External Balance, Dynamic Efficiency, and the Welfare Costs of Unilateral Permit Policy in Interdependent Economies

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Abstract

This paper investigates domestic and transboundary welfare costs of unilateral climate policy in a two–country overlapping generations model with producer carbon emissions. We show that the level of domestic welfare costs and the spillover effect on foreign welfare depend on the external balance of the policy implementing country and the dynamic (in)efficiency of the world economy. We find that under dynamic efficiency domestic welfare costs of policy implementation in a debtor country are larger than abroad. Moreover, for a debtor country, the welfare costs of a domestic policy exceed the costs of a policy by the other country.

Keywords: emission permits, trade, overlapping generations, welfare.

JEL Codes: Q52; Q54; D91.

1 Introduction

That some highly developed countries have unilaterally implemented climate policy within their boundaries to fulfill the Kyoto Protocol represents a well–known fact of this decade. Due to international interdependence, other Annex–I countries are however affected by this unilateral climate policy, e.g. the implementation of the European Union's Emissions Trading System (ETS), despite their withdrawal from the Kyoto Protocol. The withdrawal from the Protocol by some countries itself has been explained by different economic concepts: First, combating global warming is a global public good with a fundamental free–rider problem which has been discussed intensively in the game–theoretic literature (for a survey, see Finus, 2001 or more recently Endres, 2008). Moreover, from a political–economic perspective governments' decision to withdraw are based on the (low) preference of the median voter for mitigating climate change relative to the high costs of compliance (Böhringer and Vogt, 2004).

This paper takes a somewhat different approach to explain the withdrawal of some highly developed countries by investigating the domestic and transboundary welfare costs of implementing unilateral climate policy. From the perspective of a country which has withdrawn from the Protocol, we elicit the welfare costs of non–implementation assuming that the other country implemented climate policy; secondly, we show under which conditions non–implementation is to be preferred to the consequences of unilateral climate policy by the other country; Ultimately, this analysis of welfare costs can enrich the explanation why some Annex–I countries have withdrawn from the Kyoto Protocol and pertain their position against international accorded climate policy also for the Post–Kyoto era.

Our approach is based on an earlier strand of literature after the unilateral fiscal expansion in the United States in the 1980s which aimed to understand the international consequences of unilateral fiscal policy among highly developed nations. In particular, unilateral fiscal expansion was shown to reduce capital accumulation domestically and abroad (Lipton and Sachs, 1983). The economic reason for this decline in capital accumulation is that government debt implies an increase in the tax burden which reduces both savings and the supply of loanable funds for private capital accumulation (Zee, 1987). The consequences of unilateral fiscal expansion for the terms of trade were found to depend on the external balance (i.e., the net foreign asset position) of the debt expanding country (Frenkel and Razin, 1986).

As regards the factors which determine the welfare effects of a unilateral expansion of public debt, the literature points to differences in the external balance of the involved countries and the dynamic (in)efficiency of the world economy. Persson (1985) finds that the domestic welfare costs are lower (or turn even to a welfare gain) when the more indebted country has a positive external balance (is a net foreign creditor) given that the world economy is dynamically efficient (=real interest rate above natural growth rate).[1] In particular, crowding out of private capital at home and abroad increases the worldwide real interest rate, which in turn affects the welfare of international debtors and creditors differently.

While many communalities can be found among the factors determining the international differences in welfare cost of fiscal policy and of national climate policy, there is a remarkable difference regarding the impact on the terms of trade. Given that the countries are similar in terms of technology, fiscal policy does not affect the terms of trade of domestic exports and hence welfare is not affected through this channel (Farmer and Friedl, forthcoming). On the other hand, unilateral climate policy reduces production in the policy implementing country since greenhouse gas emissions are an indispensable production factor. The terms of trade of domestic exports improve and hence this positive effect on welfare counteracts the welfare cost through the output channel (in a static context, see Copeland and Taylor, 2005).

Building on the results of welfare costs analysis of fiscal policy, the question remains how the welfare costs of climate policy depend on the net foreign asset position of the involved countries and the dynamic (in)efficiency the world economy finds itself in. It is precisely this question the present paper is addressed to answer systematically within

[1] In a closed economy, however, welfare costs always emerge whenever the economy is dynamically efficient (Diamond, 1965).

a two–good, two–country overlapping generations' model with producer greenhouse gas emissions. The model extends Ono's (2002) closed economy model with a market for emission permits towards two large countries, of which one is a net creditor and the other one is a net debtor to the world economy. The domestic and foreign welfare costs of climate policy, namely a unilateral reduction of the level of emission permits in either of the countries, are derived following the approach taken for fiscal policy by Persson (1985). After determining the steady state effects of a unilateral permit reduction on capital accumulation in both countries and on the terms of trade, we show how the resulting domestic and foreign welfare costs can be disentangled into an indirect effect via the channels of capital accumulation and of terms of trade, as well as into a direct effect of the permit policy on net wage and on the real interest rate.

The main finding of this paper is that the observed abstention from internationally coordinated climate policy among developed countries can be referred to internationally diverging welfare costs driven by differences in external balances of the involved countries. There is much welfare economic rationale for the climate political reluctance of net foreign debtor countries (like the US) under dynamic efficiency (including the Golden Rule) of the world economy, but the climate political actionism of other developed countries (like the EU) cannot be equally well associated with lower welfare costs caused by positive, or less negative, external balances. Even so, the findings of this paper are worthwhile as a first step towards a comprehensive economic explanation of climate political divergences among developed nations.

This paper has five sections. In the next section we provide a description of the two–country, two–good model with nationally tradable emission permits. This will be followed by the derivation of the intertemporal equilibrium dynamics, existence and stability of steady state solutions in Section 3, and by the investigation of the steady state effects, caused by the reduction in the permit volume in one country, on the terms of trade, and on domestic and foreign capital accumulation. Section 4 is devoted to a thorough analysis and international comparison of welfare costs of unilateral policies. Section 5 summarizes our results and concludes.

2 The basic model

Consider an infinite–horizon world economy of two countries, Home H and Foreign F, which have the same population normalized to unity. Each country is composed of perfectly competitive firms and finitely lived consumers. The countries differ in their levels of public debt per capita, leading to diverging net foreign asset positions across countries. This assumption is essential for the emergence of international trade in a large open economy framework.

There are two tradeable goods, x and y^*, and each country specializes in the production of a unique good, which can be used for the purpose of consumption in both countries as well as for investment.[2] Both goods are produced by employing labor and capital, and both cause a flow of pollution. Households save in terms of internationally immobile capital and internationally mobile government bonds, where the supply of government bonds in each country is constant over time (as in Diamond, 1965). Without loss of generality, the rate of depreciation can be set at one, enabling investment of the current period to form next period's capital stock.

Regarding pollution and climate policy, we follow the established literature and focus on producer emissions (Ono, 2002; Jouvet *et al.*, 2005*a*,*b*). Due to the assumption of identical technologies across countries (and sectors), the production of each good causes pollution. In line with the empirical evidence of the European Emission Trading System (ETS), we model country–specific emission trading systems where each country's government exogenously sets a cap on carbon emissions caused by domestic production.[3]

[2]This assumption is a deviation of our model from the assumptions of the Heckscher–Ohlin model. Our model can be regarded as an OLG analoguous to Obstfeld's (1989) and Gosh's (1992) two–good, two–country ILA models.

[3]Alternatively, one could model a global emissions trading system, which would lead to equal permit prices across countries. Another possibility would be to assume that goods consumed domestically (rather than those produced) fall under the permit trading scheme.

2.1 Production and pollution

Let the domestically produced good be x and the foreign–produced good be $y^{\star}$, both in per capita terms (in the following, all foreign–country variables are denoted by a superscript asterisk). Production in each country is specified by a Cobb–Douglas production function with constant returns to scale. Total output in Home X_t is determined by three production factors, namely capital services K_t, labor services L_t, and pollution flow P_t.[4] Defining inputs and output in per capita terms $x_t \equiv X_t/L_t$, $k_t \equiv K_t/L_t$ and $p_t \equiv P_t/L_t$, yields per capita output as:

$$x_t = M\left(k_t\right)^{\alpha_K}\left(p_t\right)^{\alpha_P}, \tag{1}$$

where M denotes a productivity scalar. Total revenues of production (where the output is set as numeraire) are spent on factor costs of labor $w_t L_t$ and capital $q_t K_t$. Furthermore, following the specification of the permit market in Ono (2002), in each period emission quotas S are distributed free of charge to the firms. If the representative firm requires more allowances, it has to buy additional permits on the market for a price of e_t each. In case of excess permits, the firm gains revenues from selling them on the market. Assuming that labor supply L_t is normalized to one, the firms profit maximizing problem in per capita terms reads as follows:

$$\pi_t = M\left(k_t\right)^{\alpha_K}\left(p_t\right)^{\alpha_P} - q_t k_t - w_t + e_t\left(S - p_t\right), \tag{2}$$

$$\pi_t^{*} = M\left(k_t^{*}\right)^{\alpha_K}\left(p_t^{*}\right)^{\alpha_P} - q_t^{*} k_t^{*} - w_t^{*} + e_t^{*}\left(S^{*} - p_t^{*}\right).$$

The first order conditions of the firm in Home for an interior solution read as follows:

$$q_t = \alpha_K M\left(k_t\right)^{\alpha_K - 1}\left(p_t\right)^{\alpha_P} = \alpha_K \frac{x_t}{k_t}, \tag{3}$$

$$w_t = \left(1 - \alpha_K - \alpha_P\right) M\left(k_t\right)^{\alpha_K}\left(p_t\right)^{\alpha_P} = \left(1 - \alpha_K - \alpha_P\right) x_t, \tag{4}$$

$$e_t = \alpha_P M\left(k_t\right)^{\alpha_K}\left(p_t\right)^{\alpha_P - 1} = \alpha_P \frac{x_t}{p_t}. \tag{5}$$

[4] Ono (2002) shows that, by means of rescaling parameters, a production function which has constant returns to scale in using labor and capital as inputs and emission intensity as a scaling factor, can be transformed into a three–factor constant returns to scale production function with labor, capital and pollution as inputs.

