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Unilateral Climate Policy: Harmful or even Disastrous?*

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Abstract This paper deals with possible foreign reactions to unilateral carbon demand reducing policies. It differentiates between demand side and supply side reactions as well as between intra- and intertemporal shifts in greenhouse gas emissions. In our model, we integrate a stock-dependent marginal physical cost of extracting fossil fuels into Eichner & Pethig's (2011) general equilibrium carbon leakage model. The results are as follows: Under similar but somewhat tighter conditions than those derived by Eichner & Pethig (2011), a *weak green paradox* arises. Furthermore, a *strong green paradox* can arise in our model under supplementary constraints. That means a "green" policy measure might not only lead to a harmful acceleration of fossil fuel extraction but to an increase in the cumulative climate damages at the same time. In some of these cases there is even a cumulative extraction expansion, which we consider disastrous.

Keywords Natural Resources · Carbon Leakage · Green Paradox

JEL Classification Q31 · Q32 · Q54

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1 Introduction

There is currently a lively debate in the literature on the relevance and economic significance of the so called *green paradox*, which was initially identified by Sinn (2008). The concept of this paradox was expanded on significantly by Gerlagh (2011), who distinguishes between a *weak* and a *strong green paradox*. Following him, we consider it a weak green paradox if the announcement of a "greener" policy leads to an increase of near-term emissions and consider it a strong green paradox if such policy increases the net present value of cumulative climate damages.[1] The aim of our paper is to discuss conditions for the emergence of a weak or strong green paradox in a setting we consider appropriate for the task, i. e. in a general equilibrium world market setting in which intra- and intertemporal carbon leakage as well as changes in the cumulative emissions may occur.

In relation to our model, the current literature on intra- and intertemporal carbon leakage can be grouped along several lines: They either apply partial[2] or general[3] equilibrium settings, have multiple countries and thereby allow for intratemporal leakage,[4] differ in the number of periods,[5] etc.[6] Given the focus of this paper, the emphasis is mainly on those models that differentiate between a weak and a strong form of the green paradox. As we will see, the interpretation of these terms may differ between the papers. A broader discussion of the green paradox literature and on the channels through which it might emerge is carried out by van der Werf & Di Maria (2012).

In Sinn's (2008) initial contribution he discusses the *green paradox* basically as a timing problem. He uses a one country model in continuous time and an infinite time horizon

[1]See Gerlagh (2011, 82).

[2]These are among others Fischer & Salant (2012), Fischer & Salant (2013), Harstad (2012), Hoel (2011), Hoel (2012), Hoel (2013), and Hoel & Jensen (2012).

[3]This is particularly the case for Eichner & Pethig (2011), Eichner & Pethig (2013), and van der Ploeg & Withagen (2012).

[4]Intratemporal or spatial leakage is discussed e. g. in Eichner & Pethig (2011), Eichner & Pethig (2013), Fischer & Salant (2013), Grafton et al. (2012), and Hoel (2011).

[5]Discrete or continuous, finite or infinite models.

[6]Where these groups are of course not exclusive, depending on its properties each model fits one or more of them.

to analyze the fossil fuel supply side reactions to several demand reducing policies and demonstrates that these can have adverse effects, i. e. accelerating instead of postponing global resource extraction. The phenomenon leads to an shift of the fossil fuel extraction to the present and thus to higher current greenhouse gas emissions. A precondition for this green paradox is the existence of a resource rent. As Sinn (2008) puts (reasonable) bounds on the price elasticity of demand for fossil fuel and the marginal extraction cost,[7] there is neither full depletion in finite time nor a break off of supply with stock left in situ in his model.[8] Given this structure, the movements of the extraction path are always monotonous.[9] Therefore, second best situations with intermediate acceleration but a decrease in long-run cumulative emissions do not occur.

While Sinn (2008) rightfully emphasizes the usual absence of supply side considerations in environmental policy analyses, he was of course not the first to do so. What can be considered a special case or application of the green paradox was already highlighted by Sinclair (1992). He finds that under perfect competition, with the global warming externality and costless extraction, carbon taxes should be steadily falling. The author states that the level of taxation is irrelevant and that an over time increasing carbon tax accelerates the extraction. In reply to Uplh & Ulph's (1994) critical review of the driving assumptions in Sinclair (1992), Sinclair (1994) adds the intuition that a decrease in the market interest rate postpones extraction. Two more reasons for a decreasing carbon tax over time are mentioned: One being the irreversibility of burned fossil fuel and the other the possible emergence of backstop technologies.

In reaction to Sinn's (2008) findings, several papers have tried to assess the robustness of the green paradox and evaluate conditions for its emergence. The single country (or world economy) setting is also used by Gerlagh (2011), who introduces the distinction between the *weak* and the *strong green paradox*. He considers the first to be a situation which leads to a short-run acceleration with possible medium-run deceleration and the latter to be a situation in which climate policy actually increases the net present value of cumulative climate damages.[10] Gerlagh (2011, 87) measures cumulative climate damages

[7]See Sinn (2008, 374).

[8]See Sinn (2008, 390).

[9]See Sinn (2008, 375f.).

[10]See Gerlagh (2011, 82).

by assigning a time dependent shadow price to timestamped emission quantities. We adopt this formulation to our two period setting by a lifetime damage function, dependent on near-term and cumulative emissions, which is additive to consumption utility.

The conditions for the emergence of both kinds of paradoxes in a single country economy are extensively discussed by van der Ploeg & Withagen (2012). They consider the strong green paradox a case of a *fall in green welfare*.[11] Green welfare is modeled as the reverse of the present value of discounted damages, with instantaneous damages being dependent on CO_2 stock. This is qualitatively similar to Gerlagh's (2011) net present value of cumulative climate damages.[12] They show that a stock-dependent extraction cost may reduce the set of cases where a strong green paradox arises, especially if the cost of extracting the last drop of oil is sufficiently high compared to the price of the backstop technology.[13] But even in a situation with a strong green paradox, overall welfare may increase as a result of subsidizing a green backstop.[14]

The effect of biofuel subsidies in a two country setting is analyzed by Grafton et al. (2012). They differentiate between a weak green paradox in the sense of Gerlagh (2011)[15] and a *green paradox in the long run*.[16] In line with van der Ploeg & Withagen (2012), they show that the extraction cost's sensitivity with respect to the stock level plays a crucial role in regards to the postponement of the depletion's point in time.[17]

Other ways to endogenize the cumulative emissions are: carbon capture and storage, breaking up the proportionality between extraction and emission,[18] a sufficiently high carbon tax which reduces the fossil fuel demand to zero at some finite time,[19] or "eliminating" part of the resource stock.[20]

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[11] See van der Ploeg & Withagen (2012, 343).

[12] See van der Ploeg & Withagen (2012, 345).

[13] See van der Ploeg & Withagen (2012, 348).

[14] See van der Ploeg & Withagen (2012, 353).

[15] See Grafton et al. (2012, 338).

[16] See Grafton et al. (2012, 338).

[17] See Grafton et al. (2012, 338).

[18] See e. g. Hoel & Jensen (2012).

[19] This case assumes, at least implicitly, that fossil fuel is not essential in producing consumption commodities. See e. g. Hoel (2012).

[20] This strategy is analyzed by Harstad (2012) and Hoel (2013).

While the literature on the green paradox is already very broad, none of the models that we have mentioned, nor any other model that we are aware of, analyzes the problem without neglecting at least one of the following three features. (1) Income effects resulting from redistributed revenues are neglected by partial equilibrium models. These effects result from revenues (budget losses) generated by carbon taxes or permit trading systems (backstop subsidies). It is unclear whether the additional (or reduced) consumption induced by the redistribution alters the conditions under which a mitigation policy becomes beneficial or harmful. Additionally, feedback effects arising from the interaction with other sectors of the economy, like terms-of-trade and relative price effects discussed by Di Maria & van der Werf (2008) and van der Werf & Di Maria (2012), are often neglected by partial equilibrium approaches. (2) One-country-models rule out intratemporal (spatial) carbon leakage. (3) The intertemporal general equilibrium models with multiple countries typically assume costless extraction, which implies definite full depletion of the resource stock in finite time.

Our aim is to close this gap by endogenizing cumulative emissions in Eichner & Pethig's (2011) model. Eichner & Pethig (2011) are able to assess both intra- and intertemporal carbon leakage by choosing a three-country-two-period-model[21] to analyze the effect of reducing the size of a binding emissions cap. By neglecting the cost of extraction, the sum of emissions over both periods is exogenously determined and equal to the initial stock. We will change this by introducing a stock-dependent marginal extraction cost. This extends the former key determinants for the occurrence of a green paradox, the price elasticities of demand for fossil fuel and the intertemporal elasticities of substitution in consumption, by the elasticities of supply and the user cost in real terms.

The remainder of this paper is organized as follows: Section 2 presents the basic assumptions of the model, with a focus on the extension made to Eichner & Pethig (2011), and derives an initial market equilibrium. In Section 3 we analyze the effects of the tightening of an emissions cap in the present (period one), while Section 4 presents the results of an emission reduction in the future (period two). As our paper draws heavily on Eichner & Pethig's (2011) model, we occasionally remark how and where our model and results are distinct from their analysis. Section 5 discusses the results and concludes.

[21] Fossil fuel supply side ($i = F$), abating fossil fuel demand side ($i = A$), non-abating fossil fuel demand side ($i = N$), time up to the medium term ($t = 1$), and time up to the very long term ($t = 2$).

2 The Model

The basic structure of the model follows that of Eichner & Pethig (2011). We adopt their setting with three countries $i = A, F, N$ and two periods $t = 1, 2$. Specifically, the world consists of the fossil fuel exporter F, the emissions abating country A, and the non-abating country N.[22]

In order to integrate the idea of the strong green paradox into Eichner & Pethig's (2011) model, we modify the assumptions regarding the fossil fuel supply. To be concrete, we introduce material cost functions (see equation (1) and equation (2)).[23] We consider the marginal material extraction cost to be negatively correlated with remaining stock. Formally, we assume that in each period the marginal physical cost is positive and increases with that period's extraction (see equation (3)). Furthermore, the physical cost in the second period increases disproportionately with the first period's extraction; the physical user cost is positive and increases with each period's extraction (see equation (4)). For a given cumulative extraction, we assume that the total physical cost measured in commodity units is the higher the less balanced the extraction path is (see equation (5)).[24] Formally, this can be represented as follows:

$$x_{E1} = X^{E1}(e_{F1}), \tag{1}$$

$$x_{E2} = X^{E2}(e_{F1}, e_{F2}), \tag{2}$$

$$X^{Et}_{e_{Ft}} > 0,\ X^{Et}_{e_{Ft}e_{Ft}} > 0, \tag{3}$$

$$X^{E2}_{e_{F1}} > 0,\ X^{E2}_{e_{F1}e_{F1}} > 0,\ X^{E2}_{e_{F1}e_{F2}} = X^{E2}_{e_{F2}e_{F1}} > 0, \tag{4}$$

$$\left(X^{E2}_{e_{F1}e_{F1}} + \frac{p_{x1}}{p_{x2}} X^{E1}_{e_{F1}e_{F1}} \right) \cdot X^{E2}_{e_{F2}e_{F2}} > X^{E2}_{e_{F1}e_{F2}} \cdot X^{E2}_{e_{F2}e_{F1}}, \tag{5}$$

where x_{Et} is the commodity demand of the firm in country F in period t, X^{Et} is the material cost function of the firm in country F in period t, e_{Ft} is the fossil fuel supply

[22] To assure traceability, we try to follow Eichner & Pethig's (2011) nomenclature wherever this is appropriate. This includes terming the only available policy, namely tightening an emissions cap, as "abatement", although there is no actual abatement technology or the like in the model.

