Welfare and Environmental Effects of Subsidies and Tariffs in North-South Trade in Renewable Energy Equipment

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Abstract

A two-country, three-good general equilibrium model is developed to examine the welfare and environmental effects for countries (North and South) of demand subsidies (a feed-in tariff) to renewable energy equipment, as well as tariffs on renewable energy equipment imports. Both North and South renewable energy equipment producers engage in Cournot duopoly competition with a homogeneous product in both countries. Both countries also produce polluting fossil-fuel-generated electricity and a numeraire good. We show, inter alia, that an endogenous Northern import tariff is increasing in (independent of) a Northern (Southern) feed-in tariff premium, even if the North government does not internalize any pollution harm. A Northern feed-in tariff premium may hurt domestic environment due to a rebound effect and it may also hurt Southern welfare.[1]

JEL classification: F12, F18, H23, Q58

Keywords: Renewable energy equipment, Environmental goods, Environmental subsidies, Trade and environment, Feed-in tariff, Pollution, North-South Trade

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1 Introduction

Renewable energy (RE) is heavily promoted by both developed countries and newly industrialised countries (NICs) due to its potential to combat climate change, improve national energy security by reducing reliance on foreign oil, boost new industries and create new jobs. It is also expected by some to be the "third industrial revolution", so countries view the RE sector as a key sector for future competitiveness. However, large-scale industrial policies tend to result in trade conflicts among competing nations (Carbaugh and Brown, 2012). So it is not surprising that one of the biggest trade disputes between developed countries and NICs such as China in recent years has been over RE equipment (solar panels, wind turbines etc).

This trade dispute provides the main motivation for this paper, which aims to explore the effects of government subsidies and tariffs in North-South trade in RE equipment on economic welfare and the environment. We show, *inter alia*, that an endogenous Northern import tariff is increasing in (independent of) a Northern (Southern) feed-in tariff (FIT) premium, even if the North government does not internalize any pollution harm. An endogenous Northern import tariff always increases Northern pollution. Although a Northern FIT premium decreases the Northern pollution by inducing more renewable electricity supply from households, it may increase Northern pollution due to a rebound effect through increasing the Northern import tariff and the Northern RE equipment price. Furthermore, a marginal increase in a Northern FIT premium is likely to negatively affect Southern economic welfare. We provide straightforward conditions for the above results to hold.

The economics literature provides little analysis of the effect of liberalization of trade in environmental goods (EG),[1] despite extensive studies in the policy literature (mainly undertaken by international organizations, as noted by Nimubona (2012))[2] and relatively abundant studies of EG in the environmental economics literature (Grafton et al., 2012). To the best of our knowledge, there is virtually no economics literature modelling North-South trade in RE equipment despite the extensive media coverage and growing interest in the policy literature. A large body of economics literature exists that mainly focuses on the broad effect of trade on the environment (See for example, Bajona and Kelly, 2012; Chao and Yu, 2007; Copeland and Taylor, 2003; Copeland and Taylor, 2009; Grossman and Krueger, 1991; Managi et al., 2009). However, there is still ambiguity in the relationship between trade and the environment (Managi et al., 2009), due to its dependence on many factors such as the structure of industry and comparative advantage of countries. There is also a strand

[1]The Organization for Economic Cooperation and Development and the Statistical Office of the European Commission define EG as the set of goods that can be used "to measure, prevent, limit, minimize or correct environmental damage to water, air, and soil, as well as problems related to waste, noise and eco-systems" (OECD/Eurostat 1999, as cited in Nimubona, 2012).

[2]Silva et al., (2013) also note that renewable resources are relatively under-studied in the resource literature in spite of their growing importance.

of literature focusing on more specific issues of trade and the environment (see for example, Robertson, 2007; Taylor, 2011). This paper belongs to the latter category by focusing on a particular type of EG – RE equipment. It is worth exploring because, first, like other EG, RE equipment has the potential to create a "win-win-win" situation – "benefiting trade, the environment and development" (WTO, 2001; OECD 2003, 2005 as cited in Dijkstra and Mathew, 2010); second, unlike other types of EG such as waste treatment equipment, RE equipment has some unique characteristics: (1) RE generation is time intermittent, its productivity mainly depending on weather conditions; (2) there are diminishing returns to RE equipment given limited space for installation and other possible constraints; (3) it reduces pollution by boosting an alternative to dirty energy, instead of directly abating the pollution from dirty energy generation;[3] (4) it involves not only governments and firms but also households; (5) in contrast to most EG that are technology-intensive, resulting in heavy reliance of the South on Northern-produced EG, RE equipment production is generally more competitive in NICs due to lower technology requirements and lower production costs such as lower wage rates.

Some of the most relevant economics papers are [1] Nimubona (2012); [2] Bourgeon and Ollivier (2012); [3] Bandyopadhyay et al. (2013); [4] Dijkstra and Mathew (2010); [5] Reichenbach and Requate (2012); [6] Silva et al. (2013) and [7] Ledvina and Sircar (2012). [1]—[4] examine trade in EG and the environment, among which [2] and [3] study one type of EG: biofuels. A common difference in our analysis from [1]—[6] is that we do not consider pollution taxes,[4] but instead focus on RE subsidies which take the form of a FIT[5] with a non-negative premium over the market (fossil-fuel-generated) electricity price. [1] assumes monopolistic or oligopolistic Northern EG[6] producers selling to both Northern and Southern markets that are segmented. The South fully relies on EG imports from the North and uses an emissions tax to reduce pollution. [1] concludes that trade liberalization in EG may lead to less Southern pollution tax and more pollution because the South wants to impose import tariffs on Northern-produced EG to extract rents from Northern EG producers (whose rents are increasing in the Southern pollution tax) but cannot do so due to a free trade agreement, so it may strategically use pollution taxes as a substitute. In contrast to [1] which focuses on high-tech EG for direct non-transboundary pollution abatement, this paper focuses on a very special type of EG–renewable energy equipment, which can also be used for indirect transboundary pollution abatement. We addresses its unique characteritics mentioned above, e.g., by allowing both the North and

[3]This corresponds to the "composition effect" in the literature, which explains how pollution is affected by the composition of output (structure of industry) (Managi et al., 2009)

[4]Although we do not explicitly model an emissions tax, an exogenous increase in an emissions tax is as if we have an exogenous increase in the market price in our model, due to our assumption of perfectly competitive fossil-fuel electricity sectors in both countries.

[5]A FIT offers long-term contracts to RE sellers with a guaranteed price at which they can sell excess electricity into the grid, typically based on the cost of generation (Reichenbach and Requate, 2012).

[6]They are used for end-of-pipe pollution abatement.

South EG producers to sell in both markets. Similar to [2] and [3], we also analyse the effect of RE trade on the environment. [2] consider an agriculture sector which produces biofuels as an intermediate good and an industry sector which requires labour and a mix of fossil energy and biofuels as inputs. However, unlike [2] which assume biofuels generate less intensive pollution than fossil-fuels,[7] RE generation in this paper is assumed be pollution-free, as in [3]. Similar to [3], we examine the optimal RE subsidies in a general equilibrium trade model, but this model is different from [3] by allowing RE producers to export in both countries (they assume the North exports corn to the South in exchange for manufacturing goods). [4] cast doubt on the hoped-for "win-win-win" result of trade liberalization in EG due to their findings: liberalization is likely to improve the Southern environment and welfare, but there is likely to be a rebound effect through inducing lower pollution taxes. This paper also finds a rebound effect of RE subsidies as mentioned above. As in this paper, [4] also allow for both Northern and Southern EG producers to compete. However, they assume competition only in the South. Unlike this paper, which considers optimal tariffs on RE imports and RE subsidies, [4] only consider a pollution tax. Unlike the Cournot competition of this paper, [4] consider Bertrand competition because they assume EG producers sell technology to the downstream polluting firm at a flat license fee. [5] look at output subsidies to upstream oligopolistic RE equipment producers which can lower costs through learning by doing, and a FIT to the downstream RE equipment installers who sell renewable electricity to consumers, in the presence of competition from oligopolistic and polluting fossil-fuel utilities. However, [5] do not consider international trade, but the paper is closely related to this paper because it also specifically models a FIT, which is rarely found in the economics literature. Similar to [6], we are interested in the compatibility between higher economic welfare and a cleaner environment. In contrast to endogenous technical change (knowledge investment) in both renewable and non-renewable sectors in [6], we only propose to consider research and development in the renewable sector, as in [4]. As in [7], this paper develops a Cournot game with constant but asymmetric costs and a linear demand. However, in contrast to inter-industry competition between high-cost RE producers and an low-cost oil producer within a country (no trade) in [7], this paper studies intra-industry Cournot duopoly competition between Northern and Southern RE equipment producers.

We consider a two-country model in which households derive utility from consuming electricity[8] and a numeraire good. In each country households can buy electricity from a perfectly competitive fossil-fuel generating sector, which also generates negative environmental externalities, but can also install RE equipment that generates electricity at home.

[7] E.g., conversion of forested lands.

[8] This demand is a derived demand, of course, but the utility function here can be thought of as a reduced form of a utility function that depends on the goods and services that are actually produced through the use of electricity.

We have in mind solar photovoltaic panels, although the analysis applies to other forms of RE generation, and consequently we allow that households face diminishing productivity in the installation of RE equipment, using the most productive placements first before expanding into less sunny areas, for example. Furthermore, each household faces different productivities for their installed RE equipment across a span of time; essentially, there are sunny (good) times and less sunny (bad) times.[9] We assume that households are net sellers (buyers) of renewable (fossil-fuel-generated) electricity in good (bad) times.

