Trade and Environmental Policy as an Incentive to Adopt a Better Production Technology

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Abstract

This thesis develops a two-country two-sector international trade model with taxed pollution to analyse the effect of trade on productivity enhancing technology adoption; how this is affected by comparative advantage; and what the consequences are for the emission intensity. Trade liberalisation has a positive influence on technology adoption which is only affected by taxed pollution through the effect of environmental policy on comparative advantage. A reduction in the variable trade costs will increase the share of active firms that has adopted the technology relatively more (less) in the comparative advantage industry when initial variable trade costs are high (low). Environmental policy differences reduce (enhance) the foreign market potential of the more (less) polluting industry in the high (low) tax country. In general the difference in the effect of trade across sectors is smaller (larger) when the difference in the emission taxes across countries benefits the opposite (same) industry as the relative factor endowments. The endogenous technology choice results in an additional downward pressure on the average industry emission intensity, which implies that it provides an additional mechanism through which trade has an influence on environmental outcomes via the technique effect.

Contents

1. Introduction

Two-thirds of the change in pollution in empirical trends is due to within-sector changes in emission intensity that result from plant-level changes in emission intensity instead of entry and exit of firms with different emission intensities (Cherniwchan, 2017). Even though environmental policy changes are empirically found to be the reason for around 60% of the change in emission intensity over the years because of among other things its effect on technology upgrading of firms (Najjar & Cherniwchan, 2020), trade induced effects on emission intensity are not thought to be zero (Shapiro & Walker, 2018). Furthermore, trade is found to have a positive impact on endogenous (green) technology improvements by heterogeneous firms (Navas, 2018; Forslid, Okubo, & Ulltveit-Moe, 2018).

Given the interaction effects between international trade, production technology improvements and comparative advantage and their impact on within-firm changes in emission intensity, it is interesting to analyse the impact that trade has on the share of active polluting firms that improves their technology; how this is affected by comparative advantage; and what the consequences are for the emission intensity. Moreover, comparative advantage can be the result from emission policy (For example: Broner, Bustos, & Carvalho, 2012), when one sector needs more emissions as compared to the other sector (LaPlue, 2019). Therefore, this paper analyses the impact of international trade on endogenous technology improvements and their effect on emission intensity in a two-country, two-sector international trade model with regulated polluting heterogeneous firms. To include the possibility that environmental policy creates comparative advantage, sectors are heterogeneous in emission requirements.

The main contribution of this thesis is the definition of an international trade model based on a combination of a trade model with taxed emissions, modelled in a similar fashion as LaPlue (2019), and a model in which firms have the possibility to improve their production technology (similar to Navas (2018)). The similarity of the model in this thesis and LaPlue comes from the fact that both models use the method of (Copeland & Taylor, 2003) to include environmental pollution in a two-country, two-sector international trade model. Different is that in this thesis both sectors in both countries pollute instead of only one sector over the two countries. Additionally, the model in LaPlue (2019) does not include the endogenous technology choice that is included in this paper. Previous research has mainly focussed on either one-sector trade models to analyse the effect of trade on technology improvements or on technology improvements in the absence of pollution (Navas (2018)). The addition of pollution in this thesis' model as a third production factor results in a weakening or enhancing effect on the comparative advantage across countries that in turn leads to differences in the adoption of the productivity enhancing technology across sectors in each country as compared to a situation in which pollution is not considered. As a result the combined model includes an interaction effect of environmental policy with the comparative advantage of a country based on capital and labour endowments. Additionally, it allows to analyse the impact of endogenous technology improvements on emission intensity, which sheds light on the interaction effect of trade and environmental policy.

This thesis shows that, in the presence of emission policy, trade can still encourage firms to improve their abatement and production technology via the same mechanism previously found by Navas (2018), and that taxed pollution only has an impact on cross-sector differences in the share of firms that updates their technology via its impact on comparative advantage. The availability of a better technology leads to a positive effect of trade (additional to the effect of trade in absence of the possibility to innovate) on the average sector productivity. This trade induced additional increase in average productivity which is the result from within-firm technology improvements provides a mechanism through which trade liberalisation leads to a decline in within-firm emission intensity.