[23] These "material cost" functions can also be interpreted as "inverse production" or rather "extraction" functions. In each period, their outputs were then actual extraction quantity while their inputs were "material good" (the unique commodity of the world economy) and "current resource stock" (better tapping possibilities).

[24] $X^{E2}(e_{F1}, e_{F2})$ being strictly convex is a sufficient condition for this to hold.

in period t, $X^{Et}_{e_{Ft}}$ is the marginal physical cost of the firm in country F in period t, $X^{E2}_{e_{F1}}$ is the physical user cost of the firm in country F,[25] and p_{xt} is the commodity price in period t.

There is a representative price taking (on its input and output markets) resource extractor in the fossil fuel exporting country. As in Eichner & Pethig (2011), the market rate of interest is normalized to zero. The firm has a profit function based on the prior considerations (see equation (6)) which is maximized with respect to present and future fossil fuel supply (see equation (7) and equation (8)). The perfectly competitive fossil fuel world market has to be cleared in each period (see equation (9)). The cumulative emissions are endogenously determined (see equation (10)). Formally, this can be represented as follows:

$$\Pi^F := \sum_t [p_{et}e_{Ft} - p_{xt}X^{Et}(e_{F1}, e_{F2})], \tag{6}$$

$$p_{e1} = p_{x1}X^{E1}_{e_{F1}} + p_{x2}X^{E2}_{e_{F1}}, \tag{7}$$

$$p_{e2} = p_{x2}X^{E2}_{e_{F2}}, \tag{8}$$

$$e_{Ft} = e_{At} + e_{Nt}, \tag{9}$$

$$e_{F\Sigma} = e_{F1} + e_{F2}, \tag{10}$$

where Π^F is the profit function of the firm in country F, p_{et} is the fossil fuel price in period t, e_{it} is the fossil fuel demand of the firm in $i = A, N$ in period t, and $e_{F\Sigma}$ is the endogenously determined cumulative fossil fuel extraction.

As the aim of this paper is to analyze changes in the timing of emissions and the quantity of cumulative emissions, we limit our analysis to cases in which the cumulative extraction is strictly less than the world's physical fossil fuel stock. This means we implicitly assume that the intratemporal marginal extraction cost rises faster when the remaining stock reaches depletion, than marginal production rises when resource input falls to zero.

In what follows, the elasticities of supply for fossil fuel play an important role. Formally, these can be represented as follows:

$$\eta_{F1,1} = \frac{p_{x1}X^{E1}_{e_{F1}} + p_{x2}X^{E2}_{e_{F1}}}{p_{x1}e_{F1}X^{E1}_{e_{F1}e_{F1}} + p_{x2}e_{F1}X^{E2}_{e_{F1}e_{F1}}}, \tag{11}$$

[25] Since we only consider interior solutions in which the resource stock is not fully depleted, this intertemporal cross effect is the key dynamic of the model.

$$\eta_{F2,1} = \frac{p_{x1}X^{E1}_{e_{F1}} + p_{x2}X^{E2}_{e_{F1}}}{p_{x2}e_{F2}X^{E2}_{e_{F1}e_{F2}}}, \quad (12)$$

$$\eta_{F1,2} = \frac{p_{x2}X^{E2}_{e_{F2}}}{p_{x2}e_{F1}X^{E2}_{e_{F2}e_{F1}}}, \quad (13)$$

$$\eta_{F2,2} = \frac{p_{x2}X^{E2}_{e_{F2}}}{p_{x2}e_{F2}X^{E2}_{e_{F2}e_{F2}}}, \quad (14)$$

where $\eta_{Fs,t} := \frac{\mathrm{d}e_{Fs}}{\mathrm{d}p_{et}} \cdot \frac{p_{et}}{e_{Fs}} > 0$ is for $s \neq t$ the intertemporal and for $s = t$ the intratemporal price elasticity of supply for fossil fuel of the firm in country F in period s.

The policy tools we analyze in the subsequent sections are marginal changes in the emissions cap of the abating country today and tomorrow. We only discuss situations in which an emissions trading scheme exists (in period one) and is assumed to persist (in period two), like e. g. the *European Union Emission Trading Scheme*. Formally, this represents as follows:

$$e_{A1} = \overline{e}_{A1} \quad \text{and} \quad e_{A2} = \overline{e}_{A2}, \quad (15)$$

where $\overline{e}_{At}$ is the exogenously given (politically determined) fossil fuel demand of the firm in country A in period t.

Apart from the existence of the emissions cap, the fossil fuel demanding countries are considered to be symmetric. There are representative price taking (on its input and output markets) commodity producers with identical production functions in each country and period. These functions are increasing and strictly concave in fossil fuel demand (see equation (16) and equation (17)). A permit price has to be paid for each unit of fossil fuel consumed in the abating country in each period. Each firm has a profit function based on the above considerations (see equation (18) and equation (19)) which is maximized with respect to present and future commodity consumption (see equation (20) and equation (21)). The perfectly competitive commodity world market has to be cleared in each period (see equation (22)). Formally, this can be represented as follows:

$$x^s_{At} = X^{At}(\overline{e}_{At}), \quad (16)$$

$$x^s_{Nt} = X^{Nt}(e_{Nt}), \quad (17)$$

$$\Pi^A := \sum_t [p_{xt}X^{At}(\overline{e}_{At}) - (p_{et} + \pi_t)\overline{e}_{At}], \quad (18)$$

$$\Pi^N := \sum_t [p_{xt}X^{Nt}(e_{Nt}) - p_{et}e_{Nt}], \quad (19)$$

$$\pi_1 = p_{x1}X^{A1}_{\overline{e}_{A1}} - p_{e1} \geq 0 \quad \text{and} \quad \pi_2 = p_{x2}X^{A2}_{\overline{e}_{A2}} - p_{e2} \geq 0, \quad (20)$$

$$p_{x1}X^{N1}_{e_{N1}} = p_{e1} \quad \text{and} \quad p_{x2}X^{N2}_{e_{N2}} = p_{e2}, \tag{21}$$

$$x^s_{At} + x^s_{Nt} = x_{At} + x_{Nt} + x_{Ft} + x_{Et}, \tag{22}$$

where x^s_{it} is the commodity supply of the firm in $i = A, N$ in period t, $X^i(e_{it})$ is the production function of the firm in $i = A, N$ in period t, Π^i is the profit function of the firm in $i = A, N$, π_t is the permit price in period t, $X^i_{e_{it}}$ is the marginal physical product of the firm in $i = A, N$ in period t, and x_{it} is the commodity demand of the households in $i = A, F, N$ and the resource extractor E in period t.

In contrast to Eichner & Pethig's (2011) model,[26] in our model the initial equilibrium on the fossil fuel market is characterized by the fossil fuel prices being determined by the demand side's and the supply side's optimality conditions and an extraction of all fossil fuel *reserves*,[27] meaning those fossil fuel resources which are worthwhile extracting given their extraction cost.

The model is closed by the commodity demand of the households. There are representative lifetime utility maximizing households with identical lifetime utility functions in each country (see equation (23)). Lifetime utility is considered to be increasing, quasi-concave, and homothetic in present and future commodity consumption. In each country, the lifetime income, consisting of the maximized profit of the firm and the permit revenues in the case of the abating fossil fuel demand side, is considered as lump sum and used to finance lifetime consumption (see equation (24)). The straightforward analytical result is that each intertemporal marginal rate of substitution has to be equal to the intertemporal price ratio in equilibrium (see equation (25)). Formally, this represents as follows:

$$u_i = U(x_{i1}, x_{i2}), \qquad i = A, F, N, \tag{23}$$

$$\sum_t p_{xt}x_{it} = \begin{cases} = \Pi^{A*} + \pi_1\overline{e}_{A1} + \pi_2\overline{e}_{A2} \\ = \Pi^{i*} \end{cases}, \quad i = F, N, \tag{24}$$

[26] Where the initial equilibrium on the fossil fuel market is characterized by a determination of the intertemporal fossil fuel price by the demand side's optimality conditions and an extraction of all fossil fuel resources.

[27] "Reserves are those quantities of hydrocarbons which are anticipated to be commercially recovered from known accumulations from a given date forward" (Society of Petroleum Engineers 2005, 11).

$$\frac{U_{x_{i1}}}{U_{x_{i2}}} = \frac{p_{x1}}{p_{x2}}, \qquad i = A, F, N, \tag{25}$$

where u_i is the lifetime utility of the households, $U(x_{i1}, x_{i2})$ is its lifetime utility function, Π^{i*} is the maximized profit of the firm in $i = A, F, N$, and $U_{x_{it}}$ is the marginal utility of the households in period t.

To better understand the relationship between changes in commodity prices and commodity demands induced by tightening the emissions caps, we limit our analysis to lifetime utility functions with constant intertemporal elasticities of substitution (see equation (26)). Applying them in the optimality conditions (see equation (25)), the relative commodity demand of the households can be derived (see equation (27)). Formally, this represents as follows:

$$U(x_{i1}, x_{i2}) = (\alpha_1 x_{i1}^{-b} + \alpha_2 x_{i2}^{-b})^{-\frac{h}{b}}, \quad i = A, F, N, \tag{26}$$

$$\frac{x_{i1}}{x_{i2}} = \left(\frac{\alpha_2 p_{x1}}{\alpha_1 p_{x2}}\right)^{\sigma}, \qquad i = A, F, N, \tag{27}$$

where $\sigma := 1/(-b-1)$ is the intertemporal elasticity of substitution.

In order to derive conditions under which the strong green paradox occurs due to a "green" policy, we weight changes of present and cumulative emissions with the following climate damage function:

$$D(e_{F1}, e_{F\Sigma}) = \left(c_1 e_{F1}^d + c_2 e_{F\Sigma}^d\right)^{\frac{\iota}{d}}, \tag{28}$$

$$\mathrm{d}D(e_{F1}, e_{F\Sigma}) \gtreqless 0 \quad \Leftrightarrow \quad \mathrm{d}e_{F1} + \lambda\, \mathrm{d}e_{F\Sigma} \gtreqless 0, \tag{29}$$

where $\lambda := \frac{c_2}{c_1} \cdot \left(\frac{e_{F\Sigma}}{e_{F1}}\right)^{d-1} > 0$ is the relative weight attached to changes in cumulative emissions.