The RE equipment that households install is purchased from equipment producers and is essentially a homogeneous product from the perspective of households. Each country has one RE equipment firm. Both firms rely on a technology displaying constant returns to scale (CRS) in labour alone and engage in Cournot duopoly in both the Northern and Southern markets. We assume that the Southern RE equipment firm has a lower marginal cost.

The numeraire good producers also rely on a technology displaying a CRS technology in labour alone. Fossil-fuel electricity is generated under a CRS technology using fossil fuels alone. For simplicity, we assume that there is no scale effect or technical effect, so only a composition effect is present.[10] Pollution is a "residual" of households' renewable energy supply since the latter is a perfect substitute for fossil-fuel-generated electricity.

In this setting we consider first the general equilibrium of the model and then look at a number of comparative statics exercises to determine the consequences of policy changes and indicate the directions of optimal policy. We will also conduct some illustrative numerical solutions to shed light on the sensitivity of these policies to different weights on environmental factors in policy makers' objective functions.

Both governments in this model have two policy instruments. The first is effectively a demand subsidy that takes the form of a FIT or price at which households can sell their home-generated electricity into the national grid. This may simply be the market price of electricity or it may involve a premium above the market price to encourage households to sell excess renewable electricity. The second instrument is a tariff on RE equipment imports.

The main results of this paper are as follows. (1) Higher domestic FIT premium provides the same marginal benefit (MB) for all units of excess renewable electricity sold. However, it provides different MB to RE equipment installation, which is decreasing in the quantity of the latter due to diminishing returns to RE equipment in renewable electricity generation. (2) Under a linear demand for RE equipment,[11] given exogenous FIT premiums in both

[9] It is important to model this, as it has significant consequences for the impact of a FIT.

[10] We assume away the scale effect by assuming a quasi-linear utility function: the demand for electricity is independent of income because any increase in income is absorbed by increased consumption of the numeraire good. We assume away the technical effect by supposing that the pollution generated is proportional to fossil-fuel electricity generation, which is common in the relevant literature. See footnote 3 for a discussion of the composition effect.

[11] A linear equipment demand helps deriving clean analytical results, without losing the main insights. However, this assumption is restrictive because the results from it may not be robust for other shapes of demand curve, such as isoelastic demand, which is derived by assuming that renewable electricity generation

countries, and an endogenous Northern import tariff on Southern RE equipment:[12] even if the North government does not internalize any local or worldwide pollution, an exogenous Northern FIT premium always increases the optimal Northern tariff if the FIT premium is not too large relative to the market price (e.g., being less than the market price satisfies this sufficient condition).[13] This condition is likely to be implied by our assumption that households are net sellers in good generating times. (3) If Northern FIT premium increases the optimal Northern import tariff, then Northern FIT premium has a rebound effect on Northern pollution and it may also decrease Southern welfare. In this regard, RE subsidies may harm both economic welfare[14] and the environment, i.e. creating a "lose-lose" situation. (4) Greater incidence of good generating times is likely to increase the optimal import tariff. It may also non-monotonically affects the effect of a Northern FIT premium on the optimal domesitic import tariff.

The main contributions of this paper to the literature are three-fold. First, this paper addresses a little-studied topic in the economics literature – North-South trade in RE equipment – and adds to the relatively under-studied strand of trade and environment literature that takes into account the EG producers; for example, papers [1]—[4] above.

Second, this paper offers one example in which trade in the RE sector can be good for both economic welfare and the environment. As claimed by Copeland and Taylor (2003), free trade itself can be harmless to the environment: it is the existence of sub-optimal government policies that create problems that may be exacerbated by trade. Climate change is a global challenge due to its transboundary nature. On top of this environmental linkage between countries, international trade essentially creates an additional economic linkage. Globalization has led to greater specialization in the supply chain of RE equipment (Jha, 2009). Free trade in RE equipment allows for more efficient South RE equipment producers to compete in the North market. This enlarged market allows them both to enjoy economies of scale and to undertake more process research and development (work in progress).These both drive down the supply price of RE equipment. Cheaper RE equipment unambiguously benefits the environment for all countries. However, if government policies are suboptimal, then international trade in RE equipment may lead to undesirable or counter-intuitive consequences, such as further deterioration of environmental qualities.

Third, this paper provides a theoretical interpretation for a channel through which RE

is increasing in RE equipment installation according to a natural logarithm function. We have worked on this and one key difference is that the Cournot equilibrium price of RE equipment only depends on marginal costs of firms and the domestic import tariff, the latter now being independent of the FIT premiums in both countries.

[12]Environmental subsidies are often provided to respond domestic pressure due to some exogenous environmental shocks, e.g. Fukushima nuclear disaster. Nevertheless, we also reverse the endogeneity (as reported in Corollary 1). Furthermore, we will endogenize environmental policies and allow governments to choose an optimal policy mix in the simulation stage.

[13]See the explanations for Proposition 1 for details.

[14]A FIT premium also hurts domestic welfare by creating dead weight loss associated with under-demand and over-supply, see Section 2.3.5 for details.

subsidies can distort trade, which is one of the major concerns in the trade and environmental policy literature mainly undertaken by international organizations. As concluded by Jha (2009), subsidies may distort trade and create an "unlevel playing field" in RE equipment production, even though they are much more crucial in creating RE markets compared to import tariff reductions. Thus, Jha (2009) suggests that trade liberalization should be accompanied by subsidy reform. This paper shows that an exogenous Northern RE subsidy (a FIT premium) is likely to distort trade because a marginal increase of it is likely to increase the endogenous Northern import tariff on Southern RE equipment.

The paper is organized as follows. In Section 2, we describe the model and solve the game by backwards induction. Section 3 concludes.

2 The model

2.1 Model setup

There are two countries: a developed country denoted by North and a NIC denoted by South.[15] Both countries are endowed with L units of labour or households.[16] Labour is mobile within each country but immobile across countries. Households are homogenous and a representative household demands two non-tradable goods: electricity and a numeraire good labeled good 0. The representative household can choose to buy fossil-fuel-generated electricity E or can generate renewable electricity itself by installing RE equipment R. Fossil-fuel-generated and renewable electricity are perfect substitutes as the representative household does not internalize the pollution externality associated with the former.

The marginal productivity of RE equipment in generating renewable electricity for a household is diminishing in the quantity of equipment installed and the productivity of every unit of installed capacity is proportionately higher in good times than in bad times: this captures the fact that RE generation productivity depends on environmental conditions.

Both countries produce R, E and good 0. Thus, as shown in Figure 1, North has three sectors: R^N, E^N and 0^N ; South also has three: R^S, E^S and 0^S. The numeraire good sectors (fossil-fuel electricity sectors) in both countries are perfectly competitive and exhibit a CRS technology in labour (fossil fuels) alone. Thus, they determine the domestic wage rates.[17] Furthermore, the numeraire good is tradable, which ensures a trade balance between the two countries. Fossil-fuel electricity production generates pollution at a constant rate, pollution that causes both local environmental harm (e.g. air pollution) and worldwide environmental harm (e.g. climate change). Fossil-fuel-generated electricity is non-tradable. Both countries

[15] Superscripts N and S are used to distinguish variables that are associated with both North and South.

[16] Labour is equivalent to 'consumers' and 'households' in this model.

[17] The numeraire good is defined to have a price of one. Together with the zero profit condition, wage is the inverse of the unit labour requirement of the numeraire good. We assume that output of the numeraire good is always strictly positive in both countries.

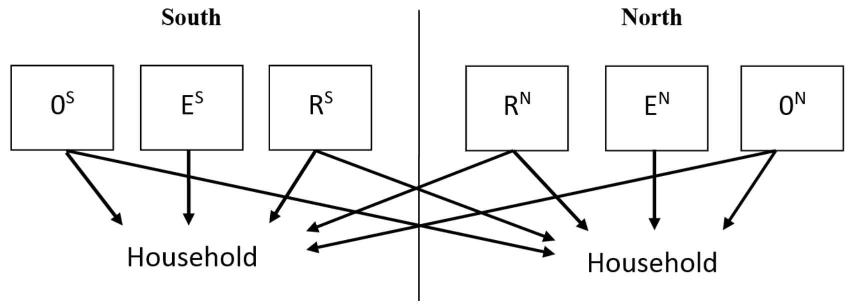

Figure 1: Trade pattern

have one RE equipment firm, producing homogenous and tradable RE equipment exhibiting a CRS technology in labour alone too. The two firms engage in Cournot competition in both countries. The Southern RE equipment firm has a lower (marginal cost) MC than its Northern competitor due to the lower Southern wage rate.

As noted, both governments have, potentially, two policy instruments: a demand subsidy (FIT) with premium $s^c \geq 0$ to encourage domestic households to sell excess renewable electricity and an import tariff on RE equipment imports.

2.2 Demand for electricity and good 0

We assume that both South and North are endowed with units of labour or households who all inelastically supply a unit of labour. All households in both countries have the same tastes and, as noted, consume two goods, electricity E and the numeraire good 0.