Profit maximization implies that the firm's revenues net of the payments to production factors lead to a profit equal to the initial endowment of permits, $e_t S$ (Ono, 2002). This profit is collected by the government and reimbursed to the young households.[5]

Production in Foreign (denoted by an asterisk) is specified by a constant–returns–to–scale Cobb-Douglas production technology, too. Thus, total Foreign output in per capita terms is determined by $y_t^* = M(k_t^*)^{\alpha_K^*}(p_t^*)^{\alpha_P^*}$. The first order conditions in Foreign are:

$$q_t^* = \alpha_K^* M \left(k_t^*\right)^{\alpha_K^*-1} \left(p_t^*\right)^{\alpha_P^*} = \alpha_K^* \frac{y_t^*}{k_t^*}, \tag{6}$$

$$w_t^* = \left(1-\alpha_K^*-\alpha_P^*\right) M \left(k_t^*\right)^{\alpha_K^*} \left(p_t^*\right)^{\alpha_P^*} = \left(1-\alpha_K^*-\alpha_P^*\right) y_t^*, \tag{7}$$

$$e_t^* = \alpha_P^* M \left(k_t^*\right)^{\alpha_K^*} \left(p_t^*\right)^{\alpha_P^*-1} = \alpha_P^* \frac{y_t^*}{p_t^*}. \tag{8}$$

2.2 Intertemporal utility maximization and international asset allocation

Household preferences are identical across and within periods and across countries. As is standard in Diamond (1965)–type OLG models, each generation lives for two periods, one working period and one retirement period. Furthermore, and in contrast to Ono (2002) and John and Pecchenino (1994), households consume in both periods. Lifetime utility depends on consumption during the working period, composed of the consumption goods of both countries, x_t^1 and y_t^1, which are weighted by expenditure shares ζ and $(1-\zeta)$, and consumption during the retirement period, x_{t+1}^2 and y_{t+1}^2. The time preference factor is denoted by β, $0 < \beta \leq 1$. For the sake of analytical tractability, household's preferences are represented by a log–linear utility function:

$$U_t = \zeta \ln x_t^1 + (1-\zeta) \ln y_t^1 + \beta \left[\zeta \ln x_{t+1}^2 + (1-\zeta) \ln y_{t+1}^2\right]. \tag{9}$$

Note that utility is independent of greenhouse gas emissions since households are short lived and it is reasonable to assume that they do not care for the benefits of delayed climate

[5] In essence, this particular modeling of the permit system guarantees that the subsidy is non–distortionary.

change in the distant future in response to reduced emissions today. Consequently, any change in lifetime utility of the households can be regarded as a welfare cost which defines a threshold value for the social benefit of delayed climate change.

In maximizing intertemporal utility the young household is constrained by a budget constraint in each period of life. When young, wage income w_t, net of a lump–sum tax τ_t imposed by the government is spent by the household on consumption of the Home good x_t^1 and the Foreign good y_t^1, whereby the expenditures on the Foreign good in terms of the Home commodity are equal to y_t^1/h_t with h_t denoting the external terms of trade of Home (units of Foreign good per one unit of Home good). Furthermore, for transferring income to their retirement period, young households save in terms of capital k_{t+1} and in terms of bonds of Home b_{t+1}^H and of Foreign $b_{t+1}^{*,H}$ times $1/h_t$. From saving, the old household gains interest income, where i_{t+1} and i_{t+1}^* denote the interest rates in Home and Foreign. When old, the household spends interest income and capital on consumption, again for the Home and Foreign good (x_{t+1}^2 and y_{t+1}^2, respectively). Thus, the first period budget constraint is given by:

$$x_t^1 + \frac{1}{h_t} y_t^1 + s_t = w_t - \tau_t, \tag{10}$$

where savings are defined as

$$s_t \equiv k_{t+1} + b_{t+1}^H + (1/h_t)\, b_{t+1}^{*,H}. \tag{11}$$

After taking account of the no–arbitrage condition for the capital market in Home ($1+i_t = q_t, \forall t$), the second period budget constraint is given by:

$$x_{t+1}^2 + \frac{1}{h_{t+1}} y_{t+1}^2 = (1+i_{t+1}) \left[k_{t+1} + b_{t+1}^H\right] + \left(1 + i_{t+1}^*\right) \frac{1}{h_{t+1}} b_{t+1}^{*,H}. \tag{12}$$

Since government bonds are perfectly mobile across Home and Foreign, the real interest parity condition holds across both countries

$$\left(1 + i_{t+1}^*\right) \frac{h_t}{h_{t+1}} = (1 + i_{t+1}). \tag{13}$$

Taking account of (11) and (13), the first and second period budget constraint can be collapsed to the following intertemporal budget constraint for Home:

$$x_t^1 + \frac{1}{h_t} y_t^1 + \frac{x_{t+1}^2}{(1+i_{t+1})} + \frac{1}{h_{t+1}} \frac{y_{t+1}^2}{(1+i_{t+1})} = w_t - \tau_t. \tag{14}$$

Since Home and Foreign consumers are specified as having identical preferences, the representative household in Foreign maximizes the following intertemporal utility function

$$U_t^* = \zeta \ln x_t^{*,1} + (1-\zeta)\ln y_t^{*,1} + \beta\left[\zeta \ln x_{t+1}^{*,2} + (1-\zeta)\ln y_{t+1}^{*,2}\right] \tag{15}$$

subject to the two budget constraints

$$h_t x_t^{*,1} + y_t^{*,1} + s_t^* = w_t^* - \tau_t^*, \tag{16}$$

$$h_{t+1}x_{t+1}^{*,2} + y_{t+1}^{*,2} = \left(1+i_{t+1}^*\right)\left(k_{t+1}^* + b_{t+1}^{*,F}\right) + h_{t+1}\left(1+i_{t+1}\right)b_{t+1}^F, \tag{17}$$

where savings are defined by

$$s_t^* \equiv k_{t+1}^* + b_{t+1}^{*,F} + h_t b_{t+1}^F. \tag{18}$$

Maximizing (9) subject to (14), and (15) subject to (16)–(17) gives the optimal consumption quantities as follows:

$$x_t^1 = \frac{\zeta}{1+\beta}\left(w_t - \tau_t\right), \qquad x_t^{*,1} = \frac{\zeta}{1+\beta}\frac{\left(w_t^* - \tau_t^*\right)}{h_t}, \tag{19}$$

$$y_t^1 = \frac{1-\zeta}{1+\beta}\left(w_t - \tau_t\right)h_t, \qquad y_t^{*,1} = \frac{1-\zeta}{1+\beta}\left(w_t^* - \tau_t^*\right), \tag{20}$$

$$x_{t+1}^2 = \frac{\beta\zeta}{1+\beta}\left(1+i_{t+1}\right)\left(w_t - \tau_t\right), \qquad x_{t+1}^{*,2} = \frac{\beta\zeta}{1+\beta}\left(1+i_{t+1}^*\right)\frac{\left(w_t^* - \tau_t^*\right)}{h_{t+1}}, \tag{21}$$

$$y_{t+1}^2 = \frac{\beta(1-\zeta)}{1+\beta}\left(1+i_{t+1}\right)\left(w_t - \tau_t\right)h_{t+1}, \qquad y_{t+1}^{*,2} = \frac{\beta(1-\zeta)}{1+\beta}\left(1+i_{t+1}^*\right)\left(w_t^* - \tau_t^*\right). \tag{22}$$

Reformulating the first period budget constraint for s_t and substituting the optimal consumption quantities for x_t^1 and y_t^1 gives

$$s_t = \sigma\left(w_t - \tau_t\right), \quad \sigma \equiv \frac{\beta}{(1+\beta)}. \tag{23}$$

Denote total bonds issued in Home by b_t and in Foreign by b_t^*. Then market clearing for Home and Foreign bonds demands

$$b_t = b_t^H + b_t^F, \qquad b_t^* = b_t^{*,H} + b_t^{*,F}. \tag{24}$$

To eliminate w_t and τ_t in (23), we first write down the government budget constraints:

$$\tau_t + e_t S = i_t b_t, \qquad \tau_t^* + e_t^* S^* = i_t^* b_t^*. \tag{25}$$

The left hand side of (25) denotes the revenues from tax income and permit trading, while the right hand side gives the interest payments to the bond holders. Acknowledging the no–arbitrage condition for the capital market in Home ($1 + i_t = q_t, \forall t$), the market clearing for the permit market in Home ($p_t = S, \forall t$), and substituting for the firm's first order conditions (3)–(5) yields an expression for s_t which depends only on k_t and exogenously given parameters:

$$s_t = \sigma \left[(1 - \alpha_K) M (k_t)^{\alpha_K} (S)^{\alpha_P} - b_t \left(\alpha_K M (k_t)^{\alpha_K - 1} (S)^{\alpha_P} - 1 \right) \right], \tag{26}$$

and, similarly for Foreign, optimal savings s_t^* are a function of k_t^* only:

$$s_t^* = \sigma \left[(1 - \alpha_K^*) M (k_t^*)^{\alpha_K^*} (S^*)^{\alpha_P^*} - b_t^* \left(\alpha_K^* M (k_t^*)^{\alpha_K^* - 1} (S^*)^{\alpha_P^*} - 1 \right) \right]. \tag{27}$$

2.3 Market clearing and international trade

For the national markets, the following additional assumptions apply. The government runs a "constant–stock" fiscal policy and thus $b_{t+1} = b_t = b, \forall t$, and $b_{t+1}^* = b_t^* = b^*, \forall t$, respectively (as in Diamond, 1965). Without loss of generality, the rate of depreciation is set to be one, therefore the investment of the current period builds next period's capital stock. We further assume that there is no population growth.