3 Acting Today

Tightening the cap in the first period ($\mathrm{d}\bar{e}_{A1} < 0$) causes carbon leakage ($\mathrm{d}e_{N1}/\,\mathrm{d}\bar{e}_{A1} < 0$) and can even lead to the weak green paradox ($\mathrm{d}e_{F1}/\,\mathrm{d}\bar{e}_{A1} < 0$). A cumulative extraction expansion ($\mathrm{d}e_{F\Sigma}/\,\mathrm{d}\bar{e}_{A1} < 0$) and the strong green paradox ($\mathrm{d}D/\,\mathrm{d}\bar{e}_{A1} < 0$) can emerge, depending on the occurrence of the weak green paradox. The solution strategy for the comparative statics in both periods is as follows: We start with analyzing the changes on the fossil fuel market, proceed with observing the effects on the commodity market, and close by combining our results.[28] On the former market, tightening the cap in the first period has an impact on the fossil fuel extraction in period one:[29]

$$\mathrm{d}e_{F1} = \underbrace{\mathrm{d}\bar{e}_{A1}}_{[1]} - \underbrace{\frac{\Gamma_0 - p_{e1}[p_{e2} + X^{E2}_{e_{F2}e_{F2}} e_{N2}|\eta_{N2}|]}{\Gamma_0}}_{[2]} \mathrm{d}\bar{e}_{A1} - \underbrace{\frac{X^{E2}_{e_{F1}} e_{N1}|\eta_{N1}|\,[p_{e2} + X^{E2}_{e_{F2}e_{F2}} e_{N2}|\eta_{N2}|]}{\Gamma_0}}_{[3]} \mathrm{d}p_{x2} \tag{30a}$$

$$= \frac{p_{e1}[p_{e2} + X^{E2}_{e_{F2}e_{F2}} e_{N2}|\eta_{N2}|]}{\Gamma_0} \mathrm{d}\bar{e}_{A1} - \frac{X^{E2}_{e_{F1}} e_{N1}|\eta_{N1}|\,[p_{e2} + X^{E2}_{e_{F2}e_{F2}} e_{N2}|\eta_{N2}|]}{\Gamma_0} \mathrm{d}p_{x2}, \tag{30b}$$

where $\Gamma_0 = \frac{p_{e2}e_{N2}|\eta_{N2}|p_{e1}e_{N1}|\eta_{N1}|}{e_{F1}\eta_{F1,2}e_{F2}\eta_{F2,1}} \cdot \left[\left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}}\right) \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}}\right) - 1\right] > 0$ and $\eta_{Nt} := \frac{X^{Nt}_{e_{Nt}}}{e_{Nt}X^{Nt}_{e_{Nt}e_{Nt}}} < 0$ is the price elasticity of demand for fossil fuel of the firm in country N in period t.

Proposition 1. *If (26) holds and the abating country A tightens its emissions cap* ($\mathrm{d}\bar{e}_{A1} < 0$),

- *the commodity price in period two falls* ($\mathrm{d}p_{x2} < 0$),
- *the emissions in the first period either decline by less than* $\mathrm{d}\bar{e}_{A1}$ $\left(\frac{\mathrm{d}e_{F1}}{\mathrm{d}\bar{e}_{A1}} \in]0,1[\right)$ *or they increase* $\left(\frac{\mathrm{d}e_{F1}}{\mathrm{d}\bar{e}_{A1}} < 0\right)$,
- *and the present fossil fuel price falls* ($\mathrm{d}p_{e1} < 0$).

Proof. See appendix A.3, equation (A.36); appendix A.3, equation (A.28); appendix A.3, equation (A.38). ■

It can be shown that the commodity price in period two decreases relative to the commodity price in period one ($\mathrm{d}p_{x2} < 0$). The intuition is that due to the demand reduction of the abating country, fossil fuel and thus the commodity which is produced using fossil fuel becomes scarcer in the first period. This means that the demand for and the supply of the commodity fall apart, resulting in a higher present and a lower future commodity price. Therefore, the commodity producer in the non-abating country shifts his commodity supply and thus his fossil fuel demand from the second to the first period.

Furthermore, it can be shown that the present fossil fuel price decreases ($\mathrm{d}p_{e1} < 0$). On the one hand, the demand for fossil fuel in period one declines (caused by $\mathrm{d}\bar{e}_{A1} < 0$). On the other hand, its supply decreases if and only if the potential rise in the physical user cost outweighs the fall in the commodity price in period two (if and only if $\mathrm{d}\left(p_{x2}X^{E2}_{e_{F1}}\right) > 0$).

[28]This method is also adopted from Eichner & Pethig (2011).

[29]See appendix A.1, equation (A.19). Throughout the rest of the article the commodity in period one is chosen as numeraire.

Nevertheless, the demand reduction is always greater than the potential supply reduction. Whether the future fossil fuel price increases or decreases is ambiguous ($\mathrm{d}p_{e2} \gtreqless 0$). On the one hand, the demand for fossil fuel in period two declines (caused by $\mathrm{d}p_{x2} < 0$). On the other hand, its supply increases if and only if the fall in the commodity price outweighs the potential rise in the marginal physical cost in period two (if and only if $\mathrm{d}\left(p_{x2}X^{E2}_{e_{F2}}\right) < 0$).

In conclusion, the demand reduction of the abating country in the first period (term [1] of equation (30a)) is accompanied by two effects, which counteract its effectiveness.

Firstly, there is a carbon price effect equal to term [2] of equation (30a). This reflects the fossil fuel demand increase of the firm in the non-abating country due to the fall in the fossil fuel price in period one. The carbon price effect causes positive carbon leakage ([2] > 0) but cannot cause the weak green paradox on its own ([2] < 1).

Secondly, there is a relative price effect of carbon intensive goods equal to term [3] of equation (30a). This reflects the relative fossil fuel demand decrease of the firm in the non-abating country due to the fall in the relative price of the commodity in period two. In conjunction with the carbon price effect the relative price effect of carbon intensive goods can cause the weak green paradox. The impact on the cumulative extraction can be represented as follows:[30]

$$\mathrm{d}e_{F\Sigma} = \frac{p_{e1}\Gamma_1}{\Gamma_0}\,\mathrm{d}\bar{e}_{A1} - \frac{X^{E2}_{e_{F1}} e_{N1}|\eta_{N1}|\,\Gamma_1}{\Gamma_0}\,\mathrm{d}p_{x2}, \tag{31}$$

where $\Gamma_1 = \frac{p_{e2}e_{N2}|\eta_{N2}|}{e_{F1}\eta_{F1,2}} \cdot \left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}} - 1\right)$.

Proposition 2. *If (26) holds and the abating country A tightens its emissions cap ($\mathrm{d}\bar{e}_{A1} < 0$), the cumulative emissions either decline by less than $\mathrm{d}\bar{e}_{A1}$ $\left(\frac{\mathrm{d}e_{F\Sigma}}{\mathrm{d}\bar{e}_{A1}} \in]0,1[\right)$ or they increase $\left(\frac{\mathrm{d}e_{F\Sigma}}{\mathrm{d}\bar{e}_{A1}} < 0\right)$ if $\Gamma_1 \geq 0$.*

Proof. The second term of (31) is greater than or equal to zero if $\Gamma_1 \geq 0$ since $\mathrm{d}p_{x2} < 0$. The first term of (31) is greater than minus one since

$$\begin{aligned} p_{e1}\Gamma_1 =& \frac{p_{e2}e_{N2}|\eta_{N2}|}{e_{F1}\eta_{F1,2}} \cdot \left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}} - 1\right) \cdot p_{e1} \\ < \Gamma_0 =& \frac{p_{e2}e_{N2}|\eta_{N2}|\,p_{e1}e_{N1}|\eta_{N1}|}{e_{F1}\eta_{F1,2}e_{F2}\eta_{F2,1}} \cdot \left[\left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}}\right) \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}}\right) - 1\right] \end{aligned}$$

[30] See appendix A.1, equation (A.21).

$$\Leftrightarrow 0 < \frac{p_{e2} e_{N2}|\eta_{N2}|\, p_{e1} e_{N1}|\eta_{N1}|}{e_{F1}\eta_{F1,2} e_{F2}\eta_{F2,1}} \cdot \left[\underbrace{\left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}} \right) \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}} \right)}_{>1} + \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} \right) - 1 \right].$$

Therefore, $\mathrm{d}e_{F\Sigma}$ is greater than $\mathrm{d}\bar{e}_{A1}$ if $\Gamma_1 \geq 0$. ∎

It can be shown that the cumulative emissions will not decline by more than $\mathrm{d}\bar{e}_{A1}$ if the reciprocal of the intertemporal price semi-elasticity of supply for fossil fuel in period one $\left(\frac{1}{e_{F1}\eta_{F1,2}}\right)$ is less than the sum of the reciprocals of the intratemporal price semi-elasticities of demand and supply for fossil fuel in period two $\left(\frac{1}{e_{N2}|\eta_{N2}|} + \frac{1}{e_{F2}\eta_{F2,2}}\right)$ (if $\Gamma_1 > 0$).[31] On the contrary, in this case they will increase if the positive effect due to the fall in the commodity price in period two outweighs the negative effect due to the tightening of the emissions cap $\left(\left|\frac{\mathrm{d}p_{x2}}{\mathrm{d}\bar{e}_{A1}}\right| > \frac{p_{e1}}{X^{E2}_{e_{F1}} e_{N1}|\eta_{N1}|}\right)$.

Whether the weak and the strong green paradox occur or not depends on the change in the future commodity price ($\mathrm{d}p_{x2}$). In order to derive the change in the future commodity price following the demand reductions and the changes in fossil fuel supply ($\mathrm{d}p_{x2}(\mathrm{d}\bar{e}_{A1}, \mathrm{d}\bar{e}_{A2}, \mathrm{d}e_{F1}, \mathrm{d}e_{F2})$), the commodity market is now taken into account. The resulting changes do not only depend on the households' preferences, but also on the resource owner's material cost function. It can be shown that the relative change in the future commodity price depends: on the intertemporal elasticity of substitution, the permit prices, the future commodity price, the commodity demand of the households, the physical user cost, the demand reductions, and the change in the present fossil fuel supply. Formally, this can be represented as follows:[32]

$$\mathrm{d}p_{x2} = \frac{p_{x2}}{\sigma} \left(\frac{\pi_1}{x^s_{A1} + x^s_{N1} - x_{E1}} \mathrm{d}\bar{e}_{A1} - \frac{\pi_2}{p_{x2}(x^s_{A2} + x^s_{N2} - x_{E2})} \mathrm{d}\bar{e}_{A2} + \Theta\, \mathrm{d}e_{F1} \right), \qquad (32)$$

where $\Theta = \frac{p_{x2} X^{E2}_{e_{F1}}}{x^s_{A1} + x^s_{N1} - x_{E1}} + \frac{p_{x2} X^{E2}_{e_{F1}}}{p_{x2}(x^s_{A2} + x^s_{N2} - x_{E2})}$.

Finally, combining the results from the fossil fuel market with the results from the commodity market (for $\mathrm{d}\bar{e}_{A2} = 0$), the change in fossil fuel supply in the first period ($\mathrm{d}e_{F1}/\,\mathrm{d}\bar{e}_{A1}$), the change in fossil fuel supply in the second period ($\mathrm{d}e_{F2}/\,\mathrm{d}\bar{e}_{A1}$), the change in the cumulative extraction ($\mathrm{d}e_{F\Sigma}/\,\mathrm{d}\bar{e}_{A1}$), and the change in the cumulative climate

[31] These terms are semi-elasticities in the following sense: They measure absolute changes in quantities in relation to relative changes in prices.