Following Copeland and Taylor (2003), a representative household takes pollution as given (it does not internalize any pollution externality). It maximizes a quasi-linear utility function subject to a household budget constraint

$$\max_{q_E, q_0} U = u(q_E, q_0) - h(z) = f(q_E) + q_0 - h(z),$$

$$s.t.\, p_E q_E + q_0 = Y$$

where$f'(q_E) > 0$, $f''(q_E) < 0$, q_E and q_0 are the consumed quantities of electricity and the numeraire good 0, z is the amount of pollution and Y is the income of the household. The utility derived from consumption of electricity $u(q_E,\, q_0)$ is assumed to be increasing and concave in q_E and q_0, and the pollution harm (welfare loss from pollution) $h(z)$ is assumed to be increasing and weakly convex.[18] We also suppose that households always demand positive amounts of both electricity and good 0. Thus, the optimal quantities of electricity

[18]This assumption is common in the relevant literature.

and good 0 demanded by a representative household are

$$q_E(p_E) = f'^{-1}(p_E)$$
$$q_0 = Y - p_E q_E(p_E)$$

The demand for electricity is independent of income, and depends solely on its own price. Total differentiation yields $f''(q_E)\,dq_E = dp_E$, thus, $q_E'(p_E) = \frac{1}{f''(q_E)} < 0$, i.e. the demand curve for electricity is downward sloping.

2.3 Supply

2.3.1 Supply of good 0

The numeraire good sector is perfectly competitive. Good 0 is generated with a CRS technology in labour alone. The production function for good is

$$q_0^c = \frac{L_0}{l_0^c},\ c = N,\, S$$

where L_0 is the labour employed in good 0 and l_0^c is the amount of labour required to produce each unit of good 0 in country $c = N,\, S$. The zero-profit condition implies $p_0^c = l_0^c w^c$. As good 0 is assumed to be our numeraire, so $p_0^c = l_0^c w^c = 1$ and the wage rate in country $c = N,\, S$ is pinned down by l_0^c

$$w^c = \frac{1}{l_0^c}$$

The assumption that South has the lower wage, then, is equivalent to assuming that $l_0^S > l_0^N$.

2.3.2 Supply of fossil-fuel-generated electricity and the associated pollution

The fossil-fuel electricity sector is perfectly competitive, generating electricity under a CRS technology using fossil fuels alone. The production function for sector E is

$$Q_E^F = \frac{F}{\gamma}$$

where Q_E^F and F are the quantities of fossil-fuel electricity generated and fossil fuels used respectively, and γ is the quantity of fossil fuels required to produce each unit of electricity. Denoting c_F^c as the MC of fossil fuels F,[19] the industry zero profit condition yields

$$p_E^{Fc} = \gamma c_F^c$$

[19] We assume a perfectly competitive fossil-fuels input market, thus the MC equals to the price of fossil-fuels.

Letting z be the amount of pollution produced during the process of fossil-fuel electricity generation, we assume that it is simply proportional to the amount of fossil fuels used

$$z = \xi F$$

From equation (4), pollution is proportional to the output of fossil-fuel-generated electricity

$$z^c = (\xi\gamma)\, Q_E^{Fc}$$

Any domestic pollution emissions cause both local (non-transboundary) environmental harm to all domestic households and world (transboundary) environmental harm to all households in both countries. We assume that the disutility or harm of pollution is proportional to the amount of local and worldwide pollution, with utility weights λ_L^c and λ_W^c respectively. Moreover, local harm is greater than worldwide harm: $\lambda_L^c > \lambda_W^c$. Thus, the aggregate harm of pollution to households in country $c = N, S$ is

$$h^c\left(z^N, z^S\right) = \lambda_L^c z^c + \lambda_W^c\left(z^N + z^S\right) = \xi\gamma\left[\lambda_L^c Q_E^{Fc} + \lambda_W^c\left(Q_E^{FN} + Q_E^{FS}\right)\right]$$

where Q_E^{FN} and Q_E^{FS} are the industry supply of fossil-fuel-generated electricity in country $c = N, S$ respectively. Furthermore, we assume that North households are harmed more (higher disutility) for any given level emission in terms of both local and worldwide harm[20]

$$\lambda_L^N > \lambda_L^S,\ \lambda_W^N > \lambda_W^S$$

We assume that there is an un-modelled sector which demands a constant large amount of fossil-fuel-generated electricity $\bar{Q}_E^{Fc}$ in country $c = N, S$.[21] Then, the fossil-fuel electricity sector always exists even when facing competition from renewable electricity:$Q_E^{Fc} > 0$.

2.3.3 Supply of RE equipment

Both North and South RE equipment firms produce a homogenous product. Each firm adopts a common CRS production technology

$$R = \frac{L_R}{l_R}$$

[20]This assumption is made due to the observation that developed countries generally exhibit higher concern for environmental harm and so is intended to reflect perceptions of harm, rather than necessarily reflecting actual harm itself.

[21]This assumption assures that all excess renewable electricity sold by households in good generating times are fully absorbed, thus any increase in renewable electricity supply reduces fossil-fuel-generated electricity demand either from other households in bad generating times or from this un-modelled sector. This assumption also assures that the fossil-fuel electricity sectors always exist in both countries, without worrying about the scenario in which the total demand of fossil-fuel electricity of households in bad times are entirely met by the renewable electricity sold by households in good times at the same point of time. This is consistent with the reality that the world is still highly dependent on fossil-fuel-generated electricity.

where L_R is the quantity of labour and l_R is the amounts of labour required to produce each unit of RE equipment. The marginal cost of R is

$$c_R^c = w^c l_R^c$$

We assume that the Northern RE equipment firm has a higher MC[22]

$$c_R^N = w^N l_R^N > c_R^S = w^S l_R^S$$

Both RE equipment firms engage in Cournot competition in both countries. Denote by q_R^{ij} the output of the RE equipment firm in country i sold in country j 's market. The profit function of an RE firm in country i is

$$\pi_R^i = p_R^i \left(Q_R^i, s^i\right) q_R^{ii} + p_R^j \left(Q_R^j, s^j\right) q_R^{ij} - c_R^i \left(q_R^{ii} + q_R^{ij}\right)$$

where $Q_R^i = q_R^{ii} + q_R^{ji}; Q_R^j = q_R^{jj} + q_R^{ij}$ are the total output in market i and j respectively.

2.3.4 Supply of renewable electricity

2.3.4.1. Demand and supply for renewable electricity

Households can choose to generate renewable electricity by installing RE equipment. As noted in the Introduction, we model the fact that households have different productivities of RE generation during the period. We suppose that all households face $\mu \in [0, 1]$ percent of good generating times (denoted by H for "high" generation) and $1 - \mu$ percent of bad generating times (denoted by L) in which the RE equipment productivity is different.[23] To keep the problem tractable we suppose that, if $\mu > 0$, at any specific point of time, some households are in the bad generating time, but some households are in the good generating times. Households in the bad generating times buy the excess renewable electricity from those in the good times indirectly through the national grid. We further assume that if there is any excess supply of renewable electricity that is not absorbed by the households in good times at any specific point of time is then absorbed by the un-modelled sector which demands a constant large quantity of electricity, as mentioned in Section 2.3.2.

There are diminishing marginal returns to RE equipment in renewable electricity generation for a household.[24] The periodised renewable electricity supply – that is, within a

[22]In future work we will allow for endogenous R&D by RE firms that affects their equipment production costs.

[23]This assumption is made due to the reality that renewable energy generation is intermittent across time. For example, solar panels are more productive during sunny day time, but less productive during cloudy or rainy days; wind turbines are more productive in windy days or seasons. This assumption also implies that bad time always exists and there is always demand for fossil-fuel electricity, so that fossil-fuel electricity sectors in both countries still exist. This assumption is consistent with the reality that the world is still highly dependent on fossil-fuel electricity.

[24]This is because all households face a space constraint to install RE equipment. To maximise electric-

good or bad period – is increasing and strictly concave in the quantity of RE equipment in both good and bad times. We assume that the periodised marginal productivity of RE equipment in a good time is simply some proportion percent higher than that in a bad time. Thus, the periodised supply of renewable electricity in time $j = H,\, L$ is $F_j\left(q_R\right)$ and

$$F_j\left(0\right) = 0;\; {F_j}'\left(q_R\right) > 0;\; {F_j}''\left(q_R\right) < 0;$$
$${F_H}'\left(q_R\right) = \left(1+\chi\right){F_L}'\left(q_R\right)\;\forall q_R,\,\chi > 0 \Leftrightarrow F_H\left(q_R\right) = \left(1+\chi\right)F_L\left(q_R\right)\;\forall q_R,\,\chi > 0$$

Thus, the non-periodised supply of renewable electricity in bad and good times given the installation level are respectively given by

$$\begin{aligned} q_E^{RL}\left(q_R\right) &= \left(1-\mu\right)F_L\left(q_R\right) = \left(1-\mu\right)\int_0^{q_R}{F_L}'\left(q_R\right)dq_R; \\ q_E^{RH}\left(q_R\right) &= \mu F_H\left(q_R\right) = \mu\left(1+\chi\right)F_L\left(q_R\right) = \mu\left(1+\chi\right)\int_0^{q_R}{F_L}'\left(q_R\right)dq_R \end{aligned}$$

Homogeneous households have the common average level of marginal productivities of RE equipment over the *entire period*

$$\bar{F}'\left(q_R\right) = \mu{F_H}'\left(q_R\right) + \left(1-\mu\right){F_L}'\left(q_R\right) = \left(1+\mu\chi\right){F_L}'\left(q_R\right)$$

and the common average amount of renewable electricity generation over the period

$$\bar{q}_E^R\left(q_R,\mu,\chi\right) = \bar{F}\left(q_R\right) = \int_0^{q_R}{\bar{F}_L}'\left(q_R\right)dq_R$$

For simplicity, we assume a zero discount rate and no installation or maintenance costs of RE equipment. So the periodised total cost of generating q_E^R amount of renewable electricity in generating times $j = H,\, L$ is just the purchasing cost of RE equipment $p_R{F_j}^{-1}\left(q_E^R\right)$. The periodised supply curve of renewable electricity is given by the MC of generating q_E^R of renewable electricity in time $j = H,\, L$ or:

$$p_E^R\left(q_E^R\right)|_j = \frac{d}{dq_E^R}\left[p_R^c F_j^{-1}\left(q_E^R\right)\right] = p_R^c {F_j^{-1}}'\left(q_E^R\right),\; j = H,\, L$$

which implies that the periodised inverse supply curve (MC of renewable electricity generation) in a bad time is $1+\chi$ higher than that in a good time: $p_E^R\left(q_E^R\right)|_L = \left(1+\chi\right)p_E^R\left(q_E^R\right)|_H$.

ity generation given this constraint, households initially install RE equipment in places where electricity generation is most productive. As they install more, they have no choice but to install in less productive places.