To complete the model, further market clearing conditions have to be specified. First, the national product markets have to be cleared. The market clearing condition requires output per capita in Home to be equal to the sum of consumption per capita of working and retired households in Home and in Foreign, and capital per capita in period $t + 1$ which is built by investments of period t:

$$x_t = x_t^1 + x_t^2 + k_{t+1} + x_t^{*,1} + x_t^{*,2}, \quad \forall t, \tag{28}$$

while the product market clearing condition in Foreign reads as follows:

$$y_t^* = y_t^{*,1} + y_t^{*,2} + k_{t+1}^* + y_t^1 + y_t^2, \quad \forall t. \tag{29}$$

Clearing of the world asset market requires the supply of savings to be equal to the demand for savings (from (11), (18), and (24)):

$$s_t + \frac{1}{h_t} s_t^* = k_{t+1} + b + \frac{1}{h_t}\left[k_{t+1}^* + b^*\right], \quad \forall t. \tag{30}$$

Defining the net foreign asset positions of Home and Foreign as

$$\phi_{t+1} \equiv k_{t+1} + b - s_t, \qquad \qquad \phi_{t+1}^* \equiv k_{t+1}^* + b^* - s_t^*, \tag{31}$$

gives the following relationship between Home's terms of trade and the net foreign asset positions of Foreign and Home:

$$h_t = -\frac{k_{t+1}^* + b^* - s_t^*}{k_{t+1} + b - s_t} \equiv -\frac{\phi_{t+1}^*}{\phi_{t+1}}, \quad \forall t. \tag{32}$$

Since $h_t > 0$, either $\phi_{t+1} > 0$ and consequently $\phi_{t+1}^* < 0$, Home is a net debtor and Foreign a net creditor, or $\phi_{t+1} < 0$ and $\phi_{t+1}^* > 0$ which means that Home is a net creditor and Foreign a net debtor.

3 The steady state and unilateral permit policy

In this section, we first present the dynamic equations describing the intertemporal equilibrium of our two–country, two–good model before deriving the steady state and the effects of unilateral permit polices on the steady state. Considering the two national no–arbitrage conditions of capital markets $(1 + i_t = q_t, 1 + i_t^* = q_t^*, \forall t)$ and the firms' first order conditions (3) and (6) in the international interest parity condition (13), the equation of motion of the terms of trade follows

$$h_{t+1} = h_t \frac{\left(1 + i_{t+1}^*\right)}{\left(1 + i_{t+1}\right)} = h_t \frac{\alpha_K^* \left(k_{t+1}^*\right)^{\alpha_K^* - 1} \left(S^*\right)^{\alpha_P^*}}{\alpha_K \left(k_{t+1}\right)^{\alpha_K - 1} \left(S\right)^{\alpha_P}}. \tag{33}$$

By inserting the optimal savings functions (26) and (27) into the international capital market clearing condition (30), we obtain the second equation of motion:

$$h_t k_{t+1} + k_{t+1}^* = h_t \left[\sigma_0 \left(k_t\right)^{\alpha_K} - b\left(\sigma\ i_t + 1\right)\right] + \sigma_0^* \left(k_t^*\right)^{\alpha_K} - b^*\left(\sigma\ i_t^* + 1\right), \tag{34}$$

where $\sigma_0 \equiv (1-\alpha_K)\,\sigma M S^{\alpha_P}$ and $\sigma_0^* \equiv (1-\alpha_K^*)\,\sigma M\,(S^*)^{\alpha_P^*}$.

Multiplying the national product market clearing condition of Home (28) by h_t and the one of Foreign (29) by $\zeta/(1-\zeta)$, inserting optimal consumptions of households in Home and Foreign, and subtracting the second from the first gives the combined product market clearing condition:

$$h_t k_{t+1} - \frac{\zeta}{(1-\zeta)} k_{t+1}^* = h_t M\,(k_t)^{\alpha_K}\,(S)^{\alpha_P} - \frac{\zeta}{(1-\zeta)} M\,(k_t^*)^{\alpha_K^*}\,(S^*)^{\alpha_P^*}\,. \tag{35}$$

The dynamic system for the terms of trade, h_t, and for the (per capita) capital stocks in Home and Foreign (k_{t+1} and k_{t+1}^* respectively) are thus described by Equations (33), (34), and (35).

A stationary state of the discrete dynamical system (33), (34) and (35) is defined by

$$(h, k, k^*) = (h_t, k_t, k_t^*) = \left(h_{t+1}, k_{t+1}, k_{t+1}^*\right).$$

Under the presumption of parameter sets which ensure the existence of at least one non–trivial steady state, these dynamic equations can be reduced to a system of three equations which determine the endogenous variables k, h and k^*:

$$KK: \quad h = -\frac{\phi^*}{\phi} \equiv -\frac{\left[k^* - M\,(k^*)^{\alpha_K^*-1}\,(S^*)^{\alpha_P^*}\,\sigma\left((1-\alpha_K^*)k^* - b^*\alpha_K^*\right) + (1-\sigma)b^*\right]}{\left[k - M\,(k)^{\alpha_K-1}\,(S)^{\alpha_P}\,\sigma\left((1-\alpha_K)k - b\alpha_K\right) + (1-\sigma)b\right]}, \tag{36}$$

and

$$GG: \quad h = \frac{\zeta}{(1-\zeta)}\frac{H^*}{H} \equiv \frac{\zeta}{(1-\zeta)}\frac{\left[M\,(k^*)^{\alpha_K^*}\,(S^*)^{\alpha_P^*} - k^*\right]}{\left[M\,(k)^{\alpha_K}\,(S)^{\alpha_P} - k\right]}, \tag{37}$$

where

$$k^* = \left(\frac{\alpha_K^*}{\alpha_K}\right)^{\frac{1}{1-\alpha_K^*}} \left(\frac{(S^*)^{\alpha_P^*}}{(S)^{\alpha_P}}\right)^{\frac{1}{1-\alpha_K^*}} (k)^{\epsilon}, \quad \epsilon \equiv \frac{1-\alpha_K}{1-\alpha_K^*}. \tag{38}$$

Equation (36) can be interpreted as the geometrical locus of all pairs (k, h) which assure international capital market clearing. The equilibrium locus of this market in $k-h$ space will be labeled, in accordance with Zee (1987, 613), as the KK-curve. Equation (37) represents the equilibrium condition for the combined product market and will be labeled GG-curve.

A steady state general equilibrium occurs when the KK–curve and the GG–curve intersect in the first quadrant. For identical production elasticities across countries, $\alpha_K = \alpha_K^*$ and $\alpha_P = \alpha_P^*$, Figure 1 depicts two typical configurations of KK- and GG-curves. Inspection of the slopes reveals that the KK-curve is U–shaped if $\phi < 0$ and inverted U–shaped if $\phi > 0$. The GG-curve is due to assumption of identical technologies horizontal. The existence of two non–trivial steady states, k^L and k^H, is proven in Appendix A.1.

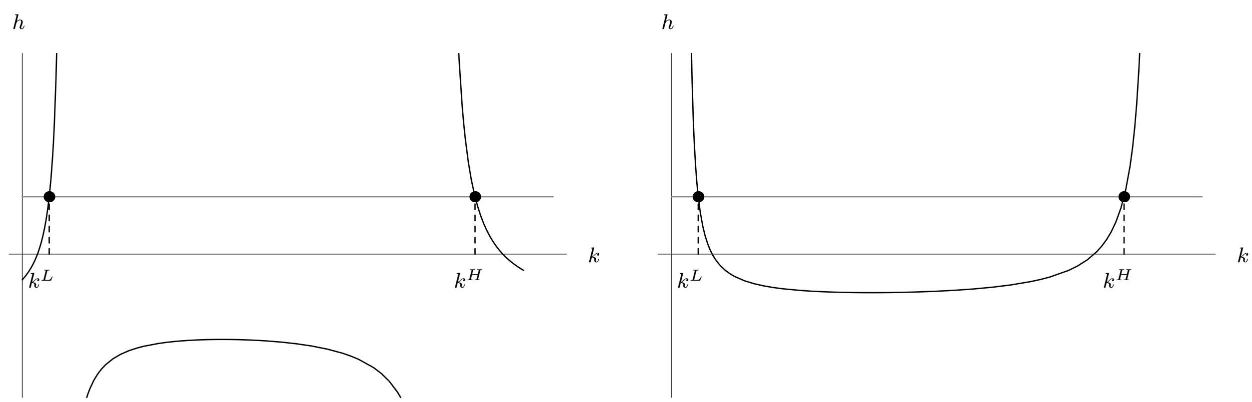

Figure 1: The KK-curves (black) and GG-curves (gray) for $\phi > 0$ (left), and $\phi < 0$ (right).

Being assured of the existence of two distinct steady–state solutions, the next step is to investigate the local stability of the two steady states. To this end, the equilibrium dynamics are linearly approximated in a small neighborhood of each of the two steady states. Due to the algebraic complexity of the Jacobian of the equilibrium dynamics around the steady states, the stability of the steady states can be proven only for small differences between α_K and α_K^* (see Appendix A.2).

For the parameter sets underlying Figure 1, the calculation of the Jacobian matrix of the dynamic system in the two steady states indicates that in the steady state with the lower capital intensity (k^L) two eigenvalues are larger and one is less than unity, while in the steady state with the higher capital intensity (k^H) one eigenvalue is larger and two are less than unity. Thus, the former steady state is saddle path unstable while the latter is saddle path stable.[6] In Figure 1, this stable steady state associated with the higher capital intensity k^H can be found as the second point of intersection of the GG– and KK–curve (for all four cases).

Knowing that the steady state associated with k^H qualifies as being locally stable, we can now turn to the investigation of the long–run effects of a unilateral permit reduction on the main variables of our model. To pursue this objective, we assume that Home implements a more stringent permit policy ($S \downarrow$) while the permit policy of Foreign remains unchanged at S^*. Alternatively, Foreign could implement a permit policy ($S^* \downarrow$) while Home's permit policy remains unchanged. We further assume that the shock is unannounced and permanent such that the households and firms cannot act anticipatory prior to the shock (e.g., by adjusting their saving decision).