The thesis is structured as follows. First, existing literature on the impact of international trade on environmental outcomes and the effect of trade and environmental policy on technology adoption is discussed. Second, the combined model is described followed by the effect of trade and comparative advantage on technology improvements and the impact of endogenous technology adoption on emission intensity that the model suggests. Thirdly, an alternative green upgrade will be discussed which only improves abatement efficiency instead of the general productivity of firms. Finally, the theoretical results from this thesis are compared to observations in reality.

2. Literature Overview

This research is connected to two main lines of literature, each consisting of two parts. First, literature on the effects of international trade on environmental outcomes and the effect of environmental policy on comparative advantage is described. These are described in the first two subsections of this chapter. Second, the literature on the impact of trade and environmental policy on technology upgrading is considered, which is described in the last two sections of this chapter. Both groups of literature bring forth insights that provide the bases for the effects analysed in this thesis.

2.1 International trade and the environment

Shapiro (2016) shows that international trade contributed to an increase of 5% in global pollution, which is for equal parts the result of shipping and production. Since this paper focusses on the effects as a result of production this section will focus on how trade influences emissions through changes in production. Traditionally, the effect of trade on the environment via this channel can be divided into three effects; the scale effect; the composition effect; and the technique effect (Copeland & Taylor, 2003). These effects are initially determined using international trade models based on the Heckscher-Ohlin structure, based on a representative firm in each sector. In theoretical research the relative size of these effects depends on the structure of the model that is considered (Balistreri, Böhringer, & Rutherford, 2018). For example, considering heterogeneous firms instead of homogenous firms changes the mechanisms through which the effects work.

The *scale effect* represents the change in emissions as a result of the expansion of production for a fixed emission intensity as a result of trade (Copeland & Taylor, 2003). Theoretically and empirically, this effect is generally positive, i.e. emissions increase because trade leads to an increase in production (Shapiro & Walker, 2018; Kreickemeier & Richter, 2014; LaPlue, 2019). The *composition effect* occurs if trade results in a change in the distribution of economic activity across sectors (Copeland & Taylor, 2003). If production shifts towards more (less) polluting industries, emissions will generally increase (decrease) as a result of this effect. The mechanism behind this effect relies on comparative advantage, trade will make the comparative advantage industries more attractive because of an increase in the relative price. Therefore, economic activity shifts towards those industries. For example, empirical research in India shows that reallocation of resources across sectors reduces emissions produced by firms (Barrows & Ollivier, 2016). The *technique effect* represents the isolated change in emission intensity, which can only be a result of environmental policy in a situation in which homogenous firms are considered (Copeland & Taylor, 2003). However, the technique effect relies on trade as well when heterogeneous firms are considered (For example: LaPlue, 2019).

Several empirical studies that decompose trends in aggregate emissions in the three effects described above find that in most cases the technique effect is able to explain the largest share of the trend (LaPlue, 2019). Within the technique effect more than half can be attributed to within-firm changes in emission intensity (Cherniwchan, 2017). Levinson (2009) shows using data from The United States that technology improvements played an important role in explaining the decrease in emissions in the manufacturing industry in The United States over the period 1987-2001. The composition effect is mostly found to be smaller in empirical research (LaPlue, 2019). Additionally, empirical research shows that exporting firms have lower emission intensities, which suggests that trade has an influence on the technique effect as well (Holladay, 2016; Forslid, Okubo, & Ulltveit-Moe, 2018; Richter & Schiersch, 2017).