Furthermore, since $F_j{}' (q_R) > 0, F_j{}'' (q_R) < 0$, the representative household's supply curve of renewable electricity is upward sloping

$$p_R^c F_j^{-1}{}'' \left(q_E^R\right) > 0$$

Assumption 1. *Given that households choose RE equipment optimally, they are always net sellers of renewable electricity in a good time but they are net buyers of fossil-fuel-generated electricity in a bad time under any FIT schemes.*

Assumption 1 assures that the FIT premium s^c is in a moderate range such that households never switch from being net buyers (sellers) to being net sellers (buyers) in bad (good) generating times.

2.3.4.2. Derived demand for RE equipment

This section explores the time-productivity weighted derived demand for RE equipment to maximize households' total surplus as both producers and consumers of renewable electricity.

Case 1: no FIT

Let q_E^F be the periodised demand for fossil-fuel-generated electricity in bad times. Then the time-productivity weighted (non-periodised) amounts of fossil-fuel-generated electricity households pay for is affected by the percentage of bad generating times $1 - \mu$. Household income only comes from its wage w^c because, without a FIT, there is no tax or extra income from selling renewable electricity. Thus, the utility maximization problem of a representative household under no FIT is

$$\max_{q_R, q_E^F, q_0} U = \mu f\left((1+\chi) F_L(q_R)\right) + (1-\mu) f\left(F_L(q_R) + q_E^F\right) + q_0 - h(z)$$

$$s.t. p_E^{Fc} (1-\mu) q_E^F + q_0 + p_R q_R = w^c$$

This problem yields first-order conditions (FOCs) as follows:

$$\begin{aligned} f'\left(F_L(q_R) + q_E^F\right) &= p_E^{Fc} \\ \mu f'\left((1+\chi) F_L(q_R)\right)(1+\chi) F_L{}'(q_R) + (1-\mu) f'\left(F_L(q_R) + q_E^F\right) F_L{}'(q_R) &= p_R^c \end{aligned}$$

which yield the time-productivity weighted demand for RE equipment, fossil-fuel-generated electricity and the numeraire good under no FIT as

$$\begin{aligned}
\tilde{q}_R &= \tilde{q}_R\left(p_E^{Fc}, p_R^c, \mu, \chi\right) \\
(1-\mu)\,\tilde{q}_E^F\left(p_E^{Fc}, p_R^c, \mu, \chi\right) &= (1-\mu)\left[f'^{-1}\left(p_E^{Fc}\right) - F_L\left(\tilde{q}_R\left(\cdot\right)\right)\right] \\
\tilde{q}_0\left(p_E^{Fc}, p_R^c, \mu, \chi\right) &= w^c - p_E^{Fc}\left(1-\mu\right)\tilde{q}_E^F\left(\cdot\right) - p_R\tilde{q}_R\left(\cdot\right)
\end{aligned}$$

Substituting the first FOC into the second FOC yields the combined FOC

$$\mu f'\left(\left(1+\chi\right)F_L\left(q_R\right)\right)\left(1+\chi\right)F_L{}'\left(q_R\right) + \left(1-\mu\right)p_E^{Fc}F_L{}'\left(q_R\right) = p_R^c$$

where the left-hand side (LHS) of the expression is the marginal benefit (MB) of installing RE equipment under no FIT. This is the time-weighted average of (i) the MB of renewable electricity in good generating times under no FIT (the willingness to pay (WTP) for the marginal excess renewable electricity $f'\left(\left(1+\chi\right)F_L\left(q_R\right)\right)$) multiplied by the marginal productivity of RE equipment in good times; and (ii) the MB of renewable electricity in bad generating times under no FIT (the avoided fossil-fuel electricity expenditure for the marginal excess renewable electricity —p_E^{Fc}) multiplied by the marginal productivity of RE equipment in bad generating times. The right-hand side (RHS) is the MC of installing RE equipment under no FIT, which is the RE equipment price.

Case 2: Demand for RE equipment under FIT with premium ($s^c \geq 0$)
Households can now sell *excess* renewable electricity to the grid at $p_E^R = p_E^{Fc} + s^c$, so they face perfectly elastic demand for renewable electricity at $p_E^{Fc} + s^c$. Since in good generating time households are assumed to be net sellers of renewable electricity, they fulfil all their demand for electricity from renewable electricity. However, households cannot buy cheaper fossil-fuel-generated electricity and sell renewable electricity to the grid at a higher price with premium simultaneously, i.e. they can only sell the *excess* renewable electricity to the grid.[25] So when they consume renewable electricity, their opportunity cost of doing so is $p_E^{Fc} + s^c$ (as they could sell to the grid at $p_E^{Fc} + s^c$ otherwise), so they consume (demand for) renewable electricity in the periodised amount $q_E^R|_{u=1} = f'^{-1}\left(p_E^{Fc} + s^c\right)$ in good generating times, when the MB equals the MC of consuming renewable electricity: $f'\left(q_E^R|_{u=1}\right) = p_E^{Fc} + s^c$. The household utility maximization problem under a FIT is

$$\max_{q_R, q_E^F, q_0} U = \mu f\left(f'^{-1}\left(p_E^{Fc} + s^c\right)\right) + \left(1-\mu\right) f\left(F_L\left(q_R\right) + q_E^F\right) + q_0 - h\left(z\right)$$

$$s.t. p_E^{Fc}\left(1-\mu\right)q_E^F + q_0 + p_R^c q_R$$

$$= w^c - t^c\left(s^c\right) + \mu\left(p_E^{Fc} + s^c\right)\left[\left(1+\chi\right)F_L\left(q_R\right) - f'^{-1}\left(p_E^{Fc} + s^c\right)\right]$$

[25] It is assumed that it is not allowed by government FIT regulations.

where $t^c(s^c)$ is the income tax levied to finance the FIT premium. Note that households demand RE equipment because (i) it directly increases utility through providing electricity; (ii) it indirectly increases utility through buying more of the numeraire good from increased income from selling excess renewable electricity in good generating times, i.e. its budget constraint is relaxed.

This problem yields FOCs:

$$\begin{aligned} f'\left(F_L(q_R)+q_E^F\right) &= p_E^{Fc} \\ (1-\mu) f'\left(F_L(q_R)+q_E^F\right) F_L{}'(q_R) &= p_R - \mu\left(p_E^{Fc}+s^c\right)(1+\chi) F_L{}'(q_R) \end{aligned}$$

which yield the time-productivity weighted demand for RE equipment, fossil-fuel-generated electricity and the numeraire good under a FIT as

$$\begin{aligned} q_R\left(p_E^{Fc}, p_R^c, \mu, \chi, s^c\right) &= F_L{}'^{-1}\left(\frac{p_R^c}{p_E^{Fc}(1+\mu\chi)+\mu s^c(1+\chi)}\right) \\ (1-\mu) q_E^F\left(p_E^{Fc}, p_R^c, \mu, \chi, s^c\right) &= (1-\mu)\left[f'^{-1}\left(p_E^{Fc}\right) - F_L(q_R(\cdot))\right] \\ q_0\left(p_E^{Fc}, p_R^c, \mu, \chi, s^c\right) &= w^c + \mu\left(p_E^{Fc}+s^c\right)\left[(1+\chi)F_L(q_R) - f'^{-1}\left(p_E^{Fc}+s^c\right)\right] \\ &\quad - t^c(s^c) - p_E^{Fc}(1-\mu) q_E^F(\cdot) - p_R^c q_R(\cdot) \end{aligned}$$

Substituting the first FOC into the second yields the combined FOC:

$$p_E^{Fc}(1+\mu\chi) F_L{}'(q_R) + s^c\mu(1+\chi) F_L{}'(q_R) = p_R^c$$

where the LHS is the MB of installing RE equipment under a FIT with a premium $s^c \geq 0$, which is the summation of the MB of renewable electricity under a FIT without a premium (at p_E^{Fc}) multiplied by the average marginal productivity of RE equipment, and the extra MB due to any FIT subsidies received, which is received only in good times. The RHS is the MC of installing RE equipment under a FIT, which is the RE equipment price.

Lemma 1.