To determine the effects of a marginal unilateral reduction of emission permits on the three dynamic variables, we totally differentiate (36), (36), and (38), with respect to S and S^*. Assuming equal production elasticities countries, i.e. $\alpha_K = \alpha_K^*$ and $\alpha_P = \alpha_P^*$, the comparative static effects of a unilateral permit policy is given in Proposition 1.

Proposition 1 *Let $\alpha_K = \alpha_K^*$ and $\alpha_P = \alpha_P^*$. An infinitesimal change of S and S^* leads to a shift of the equilibrium along the gradient given by*

$$\begin{bmatrix} \mathrm{d}h \\ \mathrm{d}k \\ \mathrm{d}k^* \end{bmatrix} = \frac{\alpha_P}{(1-\alpha_K)} \begin{bmatrix} -h \\ (1+\gamma)k \\ \gamma k^* \end{bmatrix} \frac{\mathrm{d}S}{S} + \frac{\alpha_P}{(1-\alpha_K)} \begin{bmatrix} h \\ \gamma^* k \\ (1+\gamma^*)k^* \end{bmatrix} \frac{\mathrm{d}S^*}{S^*} \tag{39}$$

where $\gamma \equiv \dfrac{\zeta b(1+\sigma i)}{k(1-\lambda_3)}$, $\gamma^* \equiv \dfrac{(1-\zeta)b^*(1+\sigma i)}{k^*(1-\lambda_3)}$, $\lambda_3 \equiv (1+i)\sigma(1-\alpha_K)\left[1+\frac{\vartheta}{k}\right]$, $\vartheta \equiv (\zeta b + (1-\zeta)b^*(S/S^*)^{\alpha_P/(1-\alpha_K)})$, *and* $\gamma > 0, \gamma^* > 0$ *for* $k = k^H$.

Proof 1 *See Appendix A.3.*

[6] For the case of equal production elasticities of capital in Home and Foreign, i.e. $\alpha_K = \alpha_K^*$, this result is analytically proven in Farmer *et al.* (2008, 32–33).

For $k = k^H$, and similar technologies across countries, Proposition 1 states that a unilateral permit policy leads to a decline in both the equilibrium values of k and $k^\star$, but with a stronger domestic effect than abroad ($1 + \gamma > \gamma^*$). Thus, in contrast to an autarky situation, the permit reducing country crowds out not only domestic capital accumulation but because of the international dependence of the countries also private capital accumulation abroad. The reason for crowding out of (steady state) capital in both countries is (38) which requires interest parity across countries. Since the decline in the domestic capital stock increases the domestic interest rate, the foreign interest rate has to increase too which leads to a decline in the foreign capital stock. Furthermore, and due to the assumption of two large economies, the permit reducing country experiences an improvement in her terms of trade because domestic prices rise relative to foreign prices.[7] To investigate the welfare consequences of a declining capital stock and an improving terms of trade is the topic of the next section.

4 The welfare cost of permit reduction

The purpose of this chapter is to investigate the welfare consequences of unilateral permit policies taking account of the net foreign asset position of the countries and the dynamic efficiency (inefficiency) of the world economy. The welfare consequences are determined by the effect of adjustments in the terms of trade and capital stocks on lifetime utility as defined by (9) and (15). Since both utility functions incorporate only consumption of goods but not environmental quality, any decline in utility can be regarded as the welfare cost of a permit policy. The higher the welfare cost of unilateral permit policy the lower is the incentive of a country to perform a unilateral reduction of emission permits.

To analyze the welfare costs of permit policies, we proceed in the following way. First, we derive the domestic and foreign welfare costs of unilateral permit policies, i.e. of a unilateral reduction in S (called H permit policy) and in $S^\star$ (F permit policy). By

[7] This can also be seen from (37) where a reduction in S leads to an improvement of the terms of trade. Thus, the foreign good in units of the domestic good becomes cheaper.

domestic welfare costs we mean a welfare loss incurred within the permit reducing country while foreign welfare costs refer to welfare losses that spill over to the other, non–reducing country. Secondly, we compare domestic and foreign welfare costs of unilateral permit polices to see whether the domestic effect is larger or smaller than the spillover effect. Thirdly, we compare the welfare costs for Home of a H and of a F permit policy.

4.1 Derivation of welfare costs

To derive the domestic steady state welfare effect of a unilateral reduction in S and $S^\star$, we define the indirect intertemporal utility function of Home as $U(x^1, y^1, x^2, y^2) \equiv V(w-\tau, 1+i, h)$ and differentiate it with respect to the dynamic variables. From the first order conditions of Home's utility maximization problem we know that $\partial U/\partial y^1 = \partial U/\partial x^1 (h)^{-1}$, $\partial U/\partial x^2 = \partial U/\partial x^1 (1+i)^{-1}$, $\partial U/\partial y^2 = \partial U/\partial x^1((1+i)h)^{-1}$. Using these FOCs and collecting similar terms, the domestic welfare costs of a unilateral reduction in Home's permit volume S are:[8]

$$\frac{\mathrm{d}V}{\mathrm{d}S} = \frac{(1+\beta)}{(w-\tau)} \left\{ \left[\frac{\partial(w-\tau)}{\partial k} + \frac{s}{(1+i)} \frac{\partial(1+i)}{\partial k} \right] \frac{\mathrm{d}k}{\mathrm{d}S} + \left[(1-\zeta) \frac{(w-\tau)}{h} \right] \frac{\mathrm{d}h}{\mathrm{d}S} + \right. \\ \left. + \left[\frac{\partial(w-\tau)}{\partial S} + \frac{s}{(1+i)} \frac{\partial(1+i)}{\partial S} \right] \right\}, \quad (40)$$

and, proceeding similarly for Foreign's utility, the total foreign welfare costs are then given by

$$\frac{\mathrm{d}V^\star}{\mathrm{d}S} = \frac{(1+\beta)}{(w^\star-\tau^\star)} \left\{ \left[\frac{\partial(w^\star-\tau^\star)}{\partial k^\star} + \frac{s\star}{(1+i^\star)} \frac{\partial(1+i^\star)}{\partial k^\star} \right] \frac{\mathrm{d}k^\star}{\mathrm{d}S} - \left[\zeta \frac{(w^\star-\tau^\star)}{h} \right] \frac{\mathrm{d}h}{\mathrm{d}S} \right\}. \quad (41)$$

Similar expressions can be derived for the welfare costs of a permit reduction in Foreign, see Appendix A.5. The domestic welfare costs of a unilateral permit reduction $\mathrm{d}V/\mathrm{d}S$

[8] To be more precise, the equality sign in (40) and (41) should be substituted for $\approx$ because of the welfare costs of a unilateral reduction of H's permit volume $V(S+\mathrm{d}S, S^\star) - V(S, S^\star)$ are exactly equal to

$$\frac{\partial V(S,S^\star)}{\partial S}\mathrm{d}S + 1/2\frac{\partial^2 V(S,S^\star)}{\partial S^2}(\mathrm{d}S)^2 + R_3(S+\mathrm{d}S, S^\star),$$

whereby $R_3(S, S^\star)$ is the remainder after two terms according to Taylor's formula (see Sydsaeter *et al.*, 2005, 77-78). Obviously, we are satisfied with a linear approximation, assuming $\mathrm{d}S$ being small.

(and $dV^\star/dS^\star$) incorporate both indirect effects of a change in S (S^*) on capital stocks and on the terms of trade as well as direct effects of a change in S on factor prices $(w - \tau)$ and $(1 + i)$. Welfare in the other, non–reducing country $dV^\star/dS$ (and $dV/dS^\star$) is affected only by the indirect effects on capital stocks and the terms of trade. Regarding the terms of trade effect, we know from the previous section that the permit reducing country experiences a terms of trade improvement while the non–reducing country is affected by a terms of trade deterioration ($dh/dS > 0$ and $dh/dS^* < 0$), leading to a welfare improvement in the reducing and to a welfare deterioration in the non–reducing country.[9]

To derive the total domestic and foreign welfare effects of unilateral permit policies, we make again use of the assumption of similar technologies across countries.

Proposition 2 *Let $\alpha_K = \alpha_K^*$ and $\alpha_P = \alpha_P^*$. The domestic welfare costs of a unilateral permit policy in Home, S, are then given by*

$$\frac{dV}{dS} = \frac{\alpha_P(1+\beta)}{S(w-\tau)} \left\{ \gamma \left[i(k+b) + \phi \right] + \zeta \frac{(1+i)k}{\alpha_K} + (1-\zeta) \frac{i\ b}{(1-\alpha_K)} \right\}, \qquad (42)$$

and foreign welfare costs, after acknowledging that $i = i^\star$ in the steady state, of Home's permit policy:

$$\frac{dV^\star}{dS} = \frac{\alpha_P(1+\beta)}{S(w^\star-\tau^\star)} \left\{ \gamma \left[i(k^\star+b^\star) + \phi^\star \right] + \zeta \frac{(1+i)k^\star}{\alpha_K} - \zeta \frac{i\ b^\star}{(1-\alpha_K)} \right\}. \qquad (43)$$

Proceeding similarly for the derivation of a unilateral Foreign permit policy yields

$$\frac{dV^\star}{dS^\star} = \frac{\alpha_P(1+\beta)}{S^\star(w^\star-\tau^\star)} \left\{ \gamma^\star \left[i(k^\star+b^\star) + \phi^\star \right] + (1-\zeta) \frac{(1+i)k^\star}{\alpha_K} + \zeta \frac{i\ b^\star}{(1-\alpha_K)} \right\}, \qquad (44)$$

$$\frac{dV}{dS^\star} = \frac{\alpha_P(1+\beta)}{S^\star(w-\tau)} \left\{ \gamma^\star \left[i(k+b) + \phi \right] + (1-\zeta) \frac{(1+i)k}{\alpha_K} - (1-\zeta) \frac{i\ b}{(1-\alpha_K)} \right\}. \qquad (45)$$

The signs of the domestic and foreign welfare costs of unilateral permit policies in Home and Foreign are summarized in Table 1.