[32] See appendix A.2, equation (A.27).

damages ($\mathrm{d}D/\mathrm{d}\overline{e}_{A1}$) with respect to the demand reduction in the present can be deduced and analyzed for algebraic signs.[33]

Thereby, conditions for the occurrence of the weak ($\mathrm{d}e_{F1}/\mathrm{d}\overline{e}_{A1} < 0$) and the strong green paradox ($\mathrm{d}D/\mathrm{d}\overline{e}_{A1} < 0$) in response to tightening the emissions cap in the first period can be simplified to the following inequalities:

$$\frac{\mathrm{d}e_{F1}}{\mathrm{d}\overline{e}_{A1}} \gtreqless 0 \quad \Leftrightarrow \quad \sigma \gtreqless \overline{\sigma} = \frac{p_{x2} X^{E2}_{e_{F1}}}{p_{e1}} \cdot \frac{\pi_1 e_{N1} |\eta_{N1}|}{x^s_{A1} + x^s_{N1} - x_{E1}}, \tag{33}$$

$$\frac{\mathrm{d}D}{\mathrm{d}\overline{e}_{A1}} \gtreqless 0 \quad \Leftrightarrow \quad \sigma \begin{cases} \gtreqless \overline{\sigma} = \frac{p_{x2} X^{E2}_{e_{F1}}}{p_{e1}} \cdot \frac{\pi_1 e_{N1} |\eta_{N1}|}{x^s_{A1} + x^s_{N1} - x_{E1}} & \text{if} \quad \Gamma^D_1 > 0 \\ \lesseqgtr \overline{\sigma} = \frac{p_{x2} X^{E2}_{e_{F1}}}{p_{e1}} \cdot \frac{\pi_1 e_{N1} |\eta_{N1}|}{x^s_{A1} + x^s_{N1} - x_{E1}} & \text{if} \quad \Gamma^D_1 < 0 \end{cases}, \tag{34}$$

where $\Gamma^D_1 = \frac{p_{e2} e_{N2} |\eta_{N2}|}{e_{F1} \eta_{F1,2}} \cdot \left(\frac{1+\lambda}{\lambda} \cdot \frac{e_{F1} \eta_{F1,2}}{e_{N2} |\eta_{N2}|} + \frac{1+\lambda}{\lambda} \cdot \frac{e_{F1} \eta_{F1,2}}{e_{F2} \eta_{F2,2}} - 1 \right) > \Gamma_1$.

From equation (33) and (34) we infer the following proposition:

Proposition 3. *If* (26) *holds and the abating country A tightens its emissions cap* ($\mathrm{d}\overline{e}_{A1} < 0$)*, the weak and the strong green paradox occur under the following conditions:*

	$\mathrm{d}e_{F1} > 0$	$\mathrm{d}e_{F1} < 0$
$\mathrm{d}D > 0$	$\sigma < \overline{\sigma}$ *and* $\Gamma^D_1 > 0$	$\sigma > \overline{\sigma}$ *and* $\Gamma^D_1 < 0$
$\mathrm{d}D < 0$	$\sigma < \overline{\sigma}$ *and* $\Gamma^D_1 < 0$	$\sigma > \overline{\sigma}$ *and* $\Gamma^D_1 > 0$

Our condition for the occurrence of the weak green paradox is stronger but closely related to Eichner & Pethig's (2011). With the marginal extraction cost, the physical user cost in real terms complement the equation ($p_{x2} X^{E2}_{e_{F1}}/p_{e1} < 1$). The inequality sign and the rest of the condition are the same as in Eichner & Pethig's (2011) model. If the elasticity of demand and the intratemporal (intertemporal) elasticity of supply for fossil fuel in the second (first) period are relatively small (large) and if the relative weight attached to changes in cumulative emissions is relatively small (if $\Gamma^D_1 > 0$), the occurrence of the weak will coincide with the occurrence of the strong green paradox (first and forth quadrant of the matrix). Otherwise, the cumulative climate damages will either change contrarily to the emissions in the first period (if $\Gamma^D_1 < 0$, second and third quadrant of the matrix) or remain unaltered (if $\Gamma^D_1 = 0$). Present and cumulative emissions will increase simultaneously if and only if $\sigma < \overline{\sigma}$ and $\Gamma_1 > 0$.[34]

[33] See appendix A.3, equations (A.28), (A.29), (A.30), and (A.31).

[34] See equation (33) and appendix A.3, equation (A.30).

4 Acting Tomorrow

In what follows, the effects of a change in the future emissions cap are analyzed. This action is announced credibly today and thus influences consumption and production decisions in the first period. Analogously to the demand reduction in the present, tightening the cap in the second period ($\mathrm{d}\overline{e}_{A2} < 0$) can cause carbon leakage ($\mathrm{d}e_{N1}/\,\mathrm{d}\overline{e}_{A2} < 0$) and can even lead to the weak green paradox ($\mathrm{d}e_{F1}/\,\mathrm{d}\overline{e}_{A2} < 0$). Contrary to the analysis in the previous section, there can be negative cumulative carbon leakage ($\mathrm{d}e_{F\Sigma}/\,\mathrm{d}\overline{e}_{A2} > 1$). A cumulative extraction expansion ($\mathrm{d}e_{F\Sigma}/\,\mathrm{d}\overline{e}_{A2} < 0$) and the strong green paradox ($\mathrm{d}D/\,\mathrm{d}\overline{e}_{A2} < 0$) can still emerge, but no longer depends on the occurrence of the weak green paradox. We start again by analyzing the changes on the fossil fuel market. Tightening the cap in the second period has an impact on the fossil fuel extraction in period one:[35]

$$\mathrm{d}e_{F1} = -\underbrace{\mathrm{d}\overline{e}_{A2}}_{[1]} + \underbrace{\frac{\Gamma_0 - p_{e2}p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}|\eta_{N1}|}{\Gamma_0}}_{[2]}\mathrm{d}\overline{e}_{A2} - \underbrace{\frac{X^{E2}_{e_{F1}}e_{N1}|\eta_{N1}|\left[p_{e2} + X^{E2}_{e_{F2}e_{F2}}e_{N2}|\eta_{N2}|\right]}{\Gamma_0}}_{[3]}\mathrm{d}p_{x2} \tag{35a}$$

$$= -\frac{p_{e2}p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}|\eta_{N1}|}{\Gamma_0}\mathrm{d}\overline{e}_{A2} - \frac{X^{E2}_{e_{F1}}e_{N1}|\eta_{N1}|\left[p_{e2} + X^{E2}_{e_{F2}e_{F2}}e_{N2}|\eta_{N2}|\right]}{\Gamma_0}\mathrm{d}p_{x2}. \tag{35b}$$

PROPOSITION 4. *If* (26) *holds and the abating country A tightens its emissions cap* ($\mathrm{d}\overline{e}_{A2} < 0$),

- *the commodity price in period two rises* ($\mathrm{d}p_{x2} > 0$),
- *and the weak green paradox occurs* $\left(\frac{\mathrm{d}e_{F1}}{\mathrm{d}\overline{e}_{A2}} < 0\right)$ *if and only if the present fossil fuel price falls* ($\mathrm{d}p_{e1} < 0$).

PROOF. See appendix A.3, equation (A.37); appendix A.3, equation (A.32) and (A.40).

■

It can be shown that the commodity price in period two increases relative to the commodity price in period one ($\mathrm{d}p_{x2} > 0$). The intuition is the same as in the previous section. Therefore, the commodity producer in the non-abating country shifts his commodity supply and thus his fossil fuel demand from the first to the second period.

Furthermore, it can be shown that the weak green paradox occurs if and only if the present fossil fuel price decreases ($\mathrm{d}e_{F1}/\,\mathrm{d}p_{e1} < 0$). With given demand for fossil fuel in period one, its supply thus has to increase. This is the case if and only if the potential

[35]See appendix A.1, equation (A.19).

fall in the physical user cost outweighs the rise in the commodity price in period two (if and only if $\mathrm{d}\left(p_{x2} X_{e_{F1}}^{E2}\right) < 0$). Whether the future fossil fuel price increases or decreases is ambiguous ($\mathrm{d}p_{e2} \gtreqless 0$). On the one hand, the demand for fossil fuel in the abating country in period two declines (caused by $\mathrm{d}\bar{e}_{A2} < 0$). On the other hand, the demand for fossil fuel in the non-abating country in period two rises (caused by $\mathrm{d}p_{x2} > 0$). Furthermore, its supply increases if and only if the potential fall in the marginal physical cost outweighs the rise in the commodity price in period two (if and only if $\mathrm{d}\left(p_{x2} X_{e_{F2}}^{E2}\right) < 0$).

Analogously to the previous section, the demand reduction of the abating country in the second period (term [1] of equation (35a)) is accompanied by two effects, which counteract its effectiveness in regards to increasing present emissions.

Firstly, there is a carbon price effect equal to term [2] of equation (35a). The carbon price effect causes negative carbon leakage ([2] > 0) but cannot prevent the weak green paradox on its own ([2] < 1).

Secondly, there is a relative price effect of carbon intensive goods equal to term [3] of equation (35a). In conjunction with the carbon price effect the relative price effect of carbon intensive goods can prevent the weak green paradox. The impact on the cumulative extraction can be represented as follows:[36]

$$\mathrm{d}e_{F\Sigma} = \frac{p_{e2}\Gamma_2}{\Gamma_0}\,\mathrm{d}\bar{e}_{A2} - \frac{X_{e_{F1}}^{E2} e_{N1}|\eta_{N1}|\,\Gamma_1}{\Gamma_0}\,\mathrm{d}p_{x2}, \tag{36}$$

where $\Gamma_2 = \frac{p_{e1} e_{N1}|\eta_{N1}|}{e_{F2}\eta_{F2,1}} \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}} - 1\right)$.

Proposition 5. *If* (26) *holds and the abating country A tightens its emissions cap* ($\mathrm{d}\bar{e}_{A2} < 0$)*, the cumulative emissions*

- *either decline by less than* $\mathrm{d}\bar{e}_{A2}$ $\left(\frac{\mathrm{d}e_{F\Sigma}}{\mathrm{d}\bar{e}_{A2}} \in]0,1[\right)$ *or they increase* $\left(\frac{\mathrm{d}e_{F\Sigma}}{\mathrm{d}\bar{e}_{A2}} < 0\right)$ *if* $\Gamma_1 \leq 0$,
- *and they decline* $\left(\frac{\mathrm{d}e_{F\Sigma}}{\mathrm{d}\bar{e}_{A2}} > 0\right)$ *if* $\Gamma_1 > 0$ *and* $\Gamma_2 \geq 0$.

Proof. The second term of (36) is greater than or equal to zero if $\Gamma_1 \leq 0$ since $\mathrm{d}p_{x2} > 0$. The first term of (36) is greater than minus one since

$$\begin{aligned} p_{e2}\Gamma_2 =& \frac{p_{e1} e_{N1}|\eta_{N1}|}{e_{F2}\eta_{F2,1}} \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}} - 1\right) \cdot p_{e2} \\ < \Gamma_0 =& \frac{p_{e2} e_{N2}|\eta_{N2}|\, p_{e1} e_{N1}|\eta_{N1}|}{e_{F1}\eta_{F1,2} e_{F2}\eta_{F2,1}} \cdot \left[\left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}}\right) \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}}\right) - 1\right] \end{aligned}$$

[36] See appendix A.1, equation (A.21).

$$\Leftrightarrow 0 < \frac{p_{e2}e_{N2}|\eta_{N2}|\, p_{e1}e_{N1}|\eta_{N1}|}{e_{F1}\eta_{F1,2}e_{F2}\eta_{F2,1}} \cdot \left[\underbrace{\left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}} \right) \cdot \left(\frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}} \right)}_{>1} + \left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} \right) - 1 \right].$$

Therefore, $\mathrm{d}e_{F\Sigma}$ is greater than $\mathrm{d}\overline{e}_{A2}$ if $\Gamma_1 \leq 0$.
The second term of (36) is less than zero if $\Gamma_1 > 0$ since $\mathrm{d}p_{x2} > 0$. The first term of (36) is less than or equal to zero if $\Gamma_2 \geq 0$. Therefore, $\mathrm{d}e_{F\Sigma}$ is less than zero if $\Gamma_1 > 0$ and $\Gamma_2 \geq 0$.