(i) Under no FIT, the demand for RE equipment (fossil-fuel electricity) is decreasing (increasing) in RE equipment price p_R^c, increasing (decreasing) in the fossil-fuel price p_E^{Fc}, but ambiguous in the percentage of good generating times μ and the productivity premium of good generating times χ, but it is more likely to be decreasing (increasing) in μ and χ when $f(q_E)$ is highly concave.

(ii) Under a FIT, the demand for RE equipment (fossil-fuel electricity) is decreasing (increasing) in p_R^c, but increasing (decreasing) in p_E^{Fc}, μ,χ and the FIT premium s^c.

(iii) The demand for RE equipment is higher under FIT than under no FIT.

Proof. See Appendix A.1. □

Discussion

(i) and (ii)

(1) With or without a FIT, a lower RE equipment price p_R^c reduces the MC of installing RE equipment and therefore increases the RE equipment demand.

(2) With or without a FIT, a greater incidence or productivity premium associated with good times (μ and χ) has a positive effect on RE equipment demand since in good times, the MC (MB) of generating renewable electricity is lower (no less) than that in bad times. However, higher μ and χ have an additional negative effect under no FIT. Absent a FIT, households can only "sell" excess renewable electricity to themselves, so the MB of installing RE equipment is their own WTP for (marginal utility from) the renewable electricity generated, which is diminishing in the quantity of the latter. When the sub-utility function for electricity is more concave, then their WTP for electricity (in this case, excess renewable electricity) and consequently the MB of installing RE equipment diminishes more rapidly, which tends to reduce RE equipment demand. This effect is only present in good times (when households are net sellers), so higher μ and χ exacerbate this effect and put downward pressure on RE equipment demand. Overall, higher μ and χ increase the RE equipment demand if and only if the negative effect is outweighed by the positive effect.

(3) Absent a FIT, the market price p_E^{Fc} increases RE equipment demand only by affecting bad generating times in which it increases avoided fossil-fuel electricity expenditure. The market price has no effect in good times under no FIT, because households are then net sellers, which implies that renewable electricity generation is more efficient than fossil-fuel electricity generation in fulfilling the electricity demand in good times. However, under a FIT, the market price increases RE equipment demand by affecting both bad and good generating times. It has the same effect as that under no FIT in bad times. In good times, the market price increases the MB of selling excess renewable electricity in good generating times, therefore provides extra MB to RE equipment installation.

(4) s^c increases the MB of selling excess renewable electricity in good times.

(iii) Under a FIT, households can sell excess renewable electricity at the market price plus a non-negative premium $p_E^{Fc}+s^c$, which is higher than their own WTP for the excess renewable electricity. So the MB of installing RE equipment increases.

Another notable difference between the two regimes is that the marginal effects of equipment price p_R^c and market price p_E^{Fc} on the demand for both RE equipment $q_R(\cdot)$ and fossil-fuel-generated electricity $q_E^F(\cdot)$ are stronger under FIT than under no FIT if and only if condition 1 of the Appendix holds. Condition 1 is more likely to hold if $f(q_E)$ is more concave, $F_L(q_R)$ is less concave and the difference between $f'((1+\chi)F_L(q_R))$ and $p_E^{Fc}+s^c$ is smaller. As mentioned for the discussions of (i) and (ii) above, the difference between no

FIT and a FIT only stems from good times, not bad times. If the Condition 1 holds, we have a steeper electricity demand curve, a flatter renewable electricity supply curve and a lower $p_E^{Fc} + s^c$. As shown in Figure 2, the periodised renewable electricity supply in good times $q_E^R(\cdot)|_{u=1}$ is where the electricity demand curve and renewable electricity supply curve intersect under no FIT, while it is where the $p_E^{Fc} + s^c$ line and the renewable electricity supply curve intersect under a FIT. Therefore, a marginal change of p_R^c (a marginal rotation of the renewable electricity supply curve of the same magnitude) results in a more dramatic change in $q_E^R(\cdot)|_{u=1}$ and thereby in RE equipment demand $q_R(\cdot)$ and fossil-fuel electricity demand $q_E^F(\cdot)$ under a FIT than under no FIT. Similar arguments apply to the marginal effect of p_E^{Fc} on $q_R(\cdot)$ and $q_E^F(\cdot)$.

2.3.5 Graphical summary of electricity demand and supply

Case 1: No FIT

As shown in Figure 2, following the explanation in the previous section, households supply the amount $q_E^{eH}(p_R^c)$ in good times at which their demand and good-time supply curves intersects; and supply q_E^{0L} in bad times at which the bad-time supply curve intersects with the fossil-fuel electricity price. Diagrammatically, the total surplus (TS) of each household is

$$\tilde{T}S_R = \left(\tilde{P}S_R + \tilde{C}S_R\right)|_{no\ FIT} = \mu(A + B + C + F + G + H) + (1 - \mu)(A + B + C + F_1)$$

Case 2: FIT with a premium $s^c \geq 0$

As a *net electricity seller* in good times, the representative household consumes $d_E^1\left(s^N\right)$ of renewable electricity and sells the excess amount $q_E^{1H}(s^c) - d_E^1(s^c)$ to the grid at $p_E^R = p_E^{Fc} + s^c$, as shown in Figure 2. The TS under FIT without and with premium are respectively given by

$$\begin{aligned} TS_R(s^c = 0) &= \left(\tilde{P}S_R + \tilde{C}S_R\right) + \mu(I) \\ &= \mu(A + B + C + F + G + H + I) + (1 - \mu)(A + B + C + F_1) \\ &= A + B + C + \mu(F + G + H + I) + (1 - \mu)F_1 \end{aligned}$$

$$TS_R(s^c > 0) = TS_R(s^c = 0) + \mu(D) = TS_R(s^c = 0) + \mu(C + D + E - C - E)$$

where area D is increasing in the premium s^c. Since households are taxed to finance the negative government surplus caused by FIT premium GS $(s^c > 0) = -C-D-E = s^c\left[q_E^{1H} - d_E^1\right]$, the dead weight loss (DWL) of a FIT with a premium compared to FIT without a premium equals to the households' TS net of income tax

$$DWL(s^c > 0) = TS(s^c > 0) - tax - TS(s^c = 0) = \mu[D - (C + D + E)] = -\mu(C + E)$$

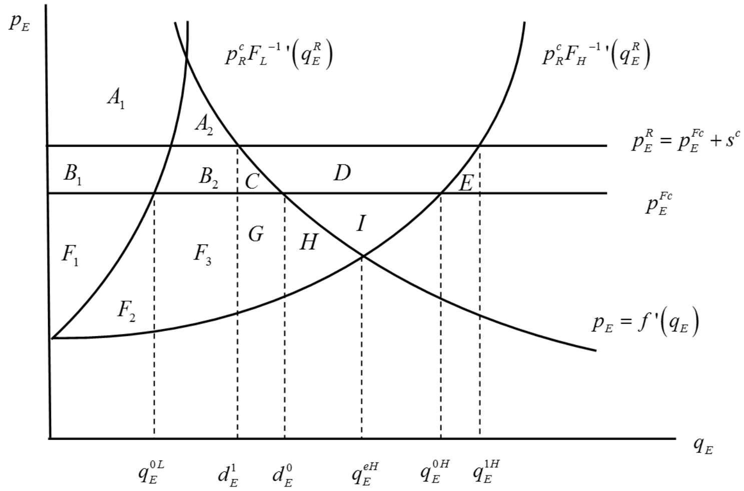

Figure 2: The representative household's periodised (long-run equilibrium) electricity consumption and production in good and bad times under no FIT and a FIT

C is a DWL associated with under-demand of electricity due to a positive FIT premium. Since households faces higher opportunity cost of consuming electricity. C is a DWL because WTP exceeds the market price for the range $d_E^0 - d_E^1$ which is given up in order to take advantage of the premium. D is a DWL associated with over-supply of renewable electricity due to the premium. This is because the MC of renewable electricity generation exceeds the MC of fossil-fuel electricity p_E^{Fc}. The FIT premium is encouraging the less efficient renewable electricity production.