[9] In a closed economy context, this type of effect was called by Meade (1952) 'pecuniary externality' to describe a situation where the changed activity level of one agent affects the financial circumstances of another agent due to a change in prices.(for a discussion, see Baumol and Oates, 1988, 14–16; 29–30)

Table 1: Domestic and foreign welfare costs of unilateral permit policies

	$\frac{dV}{dS}$	$\frac{dV}{dS^\star}$	$\frac{dV^\star}{dS}$	$\frac{dV^\star}{dS^\star}$
case 1: $\phi > 0 \wedge (i > 0)$	$+$	?	?	?
case 1a: $\phi > 0 \wedge (i = 0)$	$+$	$+$	$+^{i}$	$+^{ii}$
case 2: $\phi > 0 \wedge (i < 0)$	?	?	?	?
case 3: $\phi < 0 \wedge (i > 0)$	?	?	?	$+$
case 3a: $\phi < 0 \wedge (i = 0)$	$+^{iii}$	$+^{iv}$	$+$	$+$
case 4: $\phi < 0 \wedge (i < 0)$	?	?	?	?

$^{i)}$ if $\gamma\phi^* + \zeta k^*/\alpha_K > 0$, $^{ii)}$ if $\gamma^*\phi^* + (1-\zeta)k^*/\alpha_K > 0$,
$^{iii)}$ if $\gamma\phi + \zeta k/\alpha_K > 0$, $^{iv)}$ if $\gamma^*\phi + (1-\zeta)k/\alpha_K > 0$.

Proof 2 *See Appendix A.4*

Proposition 2 illustrates the importance of the net foreign asset position (ϕ) and the dynamic (in)efficiency of the world economy ($i = i^* \geq 0$ or $i = i^* < 0$). Depending on whether the permit reducing country is a net debtor or a net creditor to the world economy, and on whether the steady state interest rate is positive (dynamic efficiency), zero (Golden Rule), or negative (dynamic inefficiency), the terms in (42)–(45) are either unidirectional and hence the welfare cost of a permit reduction are certainly positive, or some of the terms are positive while others are negative, leading to an ambiguous welfare effect.

For the dynamically efficient case or the Golden Rule ($i \geq 0$) where Home is a net foreign debtor ($\phi > 0$), the net welfare effect of a domestic permit reduction is unambiguously negative. For the opposite case where Home is a net foreign creditor ($\phi < 0$), however, the net welfare effect can be signed unambiguously negative only for the case of the Golden Rule, as a special case of dynamic efficiency where $i = 0$, and if $|\gamma\phi|$ is smaller than $\zeta k/\alpha_K$. If in contrast the interest rate were negative in the initial steady state (dynamic inefficiency), we cannot rule out the case that $\mathrm{d}V/\mathrm{d}S$ becomes negative and hence welfare improves when the permit level is reduced. Thus, for all cases where $\mathrm{d}V/\mathrm{d}S > 0$ ($\mathrm{d}V^\star/\mathrm{d}S^\star > 0$), a unilateral reduction of the permit level leads to welfare costs that have to be outweighed by environmental benefits for the policy to be approved by the social planner. We turn next to a comparison of the domestic welfare cost and the welfare cost generated abroad.

4.2 Comparison of domestic and foreign welfare costs of a unilateral permit policy

To compare the domestic and foreign welfare costs of a unilateral permit policy, we restrict the analysis to the case of a unilateral H policy.[10] Proposition 3 states that the relative magnitude of the domestic and foreign welfare costs of a unilateral H permit policy depends on the net foreign asset position (external balance) of the countries and the dynamic (in)efficiency of the world economy.

Proposition 3 *Let $\alpha_K = \alpha_K^\star$ and $\alpha_P = \alpha_P^\star$. Moreover, suppose that Home implements a unilateral permit policy. Then,*

$$\frac{\mathrm{d}V}{\mathrm{d}S} - \frac{\mathrm{d}V^\star}{\mathrm{d}S} = \frac{\alpha_P}{S}(1+\beta)\frac{(1+i)}{(w-\tau)}\Delta \tag{46}$$

where $$\Delta \equiv \gamma\phi\left[1 + h\frac{(w-\tau)}{(w^\star-\tau^\star)}\right] + b\frac{i}{(1+i)(1-\alpha_K)}.$$

Depending on the signs of i and ϕ, three cases emerge:

(i) *For $i \geq 0$ (dynamic efficiency) and $\phi > 0$,* $\quad \dfrac{\mathrm{d}V^\star}{\mathrm{d}S} < \dfrac{\mathrm{d}V}{\mathrm{d}S}.$

(ii) *For $i = i^\star = 0$ (Golden Rule) and $\phi < 0$,* $\quad \dfrac{\mathrm{d}V^\star}{\mathrm{d}S} > \dfrac{\mathrm{d}V}{\mathrm{d}S}.$

[10] A similar analysis of the domestic and foreign welfare costs of a unilateral F permit policy can be found in Appendix A.5.

(iii) *For $i < 0$ (dynamic inefficiency), the sign of* $\frac{\mathrm{d}V}{\mathrm{d}S} - \frac{\mathrm{d}V^\star}{\mathrm{d}S}$ *is ambiguous.*

Proof 3 *From* (32), $\phi^\star = -\phi\, h$ *and furthermore* $h > 0$. *To derive* (46), *we subtract* (43) *from* (42) *and utilize that* $[(1+i)(k+b) - \sigma(w-\tau)] = (1+i)\phi + \sigma i(w-\tau)$, $(w-\tau) = (1-\alpha_K)/\alpha_K(1+i)k - bi$, *and analogously for Foreign.*

Case i: Since $\phi > 0$ *and* $i > 0$, $\Delta > 0$ *and hence* $\mathrm{d}V^\star/\mathrm{d}S < \mathrm{d}V/\mathrm{d}S$.

Case ii: Since $\phi < 0$ *and knowing that in the Golden Rule* $i = 0$, $\Delta < 0$ *and hence* $\mathrm{d}V^\star/\mathrm{d}S > \mathrm{d}V/\mathrm{d}S$.

Case iii: Since $i < 0$, Δ *involves positive and negative terms and hence the sign of* $\mathrm{d}V/\mathrm{d}S - \mathrm{d}V^\star/\mathrm{d}S$ *is ambiguous.* ■

Consequently, when Home is a net debtor ($\phi > 0$) and Foreign a net creditor ($\phi^\star < 0$), the domestic welfare costs of Home's unilateral permit reduction are larger than the welfare costs abroad (see case i of Proposition 3). If in the same situation Foreign would reduce her permits, the welfare costs in Foreign would be smaller than in Home (see case ii of Proposition 5). Thus, whether the permit–reducing country is a net debtor or a net creditor is essential for the magnitude of its welfare costs relative to the other, non–reducing country. From the perspective of a social planner who has to decide which country should unilaterally reduce its permits, the welfare costs are smaller when the net creditor country reduces its emission permits and not the net debtor country.

The economic rationale why the net creditor country encounters lower welfare costs is again the international interdependence: while a more stringent climate policy crowds out private capital in both countries, and the worldwide interest rate rises, independently of the external balance of the permit reducing country, the domestic welfare costs depend on the external balance. In particular, income is redistributed by the rising interest rate from workers/taxpayers to wealth holders in both countries. In the case of Home being a net foreign creditor, some wealth holders in Foreign are domestic residents and hence the consumption possibilities (welfare) for the domestic economy are increased and thus the welfare costs are smaller than if Home were a net foreign debtor country.

4.3 Comparison of welfare costs of a unilateral permit policy in Home and Foreign

Knowing that the net foreign asset position of a country determines whether her unilateral permit policy causes larger (smaller) domestic than foreign welfare costs, the question arises whether this relationship pertains also when comparing the domestic welfare costs of domestic and foreign unilateral permit policy.

Proposition 4 *Let $\alpha_K = \alpha_K^\star$, $\alpha_P = \alpha_P^\star$, $\zeta = (1-\zeta)$, and $S = S^*$. Then, the difference in domestic welfare costs of a domestic and and a foreign unilateral permit is given by*

$$\frac{\mathrm{d}V}{\mathrm{d}S} - \frac{\mathrm{d}V}{\mathrm{d}S^\star} = \frac{1+\beta}{(w-\tau)} \frac{\alpha_P}{S} \left\{ [i(k+b)+\phi]\,[\gamma-\gamma^*] + \frac{i\;b}{(1-\alpha_K)} \right\}. \tag{47}$$

Depending on the signs of i and ϕ, three cases emerge:

(i) *For $i \geq 0$ (dynamic efficiency) and $\phi > 0$,* $\quad \dfrac{\mathrm{d}V}{\mathrm{d}S} > \dfrac{\mathrm{d}V}{\mathrm{d}S^\star}$.

(ii) *For $i = i^\star = 0$ (Golden Rule) and $\phi < 0$,* $\quad \dfrac{\mathrm{d}V}{\mathrm{d}S} > \dfrac{\mathrm{d}V}{\mathrm{d}S^\star}$.

(iii) *For $i < 0$ (dynamic inefficiency), the sign of* $\dfrac{\mathrm{d}V}{\mathrm{d}S} - \dfrac{\mathrm{d}V}{\mathrm{d}S^\star}$ *is ambiguous.*

Proof 4 *To derive* (47)*, we subtract* (45) *from* (42)*.*

Case i: Since $\phi > 0$ and $\phi = (1+\sigma i)(1-\zeta)(b-b^*)$, $b > b^*$ which implies that $\gamma - \gamma^* = \dfrac{(1+\sigma i)\zeta(b-b^*)}{k(1-\lambda_3)} > 0$*. With $i > 0$, $\mathrm{d}V/\mathrm{d}S > \mathrm{d}V/\mathrm{d}S^\star$.*

Case ii: Since $\phi < 0$, $b < b^*$ and hence $\gamma < \gamma^*$. With $i = 0$, $\mathrm{d}V/\mathrm{d}S > \mathrm{d}V/\mathrm{d}S^\star$.