■

It can be shown that the cumulative emissions will not decline by more than $\mathrm{d}\overline{e}_{A2}$ if Γ_1 is less than zero. On the contrary, in this case they will increase if either the reciprocal of the intertemporal price semi-elasticity of supply for fossil fuel in period two $\left(\frac{1}{e_{F2}\eta_{F2,1}}\right)$ is greater than or equal to the sum of the reciprocals of the intratemporal price semi-elasticities of demand and supply for fossil fuel in period one $\left(\frac{1}{e_{N1}|\eta_{N1}|} + \frac{1}{e_{F1}\eta_{F1,1}}\right)$ (if $\Gamma_2 \leq 0$) or Γ_2 is greater than zero and the positive effect due to the tightening of the emissions cap outweighs the negative effect due to the rise in the commodity price in period two $\left(\left| \frac{\mathrm{d}p_{x2}}{\mathrm{d}\overline{e}_{A1}} \right| < \left| \frac{\Gamma_2}{\Gamma_1} \right| \frac{p_{e2}}{X^{E2}_{e_{F1}} e_{N1}|\eta_{N1}|} \right)$. Furthermore, the cumulative emissions will not increase if Γ_1 and Γ_2 are greater than or equal to zero.

Analogously to the analysis in the previous section, the commodity market is now taken into account. Equation (32) is applied again; however, this time today's cap is hold constant ($\mathrm{d}\overline{e}_{A1} = 0$).

Finally, combining the results from the fossil fuel market with the results from the commodity market, the change in fossil fuel supply in the first period ($\mathrm{d}e_{F1}/\,\mathrm{d}\overline{e}_{A2}$), the change in fossil fuel supply in the second period ($\mathrm{d}e_{F2}/\,\mathrm{d}\overline{e}_{A2}$), the change in the cumulative extraction ($\mathrm{d}e_{F\Sigma}/\,\mathrm{d}\overline{e}_{A2}$), and the change in the cumulative climate damages ($\mathrm{d}D/\,\mathrm{d}\overline{e}_{A2}$), following the demand reduction in the future, can be deduced and analyzed for algebraic signs.[37]

Similar to the demand reduction in the present, conditions for the occurrence of the weak ($\mathrm{d}e_{F1}/\,\mathrm{d}\overline{e}_{A2} < 0$) and the strong green paradox ($\mathrm{d}D/\,\mathrm{d}\overline{e}_{A2} < 0$) induced by tightening the emissions cap in the second period can be derived:

$$\frac{\mathrm{d}e_{F1}}{\mathrm{d}\overline{e}_{A2}} \gtreqless 0 \quad \Leftrightarrow \quad \sigma \lesseqgtr \widetilde{\sigma}_1 = \frac{p_{x2}X^{E2}_{e_{F1}}}{p_{e1}} \cdot \frac{\pi_2 e_{N2}|\eta_{N2}|}{p_{x2}(x^s_{A2} + x^s_{N2} - x_{E2})} \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N2}|\eta_{N2}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F2}\eta_{F2,2}} \right), \quad (37)$$

[37] See appendix A.3, equations (A.32), (A.33), (A.34), and (A.35).

$$\frac{\mathrm{d}D}{\mathrm{d}\bar{e}_{A2}} \gtreqless 0 \quad \Leftrightarrow \quad \sigma \begin{cases} \gtreqless \widetilde{\sigma}_D = \dfrac{\dfrac{p_{x2}X^{E2}_{e_{F1}}}{p_{e1}} \cdot \dfrac{\pi_2 e_{N2}|\eta_{N2}|}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}}{\left(\dfrac{-\dfrac{\Gamma^D_2}{p_{e1}e_{N1}|\eta_{N1}|}}{\dfrac{\Gamma^D_1}{p_{e2}e_{N2}|\eta_{N2}|}+\dfrac{\Theta}{\frac{\pi_2 e_{N2}|\eta_{N2}|}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}}}\right)} & \text{if} \quad \Gamma^D_2 > 0 \\ \lesseqgtr \widetilde{\sigma}_D = \dfrac{\dfrac{p_{x2}X^{E2}_{e_{F1}}}{p_{e1}} \cdot \dfrac{\pi_2 e_{N2}|\eta_{N2}|}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}}{\left(\dfrac{-\dfrac{\Gamma^D_2}{p_{e1}e_{N1}|\eta_{N1}|}}{\dfrac{\Gamma^D_1}{p_{e2}e_{N2}|\eta_{N2}|}+\dfrac{\Theta}{\frac{\pi_2 e_{N2}|\eta_{N2}|}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}}}\right)} & \text{if} \quad \Gamma^D_2 < 0 \end{cases}, \qquad (38)$$

where $\Gamma^D_2 = \frac{p_{e1}e_{N1}|\eta_{N1}|}{e_{F2}\eta_{F2,1}} \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}} - \frac{1+\lambda}{\lambda}\right) < \Gamma_2$.

From equation (37) and (38) we infer the following proposition:

PROPOSITION 6. *If (26) holds and the abating country A tightens its emissions cap ($\mathrm{d}\bar{e}_{A2} < 0$), the weak and the strong green paradox occur under the following conditions:*

	$\mathrm{d}e_{F1} > 0$	$\mathrm{d}e_{F1} < 0$
$\mathrm{d}D > 0$	$\sigma > \widetilde{\sigma}_D$ *and* $\Gamma^D_2 < 0$	$\sigma < \widetilde{\sigma}_D$ *and* $\Gamma^D_2 > 0$
$\mathrm{d}D < 0$	$\widetilde{\sigma}_D > \sigma > \widetilde{\sigma}_1$ *and* $\Gamma^D_2 < 0$ *or* $\sigma > \widetilde{\sigma}_1$ *and* $\Gamma^D_2 > 0$	$\widetilde{\sigma}_D < \sigma < \widetilde{\sigma}_1$ *and* $\Gamma^D_2 > 0$ *or* $\sigma < \widetilde{\sigma}_1$ *and* $\Gamma^D_2 < 0$

PROOF. $\widetilde{\sigma}_1 \gtreqless \widetilde{\sigma}_D$ is equivalent to $\Gamma^D_2 \gtreqless 0$ since

$$\widetilde{\sigma}_1 \gtreqless \widetilde{\sigma}_D \quad \Leftrightarrow \quad \left(\frac{e_{F2}\eta_{F2,1}}{e_{N2}|\eta_{N2}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F2}\eta_{F2,2}}\right) \gtreqless \left(\frac{\frac{\Gamma^D_1}{p_{e2}e_{N2}|\eta_{N2}|} + \frac{\Theta}{\frac{\pi_2 e_{N2}|\eta_{N2}|}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}}}{-\frac{\Gamma^D_2}{p_{e1}e_{N1}|\eta_{N1}|}}\right)$$

$$\Leftrightarrow \quad 0 \begin{cases} \lesseqgtr \dfrac{\Gamma_0}{\frac{p_{e1}e_{N1}|\eta_{N1}|p_{e2}e_{N2}|\eta_{N2}|}{e_{F2}\eta_{F2,1}}} + \dfrac{\Theta}{\frac{\pi_2 e_{N2}|\eta_{N2}|}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}} & \text{if} \quad \Gamma^D_2 > 0 \\ \gtreqless \dfrac{\Gamma_0}{\frac{p_{e1}e_{N1}|\eta_{N1}|p_{e2}e_{N2}|\eta_{N2}|}{e_{F2}\eta_{F2,1}}} + \dfrac{\Theta}{\frac{\pi_2 e_{N2}|\eta_{N2}|}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}} & \text{if} \quad \Gamma^D_2 < 0 \end{cases}.$$

■

Our condition for the occurrence of the weak green paradox is again closely related to Eichner & Pethig's (2011). With marginal extraction cost, the physical user cost in real terms weaken the condition ($p_{x2}X^{E2}_{e_{F1}}/p_{e1} < 1$). If the elasticity of demand and the intratemporal (intertemporal) elasticity of supply for fossil fuel in the second period are relatively large (small) (last term of equation (37) < 1), it will be weakened further.

Otherwise, the condition will either be strengthened (last term of equation (37) > 1) or remain unaltered (last term of equation (37) $= 1$). The inequality sign and the rest of the condition are the same as in Eichner & Pethig's (2011) model. If the elasticity of demand and the intratemporal (intertemporal) elasticity of supply for fossil fuel in the first (second) period are relatively large (small) and if the relative weight attached to changes in cumulative emissions is relatively small (if $\Gamma_2^D < 0$), the occurrence of the strong will induce the occurrence of the weak green paradox (first quadrant of the matrix). Otherwise, the emissions in the first period will decrease if the cumulative climate damages increase (if $\Gamma_2^D > 0$, second quadrant of the matrix).[38] Present and cumulative emissions will increase simultaneously if and only if $\sigma > \widetilde{\sigma}_\Sigma$ and $\Gamma_2 < 0$. [39]

5 Concluding Remarks

There are several reasons why public policies against global warming can have effects contrary to their intended aims. Carbon leakage can lead to intratemporal and intertemporal shifts in greenhouse gas emissions from the abating countries to the non-abating countries. Even within the abating countries, emissions might only be shifted intertemporally rather than there being an actual emission reduction for any abatement policies other than binding and persistent quantity restrictions. Resource owners may feel threatened by ambitious climate objectives and shift their extraction to the present so as not to be left with the bulk of their mineral deposits. Furthermore, previously untouched resources may become valuable reserves and may be extracted sooner or later due to possible price rises in coal, oil, and other fossil fuels.

We integrate a marginal extraction cost which is increasing in present, future, and cumulative supply into Eichner & Pethig's (2011) model. Through this, the cumulative fossil fuel extraction becomes endogenously determined. In our model, the qualitative results concerning the weak green paradox remain unaltered and the elasticities of demand still play an important role (see equations (33) and (37)). But if the emissions cap is

[38] This is never fulfilled if $\Gamma_1^D \geq 0$.

[39] Where $\widetilde{\sigma}_\Sigma = \frac{p_{x2} X_{e_{F1}}^{E2}}{p_{e1}} \cdot \frac{\pi_2 e_{N2} |\eta_{N2}|}{p_{x2}(x_{A2}^s + x_{N2}^s - x_{E2})} \cdot \left[\left(\frac{\Gamma_1}{p_{e2} e_{N2} |\eta_{N2}|} + \frac{\Theta}{\frac{\pi_2 e_{N2}|\eta_{N2}|}{p_{x2}(x_{A2}^s + x_{N2}^s - x_{E2})}} \right) \cdot \left(- \frac{\Gamma_2}{p_{e1} e_{N1} |\eta_{N1}|} \right)^{-1} \right]$. See appendix A.3, equation (A.34). $\widetilde{\sigma}_1 < \widetilde{\sigma}_\Sigma$ if and only if $\Gamma_2 < 0$ whereby the proof is equivalent to that above. See also equation (37).

tightened in the first period, the condition for its occurrence is strengthened due to the physical user cost in real terms (see equation (33); these are smaller than one). And if the emissions cap is tightened in the second period, not only the user cost but also the elasticities of supply in the second period play an important role for the condition for the occurrence of the weak green paradox (see equation (37)).

Furthermore, we derive conditions under which the cumulative climate damages increase due to a "green" policy. The results crucially depend on the elasticities of supply and the relative weight attached to changes in cumulative emissions (see equations (34) and (38)). If the elasticity of demand and the intratemporal (intertemporal) elasticity of supply for fossil fuel in the second (first) period are relatively small (large) and if the relative weight attached to changes in cumulative emissions is relatively small ($\Gamma_1^D > 0$), then the strong green paradox will occur due to a tightening of the emissions cap in the first period if the intertemporal elasticity of substitution is smaller than some threshold level ($\sigma < \overline{\sigma}$). Otherwise ($\Gamma_1^D < 0$), it will occur if the intertemporal elasticity of substitution is larger than this threshold level ($\sigma > \overline{\sigma}$). Following a tightening of the emissions cap in the second period, if the elasticity of demand and the intratemporal (intertemporal) elasticity of supply for fossil fuel in the first (second) period are relatively large (small) and if the relative weight attached to changes in cumulative emissions is relatively small ($\Gamma_2^D < 0$), then the cumulative climate damages will increase if the intertemporal elasticity of substitution is larger than some threshold level ($\sigma > \widetilde{\sigma}_D$). Otherwise ($\Gamma_2^D > 0$), they will increase if the intertemporal elasticity of substitution is smaller than this threshold level ($\sigma < \widetilde{\sigma}_D$).