2.3.6 Labour market

The labour market clearing condition for country $c = N, S$ is[26]

$$L_0^c + L_R^c = L$$

2.4 Governments

2.4.1 Optimal import tariff given exogenous FIT premiums in both countries

Given that both North and South governments provide an exogenous FIT premium ($s^N > 0$ and $s^S > 0$), the government in country $i = N, S$ chooses an optimal import tariff to maximise its domestic welfare. Following the relevant literature, domestic welfare is the sum of PS of domestic equipment producer, domestic households' CS for electricity and CS for the numaraire good (residual income equals wage plus households' time-weighted PS for

[26]We assume that the labour demand in the numeraire sector is always positive.

renewable electricity, which is net of equipment expenditure), GS (FIT subsidy and tariff revenue) as well as local and worldwide pollution harm

$$\max_{\tau^i \geq 0} W^i = PS_R^i + L\left[CS_E^i\left(s^i, p_E^{Fi}\right) + CS_0^i\left(p_R^i\left(s^i, \tau^i\right), \tau^i\right)\right] + GS^i - Lh^i\left(z^i\left(s^i, \tau^i\right), z^j\left(s^j\right)\right)$$
$$= \pi_R^i\left(s^N, s^S, \tau^i\right) + LCS_E^i\left(s^i, p_E^{Fi}\right) + L\left[PS_E^i\left(s^i, p_E^{Fi}, p_R^i\left(s^i, \tau^i\right)\right) + w^i\right]$$
$$-L\mu\left[(1+\chi) F_L\left(q_R^i\left(s^i, \tau^i\right)\right) - f'^{-1}\left(p_E^{Fi} + s^i\right)\right] s^i + \tau^i q_R^{ji}\left(s^i, \tau^i\right) - Lh^i\left(z^i\left(s^i, \tau^i\right), z^j\left(s^j\right)\right)$$

Note that a domestic import tariff has no effect on domestic CS for electricity since it does not affect electricity demand and electricity price. Given exogenous North and South FIT premiums, a tariff on RE equipment imports τ^i has the following marginal effects on domestic welfare: (1) it positively affects domestic RE equipment producers' profits; (2) it negatively affects domestic CS for the numaraire good through increasing domestic equipment price p_R^i–households' cost of inputs for renewable electricity generation, and thereby their PS for renewable electricity; (3) it affects FIT subsidies for the excess supply of renewable electricity of households (an effect that is negative if the import tariff increases the domestic RE equipment price ($\frac{dp_R^i(\tau^i)}{d\tau^i} > 0$), because more expensive RE equipment reduces any renewable electricity over-supply); (4) it affects domestic import tariff revenue; (5) it affects domestic pollution harm through affecting domestic RE equipment price and thereby domestic demand for fossil-fuel-generated electricity. The import tariff results in more pollution harm if it makes RE equipment more expensive which leads to less domestic installation. However, it has no effect on foreign equipment price and thereby foreign households' renewable electricity supply and foreign pollution.

2.4.2 Optimal FIT premium given exogenous domestic import tariff and foreign FIT premium

Given an exogenous domestic import tariff ($\tau^N > 0$) and an exogenous foreign FIT premium, the government in country $i = N$, S chooses an optimal FIT premium to maximise domestic welfare, which yields a FOC for the optimal FIT premium as reported in Appendix A.3. A domestic FIT premium has no effect on the foreign RE equipment price, thus it has no effect on foreign households' renewable electricity supply and thereby foreign pollution.

2.5 Model solving

For simplification, we make the following assumptions in addition to Assumption 1.

Assumption 2. *There is always some good generating time in both countries:*$\mu > 0$. *Both countries provide a FIT with an exogenous premium to domestic households:*$s^N > 0$; $s^S > 0$, *but only the North imposes an endogenous import tariff on Southern RE equipment imports:* $\tau^N > 0$; $\tau^S = 0$.

If there are no good generating times, households are never net sellers of excess renewable electricity, which makes providing a FIT redundant. Assumption 2 simplifies our analysis by assuming rigid environmental policies (FIT premiums) in both countries and just endogenising the Northern import tariff.[27]

2.5.1 Timing of the game

Stage 1: Northern and Southern governments commit to a FIT scheme with premium $s^N > 0$ and $s^S > 0$ respectively. Northern government then announces an import tariff $\tau^N \geq 0$ on RE equipment imported from the South.
Stage 2: Northern and Southern RE equipment firms engage in Cournot duopoly competition in both markets. Production starts.
Stage 3: The numeraire good sectors and fossil-fuel electricity sectors in North and South start producing.
Stage 4: Northern and Southern households make purchase decisions for RE equipment, fossil-fuel-generated electricity and the numeraire good. Production of renewable electricity as well as consumption of electricity and the numeraire good start.

2.5.2 Solving backwards

We solve the model by backward induction.[28]
Stage 4: We can express total household demand for RE equipment, fossil-fuel-generated electricity and the numeraire good in country $c = N, S$ as functions of prices, subsidies and the generation parameters, μ and χ.
Stage 3: We assume that the numeraire good is tradable and it ensures a trade balance between countries. The output of the numeraire sector in country $c = N, S$ is the total output sold to domestic market and foreign markets. We then can determine total labour used in this sector and in the fossil-fuel electricity sector, thus giving its output and, consequently, the pollution generated.
Stage 2: The Cournot equilibrium outputs in each market yield the labour used by the North and South RE equipment firms.
Stage 1: Given that both North and South governments provide an exogenous FIT premium ($s^N > 0$ and $s^S > 0$), North government chooses an optimal Northern import tariff τ^N to maximize Northern welfare.

Lemma 2. *Under Assumption 1 and Assumption 2, if the marginal productivity of RE equipment is diminishing linearly*[29]*, then*

[27] We shall endogenize environmental policies and allow governments to choose an optimal policy mix in the simulation stage. Examining the Northern import tariff first is more consistent with the reality that the trade dispute on RE equipment is triggered by developed countries imposing trade barriers on RE equipment imports from NICs.
[28] See Appendix A.4 for details.
[29] ${F_L}'(q_R) = a - bq_R > 0,\ a > 0, b > 0.$

(i) The demand for RE equipment in both countries is linear. A higher FIT premium rotates out the domestic demand curve for RE equipment without affecting its intercept on the quantity axis.
(ii) The Northern import tariff τ^N increases (decreases) Northern (Southern) RE equipment firm's output and increases (decreases) Northern RE equipment price (total output by both firms). τ^N always increases Northern RE equipment firm's profit.
(iii) An exogenous Northern FIT premium s^N increases (decreases) Northern (Southern) RE equipment firm's output in the North if and only if the Northern import tariff is sufficiently small such that $c_R^S - 2c_R^N + \tau^N(\cdot) < 0$ ($c_R^N - 2c_R^S - 2\tau^N(\cdot) > 0$). However, s^N always increases both the RE equipment price and total output in the North.
(iv) An exogenous Southern FIT premium s^S increases Northern RE equipment firm's output in the South due to $c_R^N > c_R^S$ but increases Southern RE equipment firm's output in the South if and only if $c_R^N - 2c_R^S < 0$. However, s^S always increases (decreases) the RE equipment price (total output) in the South.

Proof. See Appendix A.5. □

Discussion

(i) A higher domestic FIT premium s^c increases the choke price of the demand curve for RE equipment and makes the demand curve steeper. The intuition is that higher s^c increases the MB for all renewable electricity generated. However, the marginal productivity of RE equipment is decreasing at a constant rate b, so higher s^c increases a household's WTP for RE equipment, but at a rate which is decreasing in the quantity of RE equipment. At the intercept on the quantity axis $\frac{La}{b}$, the marginal productivity falls to zero, so the higher MB for renewable electricity has no effect on the WTP for the extra RE equipment at $\frac{La}{b}$.
(ii) Given a positive Northern import tariff, it is as if the MC of the Southern RE equipment firm increases by the amount of the import tariff. Thus, the Northern RE equipment firm benefits from this import tariff by enjoying higher output and profit at the expense of decreased output of the Southern RE equipment firm.
(iii) The Northern FIT premium s^N increases the RE equipment price p_R^N, and the total demand as well as the steepness of the demand curve of RE equipment $\left|\frac{dp_R^N}{dQ_R^N}\right|$ in the North. Higher p_R^N increases the MR of both $q_R^{NN}(\cdot)$ and $q_R^{SN}(\cdot)$. However, a steeper demand curve benefits the firm with relatively lower initial output due to higher *de facto* MC (including import tariff) because for this *de facto* less efficient firm, the price-dampening effect affects less initial output, which results in a smaller decrease in the MB due to price-dampening (when increase marginal output).
Case 1: with a sufficiently small Northern import tariff, the Northern firm has sufficiently

higher MC (c_R^N) than the *de facto* MC ($c_R^S + \tau^N$) such that the Northern firm has lower initial output. Then there are two reinforcing positive effects of s^N on $q_R^{NN}(\cdot)$: higher p_R^N increases the marginal revenue (MR) of ;$q_R^{NN}(\cdot)$ the price-dampening effect affect less negatively than the Southern firm. However, there are two counteracting effects of s^N on $q_R^{SN}(\cdot)$: higher p_R^N increases the MR of $q_R^{SN}(\cdot)$; the price-dampening effect affects $q_R^{SN}(\cdot)$ more negatively than the Northern firm. So $q_R^{SN}(\cdot)$ may fall if the latter effect dominates.
Case 2: when the import tariff is sufficiently large, and the Southern firm has higher *de facto* MC and lower initial output, we have the opposite result to Case 1. Now the price-dampening effect advantages (disadvantages) the Southern (Northern) firm.
Case 3: when the import tariff is in the middle range, the difference in *de facto* MC and therefore initial output is small, then both $q_R^{NN}(\cdot)$ and $q_R^{SN}(\cdot)$ increases (both share some of the increase in the demand bought by higher s^N).
(iv) Same argument as for (iii), except that there is no import tariff in the South market, so it is the comparison between real MC c_R^N and c_R^S, instead of *de facto* MC.

Proposition 1. *Under Assumption 1 and Assumption 2, if the marginal productivity of RE equipment is diminishing linearly, then* even *if the North government places zero valuation on the environmental quality, i.e.*$\lambda_W^N = \lambda_L^N = 0$, *an exogenous Northern FIT premium* s^N *always increases the optimal Northern tariff* $\tau^N(\cdot)$ *if Condition 3 of the Appendix holds. Condition 3 is more likely to hold if* χ, *a and* p_E^{FN} *(* $c_R^S + c_R^N + \tau^N(\cdot)$*) are (is) sufficiently small (large).*

Proof. See Appendix A.5. □

<u>*Discussion*</u>
(1) The exogenous Northern FIT premium s^N reinforces the positive effect of the optimal Northern import tariff $\tau^N(\cdot)$ on the Northern equipment firm's profit if and only if the import tariff is sufficiently small such that s^N always increases $q_R^{NN}(\cdot)$.

