage in trade during Stage 1.

Now $P = c; r_i = r_j = a - c; R = 2(a - c)$. Both firms supply 50% of the market. Country j's welfare is

$$\begin{aligned} W_j &= CS_j + \Pi_j + B_j - s_j r_j \\ &= \frac{(a-c)^2}{2} + (a-c)(c - dc + c(d-1)) + \frac{b}{2} 2(a-c) - c(1-d)(a-c) \\ &= \frac{(a-c)^2}{2} + b(a-c) - c(d-1)(a-c) \end{aligned} \tag{55}$$

country i's welfare is

$$\begin{aligned} W_i &= CS_i + \Pi_i + B_i \\ &= \frac{(a-c)^2}{2} + 0 + b(a-c) \end{aligned} \tag{56}$$

In Stage 2, both firms produce at marginal cost c, and welfare is $W_i = W_j = \frac{(a-c)^2}{2} + b(a-c)$. Can this be an equilibrium? Assume for the moment that a climate subsidy is not available and compare each country's welfare to its outcomes under trade and autarky with no production subsidy.

In order for country j to prefer trade with a production subsidy over trade without it, it must be the case that

$$\begin{aligned} (a-c)^2 + 2b(a-c) - c(d-1)(a-c) &> (a-dc)^2 + 2b(a-dc) \\ \rightarrow (a-c)(a-c+2b-dc+c) &> (a-dc)(a-dc+2b) \\ \rightarrow a-c &> a-dc \end{aligned} \tag{57}$$

This holds for all $d > 1$. Country j will always prefer trade with a production subsidy over trade without it.

What about autarky? Stage 2 outcomes will be identical, so in order for a production subsidy to be preferred welfare in Stage 1 must be greater under trade and a production subsidy. This requires

$$\frac{(a-c)^2}{2} + b(a-c) - c(d-1)(a-c) > \frac{3(a-dc)^2}{8} + \frac{b}{2}\left(\frac{a-dc}{2} + \frac{a-c}{2}\right) \tag{58}$$

However, country j can increase its domestic welfare by reducing the subsidy to $s_j = c(d-1) - \varepsilon$. This will eliminate the cost of the subsidy, while maintaining marginal cost pricing, and constitutes a pareto improvement. If production subsidies are available in both periods, the equilibrium will not support a 'catching up' subsidy.

C PERFECTLY COMPETITIVE FIRMS

Trade In the absence of subsidies, in any Stage of the game $P_i = P_j = c$, $r_i = r_j = a - c, R = 2(a-c)$. The respective countries' welfare is

$$\begin{aligned} W_i = W_j &= ar_i - \frac{r_i^2}{2} - cr_i + \frac{b}{2}R \\ &= \frac{(a-c)^2}{2} + b(a-c) \end{aligned} \tag{59}$$

Autarky Under autarky without subsidies, $P_i = c$ and $P_j = dc$. $r_i = a - c$, $r_j = a - dc$, $R = 2a - c(1+d)$. The respective countries' welfare is

$$\begin{aligned} W_i &= ar_i - \frac{r_i^2}{2} - P_i r_i + \frac{b}{2}R \\ &= \frac{(a-c)^2}{2} + ba - \frac{bc}{2}(1+d) \\ W_j &= ar_j - \frac{r_j^2}{2} - P_j r_j + \frac{b}{2}R \\ &= \frac{(a-dc)^2}{2} + ba - \frac{bc}{2}(1+d) \end{aligned} \tag{60}$$

Since both countries' welfare is higher under trade than autarky, and as there is no benefit to be derived from the high country catching up under marginal cost pricing, it will be welfare-improving for both countries to trade in both Stages of the game.

Autarky With Subsidies Under autarky, each country takes into account only its own share of the positive externality when setting subsidies, such that $s = \frac{b}{2}$. From the respective consumers' demand functions we get

$$\begin{aligned} r_i &= a - c + \frac{b}{2} \\ r_j &= a - dc + \frac{b}{2} \\ R &= 2a + b - c(1+d) < 2(a - c + b) \end{aligned} \tag{61}$$

Welfare is

$$\begin{aligned} W_i &= ar_i - \frac{r_i^2}{2} - cr_i + \frac{b}{2}R \\ &= (a-c)*(a-c+\frac{b}{2}) - \frac{(a-c+\frac{b}{2})^2}{2} + \frac{1}{2}(2a+b-c(1+d)) \\ W_j &= ar_j - \frac{r_j^2}{2} - dcr_j + \frac{b}{2}R \\ &= (a-dc)*(a-dc+\frac{b}{2}) - \frac{(a-dc+\frac{b}{2})^2}{2} + \frac{1}{2}(2a+b-c(1+d)) \end{aligned} \tag{62}$$

Trade With Consumer Subsidies Under trade and perfect competition, only the low cost firm will be active and provide any quantity at $P = c$. If governments choose a consumer subsidy, each government will subsidize at $s = \frac{b}{2}$. Both representative consumers purchase R at the same price $P = c - \frac{b}{2}$, resulting in

$$\begin{aligned} r_i = r_j &= a - c + \frac{b}{2} \\ R &= 2(a-c) + b \end{aligned} \tag{63}$$

As before, there is no benefit to catching up and both countries wish to trade in both periods.

Trade With Producer Subsidies If governments subsidize their upstream industry instead, they can influence not only their domestic consumers' demand, but also the prices faced by foreign consumers. Assuming that the high cost country does not have considerably higher subsidies than the low cost country (which cannot be an equilibrium, as previous analysis has shown), consumers in both countries face $P = c - s_i$. The low cost firm supplies the entire market such that $q_i = R$. The cost of the subsidy to government i is $s_i * R$.

$$\begin{aligned} P &= c - s_i \\ r_i = r_j &= a - c + s_i \\ R &= 2(a - c + s_i) \end{aligned} \tag{64}$$

government i will choose s_i to solve

$$\max_{\{s_i\}} W_i = ar_i - \frac{r_i^2}{2} - Pr_i + PR - cR + s_iR + \frac{b}{2}R - s_iR \tag{65}$$

From the first order condition we obtain the optimal upstream subsidy s_i:

$$s_i = \frac{b-a+c}{3} \tag{66}$$

Inserting the subsidy into consumer demand yields

$$\begin{aligned} r_i = r_j &= \frac{2a-2c+b}{3} \\ R &= \frac{2}{3}(2a-2c+b) \end{aligned} \tag{67}$$

Note that subsidies, consumption and public goods provision are lower under producer than consumer subsidies. Note also that the high cost country enjoys higher welfare than the low cost country, as the latter bears the full cost of public goods provision. The low cost country may therefore prefer to remain in autarky during both periods.