More recent theoretical research has focussed on one sector models with heterogeneous firms and provides additional insights in the relationship between the environment and trade (Cherniwchan, Copeland, & Taylor, 2017; Balistreri, Böhringer, & Rutherford, 2018). Heterogeneous firms generate an additional mechanism through which trade has an influence on environmental pollution, which can be called the reallocation effect. The *reallocation effect* is generated through the relationship between emission intensity and firm productivity (Kreickemeier & Richter, 2014). Trade results in an increase in productivity within sectors as a result of reallocation of resources towards more productive firms. The mechanism is the same as in Melitz (2003). Increased trade results in more market entry generating more competition, which forces the least productive firms to exit the market. As more productive firms pollute less because of a lower emission intensity, this reduces aggregate emissions if it is stronger than the scale effect since within sector reallocation enhances the scale effect because more productive firms produce more (Kreickemeier & Richter, 2014). The existence of this effect is able to explain why empirical research generally finds that more productive firms within a sector (and exporters) are cleaner (Cherniwchan, Copeland, & Taylor, 2017).

To my knowledge LaPlue (2019) is the first to combine all four effects into one model, creating the most inclusive model to date that is able to investigate the interaction between all traditional effects in which the reallocation effect has an influence on both the technique and the composition effect. His model includes heterogeneous firms in the model of international trade and the environment by Copeland and Taylor (2003). The inclusion of heterogeneous firms results in endogenous increases in productivity which create a technique effect even in the case of fixed environmental policy (LaPlue, 2019). This effect interacts with comparative advantage and the composition effect in this model. Trade leads to a shift of production towards the comparative advantage industry and it shows that average productivity increases more in the comparative advantage industry, which is also found in models without environmental effects such as Bernard, Redding, & Schott (2007). As more productive firms are cleaner, there are relatively larger declines in emission intensity in the comparative advantage industry which can result in a smaller composition effect (LaPlue, 2019). All in all the combination of all effects shows that only focussing on heterogeneous firms or multiple sectors will exclude several interaction effects. Considering all effects simultaneously can for example create an endogenous increase in productivity in the comparative advantage industry that dampens the effect of compositional changes in environmental outcomes, which explains why empirical research often finds a small composition effect (Cherniwchan, Copeland, & Taylor, 2017). Therefore, this thesis considers a model in which both elements are present.

2.2 Environmental Policy and Comparative Advantage

The last section shows that comparative advantage has an influence on the environmental effects of trade. Besides the fact that comparative advantage has an effect on pollution through its interaction with trade effects, emission policy can also result in comparative advantage itself, which will have an influence on emissions as well (Broner, Bustos, & Carvalho, 2012). Antweiler, Copeland, & Taylor (2001) claim that regulation has an influence on the comparative advantage of a country through its influence on production costs. Chua (2003) shows that whether unequal environmental policy stringency leads to comparative advantage of the cleaner sector in the high tax country depends on the behaviour of relative goods prices as a result of changed activity in an abatement sector. This effect is generated by different relative factor use in the abatement sector. The tax provides an upward pressure on the price in the polluting sector whereas the change in relative prices due to an increase in activity in the abatement sector can create a downward pressure. This effect is not present in the model in this thesis because it is assumed that the same intermediate inputs are used for abatement and for the production of goods.

Gong, et al., (2020) summarise the empirical evidence on the effect of environmental policy on comparative advantage. Several studies find that there is a positive effect of environmental policy on comparative advantage (Cole, Elliott, & Okubo, 2010; Millimet & Roy, 2016; Ollivier, 2016). More specifically, these studies show that the low tax country specialises in the pollution intensive industry. Cole & Elliott (2003) find that differential environmental policy influences the composition of both intra and inter-industry trade. Broner et al. (2012) use data from a range of countries to show that a change from the average low tax in the data set to the average high tax leads to a convergence of the average market shares in the clean air and labour intensive industries. This effect is almost half the size of the effect that is generally found for other sources of comparative advantage such as capital and labour endowments or skilled and unskilled labour.