Case iii: Since $i < 0$, the sign of $\mathrm{d}V/\mathrm{d}S - \mathrm{d}V^\star/\mathrm{d}S$ is ambiguous. ■

Under dynamic efficiency (the Golden Rule included) and irrespective of the external balance of a country, the domestic welfare costs of unilateral domestic permit policy are larger than those of a unilateral foreign permit policy provided that in case of a net foreign creditor the Golden Rule applies. If, however, dynamic inefficiency applies, the comparison of the domestic welfare costs of domestic and foreign unilateral permit policy turns out to be ambiguous. For numerical values of policy parameters which imply that Home is a net foreign debtor,[11] the domestic welfare costs of domestic unilateral permit policy are lower than the domestic welfare costs of foreign unilateral permit policy. Under such circumstances, and assuming that Home can either implement the permit policy herself or bear the consequences of a foreign welfare policy, the Home country might prefer to implement the policy herself rather than awaiting the consequences of spillover effects of a foreign policy.

4.4 Policy implications of welfare analysis for climate policy

In line with the domestic welfare effects of unilateral fiscal policy (Persson, 1985, p. 80), unilateral permit policy leads unambiguously to a domestic welfare loss if the policy implementing country is a net foreign debtor and if the world economy is dynamically efficient. If on the other hand the world economy is dynamically inefficient, the effect on welfare entails both positive and negative terms and hence can either be in total a cost or a gain. Thus, based on domestic welfare costs, a net debtor country is less likely to decide to implement a unilateral permit policy than a net creditor country, and particularly so if the world economy is dynamically efficient. One policy conclusion from this result is that a permit policy entails, from the perspective of the present domestic and foreign generation, a welfare loss in many circumstances—a cost, which has to be balanced by global far–distant benefits from better environmental quality like slowed global warming.

A second consideration when analyzing welfare costs of unilateral policy in an international context, refers to the possibility to shift, or 'spill over', part of the welfare costs abroad. And indeed, due to the positive terms of trade effect caused by a unilateral permit policy for the policy implementing country, domestic welfare is influenced positively while welfare

[11] For parameter values $\beta = 0.9, \alpha_K = 0.3, \alpha_P = 0.1, M = 4.5, \zeta = 0.5, b^* = 0.115, b = 0.18671835$, we have welfare costs of a domestic policy $\mathrm{d}V/\mathrm{d}S = 0.0143009$ and of a foreign policy $\mathrm{d}V^*/\mathrm{d}S = 0.0143062$ and hence $\mathrm{d}V/\mathrm{d}S < \mathrm{d}V^*/\mathrm{d}S$.

is reduced abroad. However, as important as the terms of trade effect is the effect on factor prices, which respond by an increase in interest rates and a fall in net wages due to the fall in domestic (and foreign) capital stocks. How strong the interest rate effect and the net wage effect impact on welfare depends again on the net foreign asset position and the dynamic (in)efficiency of the world economy. We find that—by comparing domestic and foreign welfare costs of unilateral permit policy of a net foreign debtor—the domestic welfare costs are larger than Foreign's under dynamic efficiency. Thus, even though part of the welfare costs are shifted to the other country, in total the policy implemented country is affected more adversely than the other country. If, on the contrary, the permit reducing country is a net foreign creditor and the pre–shock steady state is Golden Rule, the domestic welfare costs are lower than Foreign's, and thus from the perspective of the other non–implementing country this is a very undesirable outcome.

As a consequence of this international spillover of welfare costs, each country can ask herself whether it would not be better to implement a permit policy herself rather than to await the consequences of a permit policy in the other country. To answer this question, we compared in Section 4.3 domestic welfare costs of domestic and of foreign unilateral permit policy. It turns out that under dynamic efficiency and Home being a net foreign debtor, the welfare costs of the domestic policy are larger than those of foreign policy. The same is true when Home is a net foreign creditor and the pre–shock steady state is Golden Rule. Thus, in both of these cases the country is better off by not implementing a domestic permit policy but awaiting the consequences of permit policy in the other country. Under dynamic inefficiency, however, the difference between the domestic welfare costs of domestic and foreign permit policy is in general ambiguous. For some feasible parameter values, the welfare costs of domestic policy might be lower than those of foreign permit policy if Home (Foreign) is a net foreign debtor (creditor). This result suggests that large net foreign debtor countries (like the United States) might be ready to perform unilateral climate policy, rather than bearing the welfare costs of permit policy abroad, if the world economy finds itself in a dynamically inefficient situation.

5 Conclusion

This paper investigates the effects of unilateral climate policy in a two–country, two–good OLG model. After deriving the intertemporal equilibrium dynamics of the terms of trade, Home's and Foreign's capital intensities, we analyze the impact of a unilateral permit reduction on the steady state of the key economic variables. We find that the terms of trade of the policy implementing country improve while capital intensities in both countries fall stronger in the policy implementing country than abroad.

While these steady state effects of unilateral climate policy are independent of the external balance of the countries, domestic and foreign welfare show opposing effects. While the terms of trade improvement is welfare enhancing for the policy implementing country and welfare reducing for the other country, the fall in capital intensities cause a declining net wage and an increasing interest rate. In total, for the dynamically efficient case, a permit reduction by a net debtor country is associated with domestic and foreign welfare costs—and this gives an economic explanation why climate policy has been implemented with large hesitation. How strongly welfare is reduced, depends on her net foreign asset position, with the decrease in domestic (foreign) welfare being larger (smaller) when the policy implementing country is a net debtor to the world economy. Contrary to the claim that unilateral permit policy is *always* welfare reducing we can verify its validity analytically only for the case of dynamic efficiency and of the permit reducing country being a net foreign debtor.

As argued in the introduction, we investigate the differences in welfare costs of unilateral permit policy from two different angles: (i) the potential to shift, or 'spill over', part of the welfare costs abroad, and (ii) the (dis)advantage of a domestic climate policy relative to a foreign climate policy. Regarding the spillover effect in terms of welfare from the policy implementing to the other country, we find that under dynamic efficiency and the policy implementing country being a net debtor, that the policy implementing country is affected more adversely than the other country, even though part of the welfare costs is shifted to the other country. If, on the contrary, the permit reducing country is a net foreign creditor and the pre–shock steady state is Golden Rule, the domestic welfare costs are lower than abroad, and thus the spillover effect is substantial. This result motivates two conclusions: one the one hand, unilateral environmental policy harms the domestic economy and thus explains why climate policy has been implemented cautiously in the past. On the other hand, the weaker welfare costs for a net creditor country helps to better understand why the EU has been more pro–active in pursuing climate policy than the US.

When comparing, from the perspective of one country, the welfare effect of domestic climate policy relative to a foreign climate policy, it turns out that the welfare costs of the domestic policy are larger than those of foreign policy in two cases: either for a net debtor country under dynamic efficiency or for net foreign creditor country and the pre–shock steady state is Golden Rule. Thus, in both of these cases the country is better off by not implementing a domestic permit policy but awaiting the consequences of permit policy in the other country. Under dynamic inefficiency, however, a situation can result where the welfare costs of domestic policy are lower than those of foreign permit policy, particularly if the policy implementing country is a net foreign debtor.

Taking together all these diverse results on spillover effects and comparison of welfare costs across policy options, the question remains on the prevalence of (dis)incentives for a country to implement national climate policy. Starting with disincentives, there is much welfare economic rationale for the climate political reluctance of net foreign debtor countries (like the US) under dynamic efficiency (including the Golden Rule) of the world economy. Regarding incentives for implementing climate policy, we argue that lower welfare costs caused by positive, or less negative, external balances can explain only parts of the climate political actionism of other developed countries (like the EU). Thus, our dynamic general equilibrium approach for two large economies supplements the reasoning provided by static game game theory and political economics why unilateral climate policy is not in the interest of some highly developed countries even if other countries implement such a policy. It is an open question whether the welfare cost of a internationally harmonized permit policy are lower (or higher?) than those of bearing the costs of policy implementation of the other country. This leaves ample space for further research.

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A Appendix

A.1 Existence of steady states

This section is devoted to show how the existence of at least two non–trivial steady state solutions of the intertemporal equilibrium dynamics (33)–(35) can be proven. To this end, rewrite first equations (36)–(38) as follows:

$$k^* = \tilde{S}k^{\epsilon} \quad \text{where} \quad \tilde{S} \equiv \left[\frac{\alpha_K^*}{\alpha_K}\left(\frac{S^*}{S}\right)^{\alpha_P}\right]^{\frac{1}{1-\alpha_K^*}}, \tag{48}$$

$$h = \frac{\zeta}{1-\zeta}\frac{k^*}{k}\left[1+\left(1-\frac{\alpha_K}{\alpha_K^*}\right)\frac{MS^{\alpha_P}k^{\alpha_K-1}}{1-MS^{\alpha_P}k^{\alpha_K-1}}\right], \tag{49}$$

$$k = \bar{F}(k) + \Delta(k). \tag{50}$$

whereby

$$\bar{F}(k) = (1-\tilde{\alpha}_K)\sigma\frac{(1+i)}{\alpha_K} - \vartheta(k)(1+i) - \vartheta(k)(1-\sigma),$$

$$\Delta(k) = -\zeta\left(1-\frac{\alpha_K}{\alpha_K^*}\right)\frac{x}{1-\frac{(1+i)}{\alpha_K}}\phi,$$

with $(1-\tilde{\alpha}_K) \equiv \zeta(1-\alpha_K) + (1-\zeta)(1-\alpha_K^*)\frac{\alpha_K}{\alpha_K^*}$ and $\vartheta(k) \equiv \zeta b + (1-\zeta)b^*\frac{k}{k^*}$.