Comparing our results to those derived in the literature, two features stand out. First, adopted from Eichner & Pethig (2011), we show that both paradoxes can not only arise as a result of announcing future actions (Section 4), but can also be induced by immediate actions (Section 3). Second, in the literature which considers increasing marginal extraction cost (or multiple resource pools with constant but different marginal extraction costs) and carbon demand reducing policies, enhancing climate engagements do not lead to increasing cumulative emissions.[40] An exception are Hoel & Jensen (2012, 689ff.) who state that total emissions could increase; however, the net present value of cumulative

[40]See Fischer & Salant (2012, 17ff.), Gerlagh (2011, 89ff.), Grafton et al. (2012, 337ff.), Hoel (2012, 210ff.), and van der Ploeg & Withagen (2012, 351ff.).

climate damages would decrease in their setting. Even Fischer & Salant (2013, 9ff.), who consider demand and supply side reactions, find decreasing cumulative emissions due to carbon demand reducing policies in the case that the emissions per unit output are the same for all resources. In our model, cumulative emissions can increase and be carried out earlier simultaneously as a reaction to a policy measure, thus inducing a very strong form of the green paradox. This stems from our formulation of the extraction cost, which differs from the existing literature on the strong green paradox. Given this formulation, the relative price effect of carbon intensive goods[41] may alter the resource extraction path since the unique commodity serves as input in the resource extraction process. This leads to supply side reactions that are absent from the existing literature on the strong green paradox.

A Appendix

A.1 The Fossil Fuel Market

Throughout the appendix the commodity in period one is chosen as numeraire. Rearranging of (7)-(9), (20), and (21) yields:

$$p_{e1} - X^{E1}_{e_{F1}} - p_{x2} X^{E2}_{e_{F1}} = 0, \tag{A.1}$$

$$p_{e2} - p_{x2} X^{E2}_{e_{F2}} = 0, \tag{A.2}$$

$$e_{Ft} - \bar{e}_{At} - e_{Nt} = 0, \quad t = 1, 2, \tag{A.3}$$

$$X^{A1}_{\bar{e}_{A1}} - p_{e1} - \pi_1 = 0, \tag{A.4}$$

$$p_{x2} X^{A2}_{\bar{e}_{A2}} - p_{e2} - \pi_2 = 0, \tag{A.5}$$

$$X^{N1}_{e_{N1}} - p_{e1} = 0, \tag{A.6}$$

$$p_{x2} X^{N2}_{e_{N2}} - p_{e2} = 0. \tag{A.7}$$

Total differentiation of (A.1)-(A.7) yields:

$$\mathrm{d}p_{e1} - X^{E1}_{e_{F1}e_{F1}}\,\mathrm{d}e_{F1} - X^{E2}_{e_{F1}}\,\mathrm{d}p_{x2} - p_{x2}[X^{E2}_{e_{F1}e_{F1}}\,\mathrm{d}e_{F1} + X^{E2}_{e_{F1}e_{F2}}\,\mathrm{d}e_{F2}] = 0, \tag{A.8}$$

$$\mathrm{d}p_{e2} - X^{E2}_{e_{F2}}\,\mathrm{d}p_{x2} - p_{x2}[X^{E2}_{e_{F2}e_{F1}}\,\mathrm{d}e_{F1} + X^{E2}_{e_{F2}e_{F2}}\,\mathrm{d}e_{F2}] = 0, \tag{A.9}$$

$$\mathrm{d}e_{Ft} - \mathrm{d}\bar{e}_{At} - \mathrm{d}e_{Nt} = 0, \quad t = 1, 2, \tag{A.10}$$

$$X^{A1}_{\bar{e}_{A1}\bar{e}_{A1}}\,\mathrm{d}\bar{e}_{A1} - \mathrm{d}p_{e1} - \mathrm{d}\pi_1 = 0, \tag{A.11}$$

$$X^{A2}_{\bar{e}_{A2}}\,\mathrm{d}p_{x2} + p_{x2} X^{A2}_{\bar{e}_{A2}\bar{e}_{A2}}\,\mathrm{d}\bar{e}_{A2} - \mathrm{d}p_{e2} - \mathrm{d}\pi_2 = 0, \tag{A.12}$$

[41] Term [3] of equation (30a) and (35a).

$$\frac{\widehat{e}_{N1}}{\widehat{p}_{e1}} - \eta_{N1} = 0, \tag{A.13}$$

$$\frac{\widehat{e}_{N2}}{\widehat{p}_{e2} - \widehat{p}_{x2}} - \eta_{N2} = 0, \tag{A.14}$$

where $\eta_{Nt} := \frac{X^{Nt}_{e_{Nt}}}{e_{Nt} X^{Nt}_{e_{Nt} e_{Nt}}} < 0$ for $t = 1, 2$.

Inserting (A.13) and (A.14) in (A.10) and afterwards inserting in (A.8)-(A.9) yields:

$$\mathrm{d}p_{e1} - X^{E1}_{e_{F1}e_{F1}}[\mathrm{d}\overline{e}_{A1} + e_{N1}\eta_{N1}\widehat{p}_{e1}] - X^{E2}_{e_{F1}}\,\mathrm{d}p_{x2} \tag{A.15}$$
$$-p_{x2}[X^{E2}_{e_{F1}e_{F1}}[\mathrm{d}\overline{e}_{A1} + e_{N1}\eta_{N1}\widehat{p}_{e1}] + X^{E2}_{e_{F1}e_{F2}}[\mathrm{d}\overline{e}_{A2} + e_{N2}\eta_{N2}[\widehat{p}_{e2} - \widehat{p}_{x2}]]] = 0,$$

$$\mathrm{d}p_{e2} - X^{E2}_{e_{F2}}\,\mathrm{d}p_{x2} \tag{A.16}$$
$$-p_{x2}[X^{E2}_{e_{F2}e_{F1}}[\mathrm{d}\overline{e}_{A1} + e_{N1}\eta_{N1}\widehat{p}_{e1}] + X^{E2}_{e_{F2}e_{F2}}[\mathrm{d}\overline{e}_{A2} + e_{N2}\eta_{N2}[\widehat{p}_{e2} - \widehat{p}_{x2}]]] = 0.$$

Inserting (A.15) in (A.16) yields:

$$\mathrm{d}p_{e1} = -\frac{\frac{p_{e1}}{e_{N1}\eta_{N1}}[\Gamma_0 - p_{e1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]]}{\Gamma_0}\,\mathrm{d}\overline{e}_{A1} \tag{A.17}$$
$$+\frac{p_{e1}p_{e2}p_{x2}X^{E2}_{e_{F1}e_{F2}}}{\Gamma_0}\,\mathrm{d}\overline{e}_{A2} + \frac{p_{e1}X^{E2}_{e_{F1}}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\Gamma_0}\,\mathrm{d}p_{x2},$$

$$\mathrm{d}p_{e2} = \frac{p_{e1}p_{e2}p_{x2}X^{E2}_{e_{F2}e_{F1}}}{\Gamma_0}\,\mathrm{d}\overline{e}_{A1} \tag{A.18}$$
$$-\frac{\frac{p_{e2}}{e_{N2}\eta_{N2}}[\Gamma_0 - p_{e2}[p_{e1} - [X^{E1}_{e_{F1}e_{F1}} + p_{x2}X^{E2}_{e_{F1}e_{F1}}]e_{N1}\eta_{N1}]]}{\Gamma_0}\,\mathrm{d}\overline{e}_{A2} + \frac{X^{E2}_{e_{F2}}\Gamma_3}{\Gamma_0}\,\mathrm{d}p_{x2},$$

where $\Gamma_0 = [p_{e1} - [X^{E1}_{e_{F1}e_{F1}} + p_{x2}X^{E2}_{e_{F1}e_{F1}}]e_{N1}\eta_{N1}][p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}] - p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}\eta_{N1} \cdot p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N2}\eta_{N2}$ and $\Gamma_3 = \Gamma_0 + \frac{p_{x2}X^{E2}_{e_{F1}}}{p_{e2}} \cdot p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N1}\eta_{N1} \cdot p_{e2}$.

Inserting (A.13) and (A.14) in (A.10) and afterwards inserting (A.17) and (A.18) yields:

$$\mathrm{d}e_{F1} = \frac{p_{e1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\Gamma_0}\,\mathrm{d}\overline{e}_{A1} + \frac{p_{e2}p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}\eta_{N1}}{\Gamma_0}\,\mathrm{d}\overline{e}_{A2} \tag{A.19}$$
$$+\frac{X^{E2}_{e_{F1}}e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\Gamma_0}\,\mathrm{d}p_{x2},$$

$$\mathrm{d}e_{F2} = \frac{p_{e1}p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N2}\eta_{N2}}{\Gamma_0}\,\mathrm{d}\overline{e}_{A1} + \frac{p_{e2}[p_{e1} - [X^{E1}_{e_{F1}e_{F1}} + p_{x2}X^{E2}_{e_{F1}e_{F1}}]e_{N1}\eta_{N1}]}{\Gamma_0}\,\mathrm{d}\overline{e}_{A2} \tag{A.20}$$
$$+\frac{X^{E2}_{e_{F1}}e_{N1}\eta_{N1}[p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N2}\eta_{N2}]}{\Gamma_0}\,\mathrm{d}p_{x2}.$$

Adding (A.19)-(A.20) yields:

$$\mathrm{d}e_{F1} + \mathrm{d}e_{F2} = \mathrm{d}e_{F\Sigma} = \frac{p_{e1}\Gamma_1}{\Gamma_0}\,\mathrm{d}\overline{e}_{A1} + \frac{p_{e2}\Gamma_2}{\Gamma_0}\,\mathrm{d}\overline{e}_{A2} + \frac{X^{E2}_{e_{F1}}e_{N1}\eta_{N1}\Gamma_1}{\Gamma_0}\,\mathrm{d}p_{x2}, \tag{A.21}$$

where $\Gamma_1 = p_{e2} + [p_{x2}X^{E2}_{e_{F2}e_{F1}} - p_{x2}X^{E2}_{e_{F2}e_{F2}}]e_{N2}\eta_{N2}$ and $\Gamma_2 = p_{e1} - [X^{E1}_{e_{F1}e_{F1}} + p_{x2}X^{E2}_{e_{F1}e_{F1}} - p_{x2}X^{E2}_{e_{F1}e_{F2}}]e_{N1}\eta_{N1}$.