Kreickemeier & Richter (2019) show that differences in emission policy due to an unilateral increase by one of two trading countries can lead to an increase in average productivity in this country because of the reallocation effect, as more productive firms are less affected by an increase in the tax. This results in a within-firm increase in abatement intensity in the implementing country. They show that endogenous changes in the price of the other factor of production (i.e. labour) in both countries results in more abatement in the other country because an increase in the foreign tax relative to the wage rate. Additionally, LaPlue (2019) shows that differences in emission policy across countries has an influence on pre-existing comparative advantage from factor endowments through its effect on relative prices. However, some studies show why this effect might not be found. Harris, Konya, & Matyas (2003) find that environmental policy does not necessarily result in sectorial shifts when an industry is very dependent on the abundant factor in the country. Furthermore, some industries, like steel, do not respond to changes in environmental policy (Cole & Elliott, 2003).

2.3 Technology improvements

Empirical research shows that technology upgrading could be the reason why reductions in emissions are often found to be a result of per unit of output changes instead of changes in total output for a given emission intensity (Cherniwchan, 2017). In the US the decline in emissions over the period 1987-2001 can mainly be attributed to technology improvement and to a smaller extent to compositional changes in the manufacturing industry (Lenvinson, 2009). This result is also found by (Shapiro & Walker, 2018), who show that US emission changes are the result from changes in emission intensity within product categories. These reductions in emission intensity are found to be mainly the result of changing environmental policy. However, reductions in trade costs and increases in productivity did contribute to it as well (Shapiro & Walker, 2018).

International trade has an influence on technology upgrading by firms in absence of environmental pollution. Bustos (2011) shows that trade liberalisation increases the share of most productive firms that upgrade their technology in a one sector model with heterogeneous firms. The reason behind this is that the benefits of an upgrade depend on the amount of production whereas the fixed investment costs are fixed for each firm. When trade increases firms are able to expand their production, as found in Melitz (2003). As a result the benefits of a technology improvement increase whereas the costs stay the same, leading to the fact that less productive firms are able to upgrade. This effect is different across industries depending on comparative advantage (Navas, 2018). The share of firms that upgrades their technology is larger in the comparative advantage industry as a result of the relatively larger export possibilities in that sector. However, when trade costs are low trade liberalisation instead leads to a larger increase in the share of upgrading firms in the comparative disadvantage industry. This depends on factor price equalisation, which increases the relative price of the factor used in the comparative advantage industry which increases the upgrade costs and reduces the competitiveness on the export market. As such for lower levels of trade costs i.e higher levels of trade openness, the incentive to innovate declines in the comparative advantage industry and increases in the comparative disadvantage industry.

There is some research that analyses technology upgrading in combination with pollution and international trade. Cui, Lapan, & Moschini (2012) find an additional technology effect of trade by including a green technology choice into a one sector trade model with heterogeneous firms and pollution. The permit price reducing technology is adopted more by exporting firms and firms that are more productive. Empirical investigation of this result shows indeed that emission intensity is negatively associated with export status and productivity. The sorting pattern into a cleaner technology and into exporting depends on the structure of the upgrade possibility (Bertarelli & Lodi, 2019). Again a one-sector model with heterogeneous firms is used in which upgrading fully removes the environmental tax burden. A move towards a cleaner technology that only increases fixed costs leaving variable costs constant (aside from the tax burden) happens for a lower productivity level than the move towards exporting. However, when the cleaner technology both reduces the variable costs and takes away the tax burden, only the most productive exporters will invest in the technology. This result could be related to the fact that exporters benefit more from the additional reduction in variable costs because they have higher production found by Forslid, Okubo, & Ulltveit-Moe (2018). They analyse the effect of international trade on endogenous fixed abatement investments in a similar model. Trade liberalisation increases competition which reduces abatement investments and increases the access to the foreign market. They find that, independent of productivity level, exporters invest more in abatement as compared to domestic firms because exporters benefit from the additional production for the foreign market whereas non-exporters only experience increased competition.