This is because Northern equipment firm's profit is increasing in $q_R^{NN}(\cdot)$ quadratically under Cournot competition with a linear demand. Thus, the marginal effect of $\tau^N(\cdot)$ on Northern firm's profit is proportional to $q_R^{NN}(\cdot)$.

(2) s^N exacerbates the Northern households' PS loss in good times caused by $\frac{dp_R^i(\tau^i)}{d\tau^i} > 0$. $\tau^N(\cdot)$ increases Northern RE equipment price $p_R^N(\cdot)$ at a constant rate. Higher $p_R^N(\cdot)$ rotates in the representative household' renewable electricity supply curve in good times. Northern households' PS in good times decreases due to the more expensive inputs – the RE equipment. s^N has two effects on the negative effect of $\tau^N(\cdot)$ on Northern households' PS in good times, both through affecting the periodised equipment demand $q_R^N\left(p_R^N\left(s^N,\cdot\right),s^N\right)|_{u=1}$. Higher s^N directly increases $q_R^N(\cdot)|_{u=1}$ given any level of $p_R^N(\cdot)$ (can be illustrated by a

shift up of $p_E^{FN} + s^N$ line in Figure 2; note that the equilibrium price is non-periodised and households take it as given in both good and bad times); however, s^N indirectly decreases $q_R^N(\cdot)|_{u=1}$ through increasing $p_R^N(\cdot)$(can be illustrated by a inward rotation of the supply curve of renewable electricity in good times in Figure 2). Overall, the direct effect outweighs the indirect effect, so s^N increases $q_R^N(\cdot)|_{u=1}$ and thereby the periodised renewable energy supply $q_E^{RN}(\cdot)|_{u=1}$. Consequently, s^N exacerbates the PS loss in good times caused by $\frac{dp_R^i(\tau^i)}{d\tau^i} > 0$, since more expensive equipment (input) due to higher import tariff affects more units of renewable electricity supply in good times.
(3) This is because in bad times, in contrast to good times, s^N has no direct effect (households are not selling renewable electricity, thus not directly receiving s^N), but only the indirect effect through affecting $p_R^N(\cdot)$. Thus, s^N decreases the periodised renewable electricity supply in bad times $q_E^R(\cdot)|_{u=0}$. Consequently, s^N mitigates the PS loss in bad times caused by $\frac{dp_R^i(\tau^i)}{d\tau^i} > 0$, since more expensive equipment due to higher import tariff affects less units of renewable electricity supply in bad times.
(4) $\tau^N(\cdot)$ improves Northern welfare by reducing Northern households' income tax imposed to finance the FIT premium. It achieves this tax reduction by increasing $p_R^N(\cdot)$, reducing $q_E^{RN}(\cdot)|_{u=1}$ and therefore reducing FIT subsidy. s^N has three effects on the ability of $\tau^N(\cdot)$ to reduce the tax. First, s^N has a positive direct effect: for any given quantity of excess renewable electricity reduction, higher s^N implies larger total subsidy reduction. Second, s^N has a negative indirect effect as shown in Figure 3(a). This is because $\tau^N(\cdot)$ reduces the WTP by $\frac{1}{3}$ for any quantity of RE equipment. It reduces $q_R^N(\cdot)|_{u=1}$ by resulting in a parallel inward shift of the periodised equipment demand curve in good times without changing its slope. Higher s^N increases the steepness of the demand curve (see Lemma 2 (i)), and therefore reduces the ability of $\tau^N(\cdot)$ in reducing $q_R^N(\cdot)|_{u=1}$ and consequently the tax. Third, s^N has another negative indirect effect as shown in Figure 3(b). This is because higher s^N increases $q_R^N(\cdot)|_{u=1}$ overall (see the discussion for point (2) above). Higher $q_R^N(\cdot)|_{u=1}$ implies lower marginal productivity of equipment due to diminishing returns to equipment. Thus, the reduction of renewable electricity is smaller for the any reduction of RE equipment due to higher import tariff. The positive direct effect outweighs the two negative indirect effects if and only if Condition 2 of the Appendix holds, which states that it is not the absolute size of s^N matters, but the relative size of s^N compared to the market rate p_E^{FN} matters. The intuition is that if p_E^{FN} is also large, then $\Gamma\left(p_E^{FN}, s^N, \cdot\right)|_{u=1}$ is large and the periodised equipment demand curve is steeper, which reduces the first negative indirect effect, i.e. higher p_E^{FN} reduces $\left|\frac{d\left|q_R^{N\prime}(\tau^N)\right||_{u=1}}{ds^N}\right|$.[30] Furthermore, if p_E^{FN} exceeds s^N, then higher p_E^{FN} also reduces the second negative indirect effect, i.e. higher

[30] $\frac{d\left|\frac{d\left|q_R^{N\prime}(\tau^N)\right|}{ds^N}\right|}{dp_E^{FN}} = \frac{d\left(\frac{\Gamma'(s^N)}{3b\Gamma(p_E^{FN},s^N)^2}\right)}{dp_E^{FN}} = -\frac{2\Gamma'(s^N)}{3b\Gamma(p_E^{FN},s^N)^3}\Gamma'\left(p_E^{FN}\right) < 0$

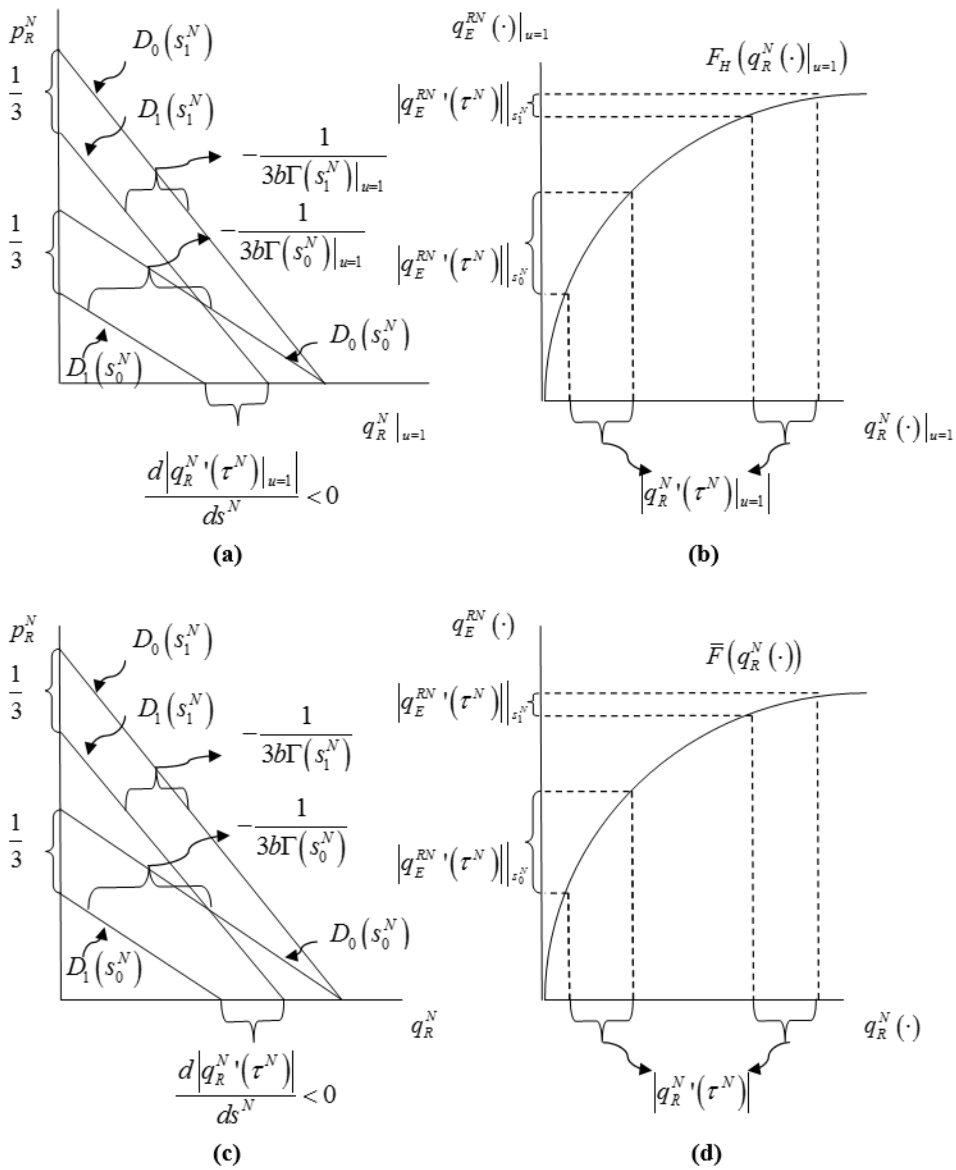

Figure 3: Illustration for Proposition 1

p_E^{FN} reduces $\frac{dq_R^N(\cdot)|_{u=1}}{ds^N}$, hence, $\left|q_E^{RN\prime}\left(\tau^N\right)\right|\Big|_{s_1^N}$ in Figure 3(b) becomes larger and closer to $\left|q_E^{RN\prime}\left(\tau^N\right)\right|\Big|_{s_0^N}$. Thus, if p_E^{FN} is large enough, the two negative indirect effects of s^N on the ability of $\tau^N(\cdot)$ to reduce the tax diminish: s^N is more likely to increase $\tau^N(\cdot)$.