A.2 The Commodity Market

The relative commodity demand of A, N, F and E is equal to:

$$q^d = \frac{\sum x_{i1}}{\sum x_{i2}} = \frac{x_{A1} + x_{N1} + x_{F1} + X^{E1}}{x_{A2} + x_{N2} + x_{F2} + X^{E2}}, \quad i = A, N, F, E. \tag{A.22}$$

Inserting (22) and (27) in (A.22) yields:

$$q^d = \left(\frac{\alpha_1 p_{x2}}{\alpha_2}\right)^{\sigma} - \left(\frac{\alpha_1 p_{x2}}{\alpha_2}\right)^{\sigma} \frac{X^{E2}}{X^{A2} + X^{N2}} + \frac{X^{E1}}{X^{A2} + X^{N2}}. \tag{A.23}$$

Total differentiation of (A.23) and afterwards inserting (A.1)-(A.7) and (27) yields:

$$\begin{aligned} \mathrm{d}q^d =& \left(\frac{\alpha_1 p_{x2}}{\alpha_2}\right)^{\sigma} \sigma \widehat{p}_{x2} - \left(\frac{\alpha_1 p_{x2}}{\alpha_2}\right)^{\sigma} \sigma \widehat{p}_{x2} \frac{X^{E2}}{X^{A2} + X^{N2}} \\ & - \left(\frac{\alpha_1 p_{x2}}{\alpha_2}\right)^{\sigma} \frac{\mathrm{d}X^{E2}(X^{A2} + X^{N2}) - X^{E2}(\mathrm{d}X^{A2} + \mathrm{d}X^{N2})}{(X^{A2} + X^{N2})^2} \\ & + \frac{\mathrm{d}X^{E1}(X^{A2} + X^{N2}) - X^{E1}(\mathrm{d}X^{A2} + \mathrm{d}X^{N2})}{(X^{A2} + X^{N2})^2} \\ =& \frac{x^s_{A1} + x^s_{N1} - x_{E1}}{x^s_{A2} + x^s_{N2}} \sigma \widehat{p}_{x2} - \frac{\frac{\pi_2}{p_{x2}} \left(\frac{x^s_{A1} + x^s_{N1}}{x^s_{A2} + x^s_{N2}} - \frac{x^s_{A1} + x^s_{N1} - x_{E1}}{x^s_{A2} + x^s_{N2} - x_{E2}}\right)}{x^s_{A2} + x^s_{N2}} \mathrm{d}\overline{e}_{A2} \\ & + \frac{X^{E1}_{e_{F1}} - X^{E2}_{e_{F1}} \cdot \frac{x^s_{A1} + x^s_{N1} - x_{E1}}{x^s_{A2} + x^s_{N2} - x_{E2}}}{x^s_{A2} + x^s_{N2}} \mathrm{d}e_{F1} - \frac{X^{E2}_{e_{F2}} \cdot \frac{x^s_{A1} + x^s_{N1}}{x^s_{A2} + x^s_{N2}}}{x^s_{A2} + x^s_{N2}} \mathrm{d}e_{F2}. \end{aligned} \tag{A.24}$$

The relative commodity supply of A and N is equal to:

$$q^s = \frac{\sum x^s_{j1}}{\sum x^s_{j2}} = \frac{X^{A1} + X^{N1}}{X^{A2} + X^{N2}}, \quad j = A, N. \tag{A.25}$$

Total differentiation of (A.25) and afterwards inserting (A.1)-(A.7) yields:

$$\begin{aligned} \mathrm{d}q^s =& \frac{(X^{A1}_{\overline{e}_{A1}} \mathrm{d}\overline{e}_{A1} + X^{N1}_{e_{N1}} \mathrm{d}e_{N1})(X^{A2} + X^{N2}) - (X^{A1} + X^{N1})(X^{A2}_{\overline{e}_{A2}} \mathrm{d}\overline{e}_{A2} + X^{N2}_{e_{N2}} \mathrm{d}e_{N2})}{(X^{A2} + X^{N2})^2} \\ =& \frac{\pi_1}{x^s_{A2} + x^s_{N2}} \mathrm{d}\overline{e}_{A1} - \frac{\frac{\pi_2}{p_{x2}} \cdot \frac{x^s_{A1} + x^s_{N1}}{x^s_{A2} + x^s_{N2}}}{x^s_{A2} + x^s_{N2}} \mathrm{d}\overline{e}_{A2} \\ & + \frac{X^{E1}_{e_{F1}} + p_{x2} X^{E2}_{e_{F1}}}{x^s_{A2} + x^s_{N2}} \mathrm{d}e_{F1} - \frac{X^{E2}_{e_{F2}} \cdot \frac{x^s_{A1} + x^s_{N1}}{x^s_{A2} + x^s_{N2}}}{x^s_{A2} + x^s_{N2}} \mathrm{d}e_{F2}. \end{aligned} \tag{A.26}$$

Equating (A.24) and (A.26) yields:

$$\mathrm{d}p_{x2} = \frac{p_{x2}}{\sigma} \left(\frac{\pi_1}{x^s_{A1} + x^s_{N1} - x_{E1}} \mathrm{d}\overline{e}_{A1} - \frac{\pi_2}{p_{x2}(x^s_{A2} + x^s_{N2} - x_{E2})} \mathrm{d}\overline{e}_{A2} + \Theta \, \mathrm{d}e_{F1} \right), \tag{A.27}$$

where $\Theta = \frac{p_{x2} X^{E2}_{e_{F1}}}{x^s_{A1} + x^s_{N1} - x_{E1}} + \frac{p_{x2} X^{E2}_{e_{F1}}}{p_{x2}(x^s_{A2} + x^s_{N2} - x_{E2})}$.

A.3 The Combined Market

A.3.1 The Quantities on the Combined Market

Inserting (A.27) in (A.19) for $\mathrm{d}\bar{e}_{A2} = 0$ yields:

$$\begin{aligned}
\mathrm{d}e_{F1} =& \frac{p_{e1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\Gamma_0}\,\mathrm{d}\bar{e}_{A1} + \frac{X^{E2}_{e_{F1}}e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\Gamma_0} \\
&\cdot \frac{p_{x2}}{\sigma}\left(\frac{\pi_1}{x^s_{A1} + x^s_{N1} - x_{E1}}\,\mathrm{d}\bar{e}_{A1} + \Theta\,\mathrm{d}e_{F1}\right) \\
=& \frac{[p_{e1}\sigma + p_{x2}X^{E2}_{e_{F1}}\frac{\pi_1 e_{N1}\eta_{N1}}{x^s_{A1}+x^s_{N1}-x_{E1}}][p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A1}.
\end{aligned} \tag{A.28}$$

Inserting (A.27) and (A.28) in (A.20) for $\mathrm{d}\bar{e}_{A2} = 0$ yields:

$$\begin{aligned}
\mathrm{d}e_{F2} =& \frac{p_{e1}p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N2}\eta_{N2}}{\Gamma_0}\,\mathrm{d}\bar{e}_{A1} + \frac{X^{E2}_{e_{F1}}e_{N1}\eta_{N1}[p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N2}\eta_{N2}]}{\Gamma_0} \\
&\cdot \frac{p_{x2}}{\sigma}\left(\frac{\pi_1}{x^s_{A1} + x^s_{N1} - x_{E1}}\,\mathrm{d}\bar{e}_{A1}\right. \\
&\left. +\Theta\frac{[p_{e1}\sigma + p_{x2}X^{E2}_{e_{F1}}\frac{\pi_1 e_{N1}\eta_{N1}}{x^s_{A1}+x^s_{N1}-x_{E1}}][p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A1}\right) \\
=& \frac{[p_{e1}\sigma + p_{x2}X^{E2}_{e_{F1}}\frac{\pi_1 e_{N1}\eta_{N1}}{x^s_{A1}+x^s_{N1}-x_{E1}}]p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N2}\eta_{N2}}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A1}.
\end{aligned} \tag{A.29}$$

Adding (A.28) and (A.29) yields:

$$\mathrm{d}e_{F1} + \mathrm{d}e_{F2} = \mathrm{d}e_{F\Sigma} = \frac{[p_{e1}\sigma + p_{x2}X^{E2}_{e_{F1}}\frac{\pi_1 e_{N1}\eta_{N1}}{x^s_{A1}+x^s_{N1}-x_{E1}}]\Gamma_1}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A1}. \tag{A.30}$$

Inserting (A.28) and (A.30) in (29) yields:

$$\begin{aligned}
&\mathrm{d}D(e_{F1}, e_{F\Sigma}) \gtreqless 0 \\
\Leftrightarrow\quad & [p_{e1}\sigma + p_{x2}X^{E2}_{e_{F1}}\frac{\pi_1 e_{N1}\eta_{N1}}{x^s_{A1} + x^s_{N1} - x_{E1}}][[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}] + \lambda\Gamma_1]\,\mathrm{d}\bar{e}_{A1} \gtreqless 0.
\end{aligned} \tag{A.31}$$

Inserting (A.27) in (A.19) for $\mathrm{d}\bar{e}_{A1} = 0$ yields:

$$\begin{aligned}
\mathrm{d}e_{F1} =& \frac{p_{e2}p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}\eta_{N1}}{\Gamma_0}\,\mathrm{d}\bar{e}_{A2} + \frac{X^{E2}_{e_{F1}}e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\Gamma_0} \\
&\cdot \frac{p_{x2}}{\sigma}\left(-\frac{\pi_2}{p_{x2}(x^s_{A2} + x^s_{N2} - x_{E2})}\,\mathrm{d}\bar{e}_{A2} + \Theta\,\mathrm{d}e_{F1}\right) \\
=& \frac{p_{e2}\sigma p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}\eta_{N1}}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A2} \\
&- \frac{p_{x2}X^{E2}_{e_{F1}}\frac{\pi_2 e_{N1}\eta_{N1}}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A2}.
\end{aligned} \tag{A.32}$$

Inserting (A.27) and (A.32) in (A.20) for $\mathrm{d}\bar{e}_{A1} = 0$ yields:

$$\mathrm{d}e_{F2} = \frac{p_{e2}[p_{e1} - [X^{E1}_{e_{F1}e_{F1}} + p_{x2}X^{E2}_{e_{F1}e_{F1}}]e_{N1}\eta_{N1}]}{\Gamma_0}\,\mathrm{d}\bar{e}_{A2} \tag{A.33}$$

$$+\frac{X^{E2}_{e_{F1}} e_{N1}\eta_{N1}[p_{x2}X^{E2}_{e_{F2}e_{F1}} e_{N2}\eta_{N2}]}{\Gamma_0}\cdot\frac{p_{x2}}{\sigma}\left(-\frac{\pi_2}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}\,\mathrm{d}\bar{e}_{A2}\right.$$

$$+\Theta\frac{p_{e2}\sigma p_{x2}X^{E2}_{e_{F1}e_{F2}} e_{N1}\eta_{N1}}{\sigma\Gamma_0-p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A2}$$

$$\left.-\Theta\frac{p_{x2}X^{E2}_{e_{F1}}\frac{\pi_2 e_{N1}\eta_{N1}}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}{\sigma\Gamma_0-p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A2}\right)$$

$$=\frac{p_{e2}\sigma[p_{e1}-[X^{E1}_{e_{F1}e_{F1}}+p_{x2}X^{E2}_{e_{F1}e_{F1}}]e_{N1}\eta_{N1}]}{\sigma\Gamma_0-p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A2}$$

$$-\frac{p_{x2}X^{E2}_{e_{F1}}\frac{\pi_2 e_{N1}\eta_{N1}}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}p_{x2}X^{E2}_{e_{F2}e_{F1}} e_{N2}\eta_{N2}+p_{e2}p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}}{\sigma\Gamma_0-p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A2}.$$

Adding (A.32) and (A.33) yields:

$$\mathrm{d}e_{F1}+\mathrm{d}e_{F2}=\mathrm{d}e_{F\Sigma}=\frac{p_{e2}\sigma\Gamma_2-p_{x2}X^{E2}_{e_{F1}}\frac{\pi_2 e_{N1}\eta_{N1}}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}\Gamma_1-p_{e2}p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}}{\sigma\Gamma_0-p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}\,\mathrm{d}\bar{e}_{A2}. \tag{A.34}$$