Next, consider the case of identical production technologies, i.e. $\alpha_K = \alpha_K^*$. Clearly, $\Delta(k) = 0$ and (50) reduces to

$$k = F(k) \equiv (1-\alpha_K)\sigma\frac{(1+i)}{\alpha_K} - \vartheta\sigma(1+i) - \vartheta(1-\sigma),$$

with $\vartheta \equiv (\zeta b + (1-\zeta)b^*\tilde{S}^{-1})$. Theorem 1 from Farmer *et al.* (2008, 13–14), which is reproduced as Lemma 1 below, provides sufficient conditions for exactly two strictly positive solutions of equation $k = F(k)$.

Lemma 1 *Let the parameter vector* $\omega = (\alpha_K, \alpha_P, \beta, \zeta, M, S, \vartheta)$ *be an element of the parameter space* $\Omega = [0,1]^4 \times \mathbb{R}_+^3$. *For any* $\omega \in \Omega$ *there exists* $\overline{\vartheta} \in \mathbb{R}_{++}$ *such that*

1. *for* $\vartheta < \overline{\vartheta}$ *there are one trivial* $(k = 0)$ *and two non–trivial steady states* k^L *and* k^H *with* $0 < k^L < k^H < \overline{k}$*,*

2. *for* $\vartheta = \overline{\vartheta}$ *there are one trivial and one non–trivial steady state, and*

3. *for* $\vartheta > \overline{\vartheta}$ *there is only the trivial steady state.*

Proof 5 *see Appendix A.1 in Farmer* et al. *(2008).*

The third step is to prove the existence of at least two strictly positive solutions of the equation $k = \bar{F}(k) + \Delta(k)$. The central insight here is that $\bar{F}(k) + \Delta(k)$ depends continuously on α_K^*.

Theorem 1 *For every parameter set* $\omega = (\alpha_K, \alpha_K^*, \alpha_P, \beta, \zeta, M, S, b, b^*) \in \Omega = [0,1]^5 \times \mathbb{R}_+^3$ *with* $|\alpha_K - \alpha_K^*|$ *sufficiently small some (non–unique)* $\bar{b}, \bar{b}^* > 0$ *exist such that for all* $b \in (0, \bar{b})$ *and* $b^* \in (0, \bar{b}^*)$ *there are at least two non–trivial steady state solutions* (h, k, k^*)*.*

Proof 6 *For* $\alpha_K = \alpha_K^*$ *we know from Lemma 1 that for all* $\vartheta < \bar{\vartheta}$ *exactly two solutions* $0 < k^L < k^H$ *of* $k = \bar{F}(k) + \Delta(k)$ *occur. Since* $\bar{F}(k) + \Delta(k)$ *depends continuously on* α^**, there is some interval* $\Lambda = (\alpha_-, \alpha_+)$ *such that for all* $\alpha_K^* \in \Lambda$ *at least two distinct solutions* $0 < \tilde{k}^L < \tilde{k}^H$ *exist*[12]*.* ■

A.2 Saddle–path stability of steady states

To prove the dynamic stability of a non–trivial steady state solution, we consider the Jacobian of the dynamic system (33)–(35) in a small neighborhood around both non–trivial steady state solutions. Again, we focus first on the case of identical production elasticities of capital. Theorem 2 from (Farmer *et al.*, 2008, 15) claims that for $\vartheta < \bar{\vartheta}$, at the lower steady state solution, k^L, two eigenvalues of the Jacobian are larger than one

[12] The analysis of $\bar{F}(k) + \Delta(k)$ shows, however, that for $\alpha_K < \alpha_K^*$ a third steady state $k^\infty > k^H$ exists.

and one eigenvalue equals $\alpha_K < 1$, while at the larger steady state solution of $k = F(k)$ two eigenvalues are less than one and one eigenvalue is larger than one. Hence, the lower steady state is saddle–path unstable while the larger steady state is saddle–path stable.

In considering the general case $\alpha_K \neq \alpha_K^*$, we focus again at a sufficiently small difference between α_K and α_K^*. Under this assumption, Theorem 2 of (Farmer *et al.*, 2008, 15) can be generalized as the following Theorem 2.

Theorem 2 *For every parameter set* $\omega \in \Omega$ *with* $|\alpha_K - \alpha_K^*|$ *sufficiently small some (non–unique)* $\bar{b}, \bar{b}^* > 0$ *exist such that for all* $b \in (0, \bar{b})$ *and* $b^* \in (0, \bar{b}^*)$ *the larger strictly positive solution of* $k = \bar{F}(k) + \Delta(k)$ *is saddle–path stable.*

Proof 7 *For* $\alpha_K = \alpha_K^*$ *see the proof to Theorem 2 of (Farmer* et al.*, 2008, 32–33) Again, since* $k = \bar{F}(k) + \Delta(k)$ *depends continuously on* α^**, there is some interval* $\Lambda_1 = (\alpha_-^1, \alpha_+^1)$ *such that for all* $\alpha_K^* \in \Lambda_1 \subset \Lambda$ *the larger solution* k^H *of* $k = \bar{F}(k) + \Delta(k)$ *is saddle–path stable.* ■

A.3 Proof of Proposition 1

To determine the effects of a marginal unilateral reduction of emission permits on the three dynamic variables, we totally differentiate (36), (36), and (38), with respect to S and S^*. This yields:

$$\begin{bmatrix} 0 & -\epsilon(\frac{k^*}{k}) & 1 \\ \phi & h\frac{\partial\phi}{\partial k} & \frac{\partial\phi^*}{\partial k^*} \\ (1-\zeta)H & (1-\zeta)h\frac{\partial H}{\partial k} & -\zeta\frac{\partial H^*}{\partial k^*} \end{bmatrix} \begin{bmatrix} \mathrm{d}h \\ \mathrm{d}k \\ \mathrm{d}k^* \end{bmatrix} = \begin{bmatrix} -\frac{\alpha_P}{1-\alpha_K^*}\frac{k^*}{S} \\ -h\frac{\partial\phi}{\partial S} \\ -(1-\zeta)h\frac{\partial H}{\partial S} \end{bmatrix} \mathrm{d}S + \begin{bmatrix} \frac{\alpha_P^*}{1-\alpha_K^*}\frac{k^*}{S^*} \\ -\frac{\partial\phi^*}{\partial S^*} \\ \zeta\frac{\partial H^*}{\partial S^*} \end{bmatrix} \mathrm{d}S^* \tag{51}$$

After defining the slopes of the KK- and GG-curve curve at the steady state by

$$\frac{\mathrm{d}h}{\mathrm{d}k}_{|KK} = -\frac{\left[h\frac{\partial\phi}{\partial k} + \frac{\partial\phi^*}{\partial k^*}\frac{\partial k^*}{\partial k}\right]}{\phi}, \quad \frac{\mathrm{d}h}{\mathrm{d}k}_{|GG} = \frac{-(1-\zeta)h\frac{\partial H}{\partial k} + \zeta\frac{\partial H^*}{\partial k^*}\frac{\partial k^*}{\partial k}}{(1-\zeta)H} \tag{52}$$

and the shift of these curves caused by a change in S and S^* by

$$\frac{\partial h}{\partial S}_{|KK} = -\frac{\left[h\dfrac{\partial \phi}{\partial S} + \dfrac{\partial \phi^*}{\partial k^*}\dfrac{\partial k^*}{\partial S}\right]}{\phi}, \quad \frac{\partial h}{\partial S}_{|GG} = \frac{-(1-\zeta)h\dfrac{\partial H}{\partial S} + \zeta\dfrac{\partial H^*}{\partial k^*}\dfrac{\partial k^*}{\partial S}}{(1-\zeta)H}, \tag{53}$$

$$\frac{\partial h}{\partial S^*}_{|KK} = -\frac{\left[\dfrac{\partial \phi^*}{\partial k^*}\dfrac{\partial k^*}{\partial S^*} + \dfrac{\partial \phi^*}{\partial S^*}\right]}{\phi}, \quad \frac{\partial h}{\partial S^*}_{|GG} = \frac{\zeta\left[\dfrac{\partial H^*}{\partial S^*} + \dfrac{\partial H^*}{\partial k^*}\dfrac{\partial k^*}{\partial S^*}\right]}{(1-\zeta)H} \tag{54}$$

the solution of (51) by using Cramer's rule reads as follows:

$$\begin{bmatrix} \mathrm{d}h \\ \mathrm{d}k \\ \mathrm{d}k^* \end{bmatrix} = \begin{bmatrix} \dfrac{\mathrm{d}h}{\mathrm{d}k}_{|KK}\dfrac{\partial h}{\partial S}_{|GG} - \dfrac{\mathrm{d}h}{\mathrm{d}k}_{|GG}\dfrac{\partial h}{\partial S}_{|KK} \\ \dfrac{\partial h}{\partial S}_{|GG} - \dfrac{\partial h}{\partial S}_{|KK} \\ \left[\dfrac{\partial h}{\partial S}_{|GG} - \dfrac{\partial h}{\partial S}_{|KK}\right]\dfrac{\partial k^*}{\partial k} - \left[\dfrac{\mathrm{d}h}{\mathrm{d}k}_{|KK} - \dfrac{\mathrm{d}h}{\mathrm{d}k}_{|GG}\right]\dfrac{\partial k^*}{\partial S} \end{bmatrix} \frac{\mathrm{d}S}{\left[\frac{\mathrm{d}h}{\mathrm{d}k}_{|KK} - \frac{\mathrm{d}h}{\mathrm{d}k}_{|GG}\right]} \tag{55}$$

$$\begin{bmatrix} \mathrm{d}h \\ \mathrm{d}k \\ \mathrm{d}k^* \end{bmatrix} = \begin{bmatrix} \dfrac{\mathrm{d}h}{\mathrm{d}k}_{|KK}\dfrac{\partial h}{\partial S^*}_{|GG} - \dfrac{\mathrm{d}h}{\mathrm{d}k}_{|GG}\dfrac{\partial h}{\partial S^*}_{|KK} \\ \dfrac{\partial h}{\partial S^*}_{|GG} - \dfrac{\partial h}{\partial S^*}_{|KK} \\ \left[\dfrac{\partial h}{\partial S^*}_{|GG} - \dfrac{\partial h}{\partial S^*}_{|KK}\right]\dfrac{\partial k^*}{\partial k} - \left[\dfrac{\mathrm{d}h}{\mathrm{d}k}_{|KK} + \dfrac{\mathrm{d}h}{\mathrm{d}k}_{|GG}\right]\dfrac{\partial k^*}{\partial S^*} \end{bmatrix} \frac{\mathrm{d}S^*}{\left[\frac{\mathrm{d}h}{\mathrm{d}k}_{|KK} - \frac{\mathrm{d}h}{\mathrm{d}k}_{|GG}\right]} \tag{56}$$