Condition 2 is implied by Assumption 1 (i.e. households are always net sellers in good times) if and only if Condition 3 of the Appendix holds, because Assumption 1 also implies an upper bound of s^N: higher s^N increases $p_R^N(\cdot)$, and rotates in the renewable electricity supply curve, which makes households less likely to be net sellers in good times. To maintain Assumption 1, s^N has to be less than a threshold which is decreasing in but increasing in $c_R^S + c_R^N + \tau^N$, χ, p_E^{FN} and a (lower threshold associated with Assumption 1 increases the strictness, thus it is more likely for Assumption 1 to imply a positive pressure in term 4). Higher $c_R^S + c_R^N + \tau^N$ increases $p_R^N(\cdot)$ and makes being net seller harder and thereby requires smaller s^N. Although lower χ and a mitigate $p_R^{N\prime}\left(s^N\right)$ and indirectly makes being net seller easier, lower and imply lower marginal productivity of equipment in good times, thereby directly rotate in renewable energy supply curve. Overall, the direct effect outweighs the indirect effect: lower χ and a make being net seller harder and thereby require smaller s^N. Similarly, lower p_E^{FN} also requires smaller s^N (being a net seller requires a large enough p_E^{FN} which is above the intersection of electricity demand curve and renewable electricity supply curve).

(5) s^N increases the marginal effect of the Northern import tariff on tariff revenue if the import tariff is sufficiently large. This is because on the one hand, s^N increases imports from the South given a sufficiently large import tariff; on the other hand, s^N mitigates the negative marginal effect of import tariff on import (see the explanation for Lemma 2 (iii), case 2). Overall, the two effects reinforce each other if the import tariff is sufficiently large.
(6) $\tau^N(\cdot)$ decreases Northern welfare by increasing Northern households' demand for fossil-fuel-generated electricity and thereby Northern environmental harm. This is because higher $\tau^N(\cdot)$ increases $p_R^N(\cdot)$ and reduces Northern non-periodised equipment demand $q_R^N(\cdot)$ and thereby Northern non-periodised renewable electricity supply $q_E^{RN}(\cdot)$. Analogous to point (4) above, s^N has two indirect effects on the ability of $\tau^N(\cdot)$ to reduce $q_E^{RN}(\cdot)$, as shown by Figure 3(c) and (d). The only difference is that we are looking at non-periodised instead of periodised renewable electricity supply. Thus, the intuitions for Figure 3(a) and (c) as well as for Figure 3(b) and (d) are the same. Since s^N also increases the non-periodised renewable electricity supply as shown in Figure 3(d),[31] the two negative indirect effects illustrated by Figure 3(c) and (d) also reinforce each other: higher s^N always reduces the ability of $\tau^N(\cdot)$ to reduce $q_E^{RN}(\cdot)$. Consequently, higher s^N reduces the ability of $\tau^N(\cdot)$ in harming the Northern environment and has a positive effect on $\tau^N(\cdot)$.

[31] We have $\frac{dq_R^N(\cdot)}{ds^N} = \frac{1}{L}\frac{dQ_R^N(\cdot)}{ds^N} = \frac{1}{3b}\left(c_R^S + c_R^N + \tau^N\right)\Gamma\left(s^N\right)^{-2}\Gamma'\left(s^N\right) > 0$ using Cournot equilibrium equipment demand. The direct positive effect of s^N on through $q_R^N(\cdot)$ boosting equipment demand outweighs its indirect negative effect through pushing up equipment price.

Overall, s^N has a deterministic negative pressure on the optimal Northern import tariff in (2), and possible negative pressures in (1) and (4). From Appendix A.5, the positive pressure in (5) outweighs the possible negative pressure in (1); and the sum of positive pressures in (1), (3) and (5) outweigh the deterministic negative pressure in (2). Since the pressure in (6) is zero (positive) if the North government places no (positive) valuation on environmental quality, thus, overall, even if the pressure in (6) is zero, an exogenous Northern FIT premium has an positive marginal effect on the optimal Northern import tariff, if the pressure in (4) is positive (if Condition 3 of the Appendix holds).

Corollary 1.
(i) (reverse endogeneity) Under Assumption 1 and Assumption 2, if the marginal productivity of RE equipment is diminishing linearly, then even if the North government places zero valuation on the environmental quality, i.e.$\lambda_W^N = \lambda_L^N = 0$, an exogenous Northern tariff τ^N always increases the optimal Northern FIT premium $s^N(\cdot)$ if Condition 4 of the Appendix holds.
(ii) The ratio of good generating times μ is likely to increase the optimal Northern import tariff. It may also non-monotonically affect the effect of a Northern FIT premium on the optimal domesitic import tariff.
(iii) Ceteris Paribus, if Northern government only cares about the profit of domestic equipment producer, then an exogenous Northern FIT premium s^N increases (decreases) the optimal Northern tariff $\tau^N(\cdot)$ if and only if $\tau^N(\cdot) < (>)\, 2c_R^N - c_R^S$.

Proof. See Appendix A.6. □

Discussion
(i) indicates that exogenous trade liberalization in equipment imported from the South is likely to decrease optimal Northern FIT subsidy. Analogously, the ultimate effects on Northern pollution and Southern welfare are ambigous too, which depends on the relative size of direct effect and the rebound effect.
(ii) The negative effect of μ on $\tau^N(\cdot)$ is only through exacerbating the negative effect of the import tariff on Northern households' PS in good times. However, this effect is partially offset by its opposite effect associated with bad times. Thus, μ increases $\tau^N(\cdot)$ if all other positive effects outweigh the remaining negative effect. Appendix A.5 also shows that compared to μ and s^N, χ and p_E^{FN} are less likely to increase $\tau^N(\cdot)$. The main reason is that higher χ reduces MC of renewable electricity supply and rotates out renewable energy supply curve. In contrast to μ and s^N, p_E^{FN} has an extra negative effect on through affecting bad times. In bad times, p_E^{FN} not only has an indirect effect through affecting $p_R^N(\cdot)$, but also has an extra direct effect, which outweighs the indirect effect. Thus, p_E^{FN} increases

periodised renewable electricity supply in bad times, and have extra excerbation of PS loss caused by $\frac{dp_R^i(\tau^i)}{d\tau^i} > 0$ (similar reasoning to the discussion point (2) for Proposition 1).
(iii) See the discussion for Lemma 2 (iii) and note that the profit of Northern equipment producer is quadratic in its output in the North under Cournot duopoly competition.

Proposition 2.
(i)If $\frac{d\tau^N(\cdot)}{ds^N} > 0$, a marginal increase in the exogenous Northern FIT premium s^N has a negative indirect (rebound) effect on Northern environment. Higher s^N may ultimately hurt Northern environment if and only if the rebound effect outweighs the positive direct effect.
(ii) If $\frac{d\tau^N(\cdot)}{ds^N} > 0$, a marginal increase in the exogenous Northern FIT premium s^N hurts Southern welfare if $c_R^N - 2c_R^S - 2\tau^N(\cdot) > 0$ and $\lambda_W^S = 0$.

Proof. See Appendix A.7. □

Discussion
(i) The Northern FIT premium has a rebound fire effect on Northern pollution if it increases the Northern optimal import tariff. This is because the latter increases Northern RE equipment price and decreases Northern households' renewable electricity supply. To determine the relative size of the counteractive direct and indirect effects, we need to rely on specifications of functional forms.
(ii) If the Northern import tariff is sufficiently small such that s^N decreases Southern RE firm's output in the North (see Lemma 2(iii)), then s^N has a negative direct effect on Southern RE firm's profit ($\lambda_W^S = 0$ ensures that possible improvement in Northern environment due to s^N is ignored by the South). s^N always has a negative indirect effect on Southern RE firm's profit through its positive effect on the Northern import tariff, which negatively affects Southern RE firm's profit. In this case, the direct and indirect effects reinforce each other.

3 Conclusions

This paper examines how subsidies and import tariffs in North-South trade in renewable energy equipment affect economic welfare as well as the environment. Under some general assumptions, we find that an endogenous Northern import tariff is increasing in (independent of) a Northern (Southern) feed-in tariff premium, even if the North government does not internalize any pollution harm. This positive relationship remains if we reverse the endogeneity (i.e. an endogenous Northern feed-in tariff premium is increasing in a Northern import tariff). The optimal Northern import tariff is also likely to be increasing in the incidence associated with good times. A Northern import tariff always increases Northern pollution. Although a Northern feed-in tariff premium decreases Northern pollution by inducing more renewable electricity supply, it may increase Northern pollution due to a rebound effect through increasing the Northern import tariff and the Northern renewable energy equipment price. Furthermore, a marginal increase in a Northern feed-in tariff premium may decrease Southern economic welfare. This paper provides only a first step to better understanding the question, and there are many avenues for extension that we are currently pursuing. The first is to endogenize environmental policies and allow governments to choose an optimal policy mix. The second is to introduce endogenous technological change in the renewable energy equipment sector. The third is to conduct some illustrative numerical solutions to shed light on the sensitivity of these policies to different weights on environmental factors in policy makers' objective functions. Fourth, we shall calibrate the model to data in order to get more precise quantitative predictions of policy implications.

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