Inserting (A.32) and (A.34) in (29) yields:

$$\mathrm{d}D(e_{F1},e_{F\Sigma})\gtreqless 0 \tag{A.35}$$

$$\Leftrightarrow\quad [p_{e2}\sigma[p_{x2}X^{E2}_{e_{F1}e_{F2}} e_{N1}\eta_{N1}+\lambda\Gamma_2]-p_{x2}X^{E2}_{e_{F1}}\frac{\pi_2 e_{N1}\eta_{N1}}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}$$

$$\cdot[[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]+\lambda\Gamma_1]-\lambda p_{e2}p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}]\,\mathrm{d}\bar{e}_{A2}\gtreqless 0.$$

A.3.2 The Prices on the Combined Market

Inserting (A.28) in (A.27) for $\mathrm{d}\bar{e}_{A2}=0$ yields:

$$\frac{\mathrm{d}p_{x2}}{\mathrm{d}\bar{e}_{A1}}=\frac{p_{x2}}{\sigma}\left(\frac{\pi_1}{x^s_{A1}+x^s_{N1}-x_{E1}}\right. \tag{A.36}$$

$$\left.+\Theta\frac{[p_{e1}\sigma+p_{x2}X^{E2}_{e_{F1}}\frac{\pi_1 e_{N1}\eta_{N1}}{x^s_{A1}+x^s_{N1}-x_{E1}}][p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}{\sigma\Gamma_0-p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}\right)$$

$$=\frac{p_{x2}\frac{\pi_1}{x^s_{A1}+x^s_{N1}-x_{E1}}\Gamma_0+p_{e1}p_{x2}\Theta[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}{\sigma\Gamma_0-p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}$$

$$>0.$$

Inserting (A.32) in (A.27) for $\mathrm{d}\bar{e}_{A1}=0$ yields:

$$\frac{\mathrm{d}p_{x2}}{\mathrm{d}\bar{e}_{A2}}=\frac{p_{x2}}{\sigma}\left(-\frac{\pi_2}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}\right. \tag{A.37}$$

$$\left.+\Theta\frac{p_{e2}\sigma p_{x2}X^{E2}_{e_{F1}e_{F2}} e_{N1}\eta_{N1}-p_{x2}X^{E2}_{e_{F1}}\frac{\pi_2 e_{N1}\eta_{N1}}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}{\sigma\Gamma_0-p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}} e_{N2}\eta_{N2}]}\right)$$

$$= -\frac{p_{x2}\frac{\pi_2}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}\Gamma_0 - p_{e2}p_{x2}\Theta p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}\eta_{N1}}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$<0.$$

Inserting (A.36) in (A.17) for $\mathrm{d}\bar{e}_{A2} = 0$ yields:

$$\frac{\mathrm{d}p_{e1}}{\mathrm{d}\bar{e}_{A1}} = -\frac{\frac{p_{e1}}{e_{N1}\eta_{N1}}[\Gamma_0 - p_{e1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]]}{\Gamma_0} + \frac{p_{e1}X^{E2}_{e_{F1}}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\Gamma_0} \tag{A.38}$$

$$\cdot\frac{p_{x2}\frac{\pi_1}{x^s_{A1}+x^s_{N1}-x_{E1}}\Gamma_0 + p_{e1}p_{x2}\Theta[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$= -\frac{\frac{p_{e1}}{e_{N1}\eta_{N1}}\sigma[\Gamma_0 - p_{e1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$+\frac{p_{e1}p_{x2}X^{E2}_{e_{F1}}[\frac{\pi_1}{x^s_{A1}+x^s_{N1}-x_{E1}}+\Theta][p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$>0.$$

Inserting (A.36) in (A.18) for $\mathrm{d}\bar{e}_{A2} = 0$ yields:

$$\frac{\mathrm{d}p_{e2}}{\mathrm{d}\bar{e}_{A1}} = \frac{p_{e1}p_{e2}p_{x2}X^{E2}_{e_{F2}e_{F1}}}{\Gamma_0} + \frac{X^{E2}_{e_{F2}}\Gamma_3}{\Gamma_0} \tag{A.39}$$

$$\cdot\frac{p_{x2}\frac{\pi_1}{x^s_{A1}+x^s_{N1}-x_{E1}}\Gamma_0 + p_{e1}p_{x2}\Theta[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$= \frac{p_{e1}p_{e2}\sigma p_{x2}X^{E2}_{e_{F2}e_{F1}} + p_{x2}X^{E2}_{e_{F2}}\frac{\pi_1}{x^s_{A1}+x^s_{N1}-x_{E1}}\Gamma_3 + p_{e1}p_{x2}X^{E2}_{e_{F2}}\Theta[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$>0 \Leftarrow \Gamma_3 > 0.$$

Inserting (A.37) in (A.17) for $\mathrm{d}\bar{e}_{A1} = 0$ yields:

$$\frac{\mathrm{d}p_{e1}}{\mathrm{d}\bar{e}_{A2}} = \frac{p_{e1}p_{e2}p_{x2}X^{E2}_{e_{F1}e_{F2}}}{\Gamma_0} + \frac{p_{e1}X^{E2}_{e_{F1}}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\Gamma_0} \tag{A.40}$$

$$\cdot -\frac{p_{x2}\frac{\pi_2}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}\Gamma_0 - p_{e2}p_{x2}\Theta p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}\eta_{N1}}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$= \frac{p_{e1}p_{e2}\sigma p_{x2}X^{E2}_{e_{F1}e_{F2}} - p_{e1}p_{x2}X^{E2}_{e_{F1}}\frac{\pi_2}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$= \frac{p_{e1}}{e_{N1}\eta_{N1}}\cdot\frac{\mathrm{d}e_{F1}}{\mathrm{d}\bar{e}_{A2}} \gtreqless 0 \Leftrightarrow \frac{\mathrm{d}e_{F1}}{\mathrm{d}\bar{e}_{A2}} \lesseqgtr 0.$$

Inserting (A.37) in (A.18) for $\mathrm{d}\bar{e}_{A1} = 0$ yields:

$$\frac{\mathrm{d}p_{e2}}{\mathrm{d}\bar{e}_{A2}} = -\frac{\frac{p_{e2}}{e_{N2}\eta_{N2}}[\Gamma_0 - p_{e2}[p_{e1} - [X^{E1}_{e_{F1}e_{F1}} + p_{x2}X^{E2}_{e_{F1}e_{F1}}]e_{N1}\eta_{N1}]]}{\Gamma_0} + \frac{X^{E2}_{e_{F2}}\Gamma_3}{\Gamma_0} \tag{A.41}$$

$$\cdot -\frac{p_{x2}\frac{\pi_2}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}\Gamma_0 - p_{e2}p_{x2}\Theta p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}\eta_{N1}}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2}-p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$= -\frac{\frac{p_{e2}}{e_{N2}\eta_{N2}}\sigma[\Gamma_0 - p_{e2}[p_{e1} - [X^{E1}_{e_{F1}e_{F1}} + p_{x2}X^{E2}_{e_{F1}e_{F1}}]e_{N1}\eta_{N1}]]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}$$

$$- \frac{p_{x2}X^{E2}_{e_{F2}}\frac{\pi_2}{p_{x2}(x^s_{A2}+x^s_{N2}-x_{E2})}\Gamma_3 - p_{e2}p_{x2}\Theta p_{x2}e_{N1}\eta_{N1}[X^{E2}_{e_{F2}}X^{E2}_{e_{F1}e_{F2}} - X^{E2}_{e_{F1}}X^{E2}_{e_{F2}e_{F2}}]}{\sigma\Gamma_0 - p_{x2}X^{E2}_{e_{F1}}\Theta e_{N1}\eta_{N1}[p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}]}.$$

A.4 The Gammas

$$\begin{aligned}
\Gamma_0 =& [p_{e1} - [X^{E1}_{e_{F1}e_{F1}} + p_{x2}X^{E2}_{e_{F1}e_{F1}}]e_{N1}\eta_{N1}][p_{e2} - p_{x2}X^{E2}_{e_{F2}e_{F2}}e_{N2}\eta_{N2}] \\
& - p_{x2}X^{E2}_{e_{F1}e_{F2}}e_{N1}\eta_{N1} \cdot p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N2}\eta_{N2} \\
=& \frac{p_{e2}e_{N2}|\eta_{N2}|\,p_{e1}e_{N1}|\eta_{N1}|}{e_{F1}\eta_{F1,2}e_{F2}\eta_{F2,1}} \cdot \left[\left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}}\right) \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}}\right) - 1\right],
\end{aligned} \tag{A.42}$$

$$\begin{aligned}
\Gamma_1 =& p_{e2} + [p_{x2}X^{E2}_{e_{F2}e_{F1}} - p_{x2}X^{E2}_{e_{F2}e_{F2}}]e_{N2}\eta_{N2} \\
=& \frac{p_{e2}e_{N2}|\eta_{N2}|}{e_{F1}\eta_{F1,2}} \cdot \left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}} - 1\right), \\
\gtreqless & 0 \quad \Leftrightarrow \quad \frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}} \gtreqless 1,
\end{aligned} \tag{A.43}$$

$$\begin{aligned}
\Gamma_2 =& p_{e1} - [X^{E1}_{e_{F1}e_{F1}} + p_{x2}X^{E2}_{e_{F1}e_{F1}} - p_{x2}X^{E2}_{e_{F1}e_{F2}}]e_{N1}\eta_{N1} \\
=& \frac{p_{e1}e_{N1}|\eta_{N1}|}{e_{F2}\eta_{F2,1}} \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}} - 1\right), \\
\gtreqless & 0 \quad \Leftrightarrow \quad \frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}} \gtreqless 1,
\end{aligned} \tag{A.44}$$

$$\begin{aligned}
\Gamma_3 =& \Gamma_0 + \frac{p_{x2}X^{E2}_{e_{F1}}}{p_{e2}} \cdot p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N1}\eta_{N1} \cdot p_{e2} \\
=& \frac{p_{e2}e_{N2}|\eta_{N2}|\,p_{e1}e_{N1}|\eta_{N1}|}{e_{F1}\eta_{F1,2}e_{F2}\eta_{F2,1}} \cdot \left[\left(\frac{e_{F1}\eta_{F1,2}}{e_{N2}|\eta_{N2}|} + \frac{e_{F1}\eta_{F1,2}}{e_{F2}\eta_{F2,2}}\right) \cdot \left(\frac{e_{F2}\eta_{F2,1}}{e_{N1}|\eta_{N1}|} + \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}}\right) - 1\right. \\
& \left. - \frac{p_{x2}X^{E2}_{e_{F1}}}{p_{e1}} \cdot \frac{e_{F2}\eta_{F2,1}}{e_{N2}|\eta_{N2}|}\right], \\
>& \underline{\Gamma_3} = p_{x2}X^{E2}_{e_{F1}}[p_{x2}X^{E2}_{e_{F2}} + p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N1}\eta_{N1}] \\
& \quad = p_{x2}X^{E2}_{e_{F1}} \cdot p_{x2}X^{E2}_{e_{F2}e_{F1}}e_{N1}|\eta_{N1}|\left(\frac{e_{F1}|\eta_{F1,2}|}{e_{N1}|\eta_{N1}|} - 1\right), \\
& \quad \gtreqless 0 \quad \Leftrightarrow \quad \frac{e_{F1}\eta_{F1,2}}{e_{N1}|\eta_{N1}|} \gtreqless 1,
\end{aligned} \tag{A.45}$$

where $\underline{\Gamma_3}$ is a lower limit for Γ_3.

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