To show that $\mathrm{d}h/\mathrm{d}S = -\alpha_P h/[S(1-\alpha_K)]$, we proceed in two steps. First, we show that $\alpha_K = \alpha_K^*$ and $\alpha_P = \alpha_P^*$ implies that $\mathrm{d}h/\mathrm{d}k_{|GG} = 0$. From (52) we know that $\mathrm{d}h/\mathrm{d}k_{|GG} = [-(1-\zeta)h\partial H/\partial k + \zeta\partial H^*/\partial k^*\partial k^*/\partial k]/[(1-\zeta)H]$. Acknowledging the definition $H = MS^{\alpha_P}k^{\alpha_K} - k$, $\partial H/\partial k = 1 + i - 1 = i$ follows. Analogously, $\partial H^*/\partial k^* = 1 + i^* - 1 = i^*$ holds, and hence $\mathrm{d}h/\mathrm{d}k_{|GG} = [-(1-\zeta)hi + \zeta i^*\epsilon(k^*/k)]/[(1-\zeta)H]$. Since $i^* = i$, $\epsilon = 1$, $k^* = \tilde{S}k$ and $h = \zeta/(1-\zeta)\tilde{S}$, $\mathrm{d}h/\mathrm{d}k_{|GG} = 0$ follows. Second, $\mathrm{d}h/\mathrm{d}k_{|GG} = 0$ implies that from (55) $\mathrm{d}h/\mathrm{d}S = \partial h/\partial S_{|GG} = [-(1-\zeta)h\partial H/\partial S + \zeta\partial H^*/\partial k^*\partial k^*/\partial S]/[(1-\zeta)H]$. Since $\partial H/\partial S = \alpha_P/\alpha_K(1+i)k/S$, and again using $h = \zeta/(1-\zeta)\tilde{S}$, $\mathrm{d}h/\mathrm{d}S = \partial h/\partial S_{|GG} = -\alpha_P/(1-\alpha_K)h/S$. Applying a similar argument to derive the other differentials, and acknowledging that for $\alpha_K = \alpha_K^*$ and $\alpha_P = \alpha_P^*$ (36)–(38) reduce to $k + \vartheta(1-\sigma) = \sigma(1+i)/\alpha_K\,[(1-\alpha_K)k - \alpha_K\vartheta]$ brings forth the stated result. ■

A.4 Proof of Proposition 2

To derive the welfare costs of Foreign's unilateral permit policy, we proceed analogously as for Home's policy and use the derivatives of the indirect intertemporal utility functions. This gives as domestic welfare costs for Foreign caused by a change in $S^\star$:

$$\frac{\mathrm{d}V^\star}{\mathrm{d}S^\star} = \frac{(1+\beta)}{(w^\star-\tau^\star)} \left\{ \left[\frac{\partial(w^\star-\tau^\star)}{\partial k^\star} + \frac{s^\star}{(1+i^\star)} \frac{\partial(1+i^\star)}{\partial k^\star} \right] \frac{\mathrm{d}k^\star}{\mathrm{d}S^\star} - \left[\zeta \frac{(w^\star-\tau^\star)}{h} \right] \frac{\mathrm{d}h}{\mathrm{d}S^\star} + \right. \\ \left. + \left[\frac{\partial(w^\star-\tau^\star)}{\partial S^\star} + \frac{s^\star}{(1+i^\star)} \frac{\partial(1+i^\star)}{\partial S^\star} \right] \right\}, \quad (57)$$

and as welfare costs abroad:

$$\frac{\mathrm{d}V}{\mathrm{d}S^\star} = \frac{(1+\beta)}{(w-\tau)} \left\{ \left[\frac{\partial(w-\tau)}{\partial k} + \frac{s}{(1+i)} \frac{\partial(1+i)}{\partial k} \right] \frac{\mathrm{d}k}{\mathrm{d}S^\star} + \left[(1-\zeta) \frac{(w-\tau)}{h} \right] \frac{\mathrm{d}h}{\mathrm{d}S^\star} \right\}. \quad (58)$$

To derive (42)-(45), note that $\alpha_K = \alpha_K^*$ and $\alpha_P = \alpha_P^*$ implies that $k + \vartheta(1-\sigma) = \sigma(1+i)/(\alpha_K)\left[(1-\alpha_K)k - \alpha_K\vartheta\right]$. Furthermore, $(w-\tau) = (1-\alpha_K)/\alpha_K(1+i)k - i\,b$ and $\phi = k+b-s$ and equivalently for Foreign, $(w^\star-\tau^\star) = (1-\alpha_K)/\alpha_K(1+i)k^\star - i\,b^\star$ and $\phi^\star = -h\phi = k^\star + b^\star - s^\star$, and hence

$$\begin{aligned} \left[\frac{\partial(w-\tau)}{\partial k} + \frac{s}{(1+i)} \frac{\partial(1+i)}{\partial k} \right] &= \frac{(1-\alpha_K)}{k} \left[i(k+b) + \phi \right] \\ \left[\frac{\partial(w^\star-\tau^\star)}{\partial k^\star} + \frac{s^\star}{(1+i^\star)} \frac{\partial(1+i^\star)}{\partial k^\star} \right] &= \frac{(1-\alpha_K)}{k^\star} \left[i(k^\star+b^\star) - h\phi \right] \\ \left[\frac{\partial(w-\tau)}{\partial S} + \frac{s}{(1+i)} \frac{\partial(1+i)}{\partial S} \right] &= \frac{\alpha_P}{S} (w-\tau-b+s) \\ \left[\frac{\partial(w^\star-\tau^\star)}{\partial S^\star} + \frac{s^\star}{(1+i^\star)} \frac{\partial(1+i^\star)}{\partial S^\star} \right] &= \frac{\alpha_P}{S^\star} (w^\star-\tau^\star-b^\star+s^\star) \end{aligned}$$

To sign (42), acknowledge that $\mathrm{d}V/\mathrm{d}S > 0$ is certainly positive if $\phi > 0$ and $i \geq 0$. If $\phi < 0$ and $i = 0$ (Golden Rule), $\mathrm{d}V/\mathrm{d}S > 0$ if $\gamma\phi + \zeta k/\alpha_K > 0$. In all other cases summarized in Table 1, both positive and negative terms prevail, and thus $\mathrm{d}V/\mathrm{d}S$ is ambiguous. For the three other welfare effects, a similar argument applies, the specific conditions are summarized in Table 1. ■

A.5 Proof of Proposition 2

To derive the relative magnitude of the domestic and foreign welfare costs of a unilateral F permit policy, we proceed as in Section 4.2.

Proposition 5 *Let $\alpha_K = \alpha_K^\star$ and $\alpha_P = \alpha_P^\star$. Moreover, suppose that $1+i \geq 1$ (dynamic efficiency) and Foreign implements a unilateral permit policy. Then,*

$$\frac{\mathrm{d}V^\star}{\mathrm{d}S^\star} - \frac{\mathrm{d}V}{\mathrm{d}S^\star} = \frac{\alpha_P}{S^\star}(1+\beta)\frac{(1+i^\star)}{(w^\star-\tau^\star)}\Delta^\star \tag{59}$$

where $$\Delta^\star \equiv \gamma^\star\phi^\star\left[1+h\frac{(w^\star-\tau^\star)}{(w-\tau)}\right] + b^\star\frac{i^\star}{(1+i^\star)(1-\alpha_K)}.$$

Depending on the signs of i and ϕ, three cases emerge:

(i) *For $i \geq 0$ (dynamic efficiency) and $\phi < 0$,* $\dfrac{\mathrm{d}V^\star}{\mathrm{d}S^\star} > \dfrac{\mathrm{d}V}{\mathrm{d}S^\star}$.

(ii) *For $i = i^\star = 0$ (Golden Rule) and $\phi > 0$,* $\dfrac{\mathrm{d}V^\star}{\mathrm{d}S^\star} < \dfrac{\mathrm{d}V}{\mathrm{d}S^\star}$.

(iii) *For $i < 0$ (dynamic inefficiency), the sign of* $\dfrac{\mathrm{d}V^\star}{\mathrm{d}S^\star} - \dfrac{\mathrm{d}V}{\mathrm{d}S^\star}$ *is ambiguous.*

Proof 8 *From* (32), $\phi^\star = -\phi\, h$ *and furthermore* $h > 0$. *To derive* (59)*, we subtract* (45) *from* (44) *and utilize that* $[(1+i)(k+b) - \sigma(w-\tau)] = (1+i)\phi + \sigma i(w-\tau)$, $(w-\tau) = (1-\alpha_K)/\alpha_K(1+i)k - bi$, *and analogously for Foreign.*

Case i: Since $\phi < 0 \Longleftrightarrow \phi^\star > 0$ *and* $i >$, $\Delta^\star > 0$ *and hence* $\mathrm{d}V^\star/\mathrm{d}S^\star > \mathrm{d}V/\mathrm{d}S^\star$.

Case ii: Since $\phi > 0 \Longleftrightarrow \phi^\star < 0$ *and knowing that in the Golden Rule* $i = 0$, $\Delta^\star < 0$ *and hence* $\mathrm{d}V^\star/\mathrm{d}S^\star < \mathrm{d}V/\mathrm{d}S^\star$.

Case iii: Since $i < 0$, $\Delta^\star$ *involves positive and negative terms and hence the sign of* $\mathrm{d}V^\star/\mathrm{d}S^\star - \mathrm{d}V/\mathrm{d}S^\star$ *is ambiguous.* ■