2.4 Environmental Policy and Technology Choice

Some studies analyse the effect of *environmental policy* on technology upgrading in international trade models with heterogeneous firms. Cao, Qiu, & Zhou (2016) show that environmental policy leads to heterogeneous responses in abatement technology investments based on productivity. If productivity and abatement technology are complementary more productive firms invest more in abatement technology. They also find that the least productive firms will invest less when tax increases. However, Forslid, et al. (2018) find that the incentive to invest in abatement declines for more productive firms as they have a lower emission intensity than less productive firms so they are less affected by the tax increase leading to lower incentives to invest. Furthermore, the way in which selection into an upgrade as result of environmental policy happens depends on the height of the fixed investment costs (Najjar & Cherniwchan, 2020). If heterogeneous firms are able to invest in a technology that fully takes away the tax liability, high investment costs result in relatively more entry and exit effects and low investment costs results in relatively more process innovation. These results are confirmed an empirical analysis on the trend in pollution in Canada.

Additionally, there is an interaction effect of environmental policy and trade liberalisation on the adoption of a different technology (Cui, 2017). This result is found in a one sector international trade model in which the technology upgrade is either clean (labour biased) or dirty (emission biased). Independent of the type of the possible upgrade technology, trade liberalisation results in more firms that upgrade. However, environmental policy has an influence on this when the upgrade technology is clean. If policy becomes more stringent, it is more expensive to use emissions in production and more firms will upgrade their technology and vice versa. Similarly, Qiu, Zhou, & Wei (2018) show that environmental policy can trigger innovation. However, Cordella & Devarajan (2019) find that relaxing environmental policy will incentivise firms to upgrade their technology. The effect international trade has on emissions, depends on the nature of the better technology. If it is clean (dirty) total emissions will decline (increase) (Cui, 2017).

Gong et al. (2020) propose a mechanisms through which environmental regulation has an influence on technology upgrading and interacts with environmental policy and comparative advantage. They argue that environmental policy can reduce an existing comparative advantage for a polluting industry as this industry is more affected by higher emission taxes or permit prices. An increase in the policy level results in a change in the trade structure towards the nonpolluting industry. To counteract this effect Gong et al. (2020) suggest that this will induce innovation in the polluting industry which is first enhanced and then suppressed as policy becomes more stringent. This essentially implies that the negative impact of policy on comparative advantage of the polluting industry increases the incentive to innovate in this industry.

3. Model

In this section the model is described which is used to determine the effects of trade and comparative advantage, as a result of either factor endowments or environmental policy, on the propensity of firms to invest in their production and abatement technology. The model introduces both pollution (in a similar fashion as LaPlue (2019)) and the possibility to upgrade (as in Navas (2018)) the production and abatement technology into the trade model by Bernard, et al. (2007). The model in this thesis includes aspects of both models to be able to analyse the effect of international trade on technology choice in the presence of comparative advantage as a result from both relative factor endowments and environmental policy. The inclusion of Environmental pollution makes this model different from Navas (2018). The main difference with LaPlue (2019) is the introduction of the technology choice. This upgrade will improve both the productivity for producing potential output and the abatement efficiency and is assumed to increase the productivity parameter of the firm with a constant factor. However, they have to spend resources on the investment. Another difference to LaPlue (2019) is that the model in this thesis includes pollution in both countries and both sectors.

The possibility of upgrading leads to a trade-off between lower marginal costs and higher fixed costs. As a result some firms find it profitable to improve their technology and others do not. In equilibrium this depends on the productivity that the firm receives upon entry. Trade liberalisation impacts the productivity level for which adopting the new technology is profitable. The analysis below will show that indeed the share of firms that upgrades their technology in a given sector depends on the openness of trade and interacts with comparative advantage. The introduction of pollution and environmental policy into the model allows for the analysis of how this influences the comparative advantage in a country and therefore how it might influence technology upgrading.

3.1 Consumer demand

Consider two countries, home and foreign $n \in \{H, F\}$[1], and two sectors in each country $i \in \{1, 2\}$. In each sector a continuum of firms produce a differentiated good from the set of varieties $\omega \in \Omega$. In each country there is a representative consumer that receives utility (U) from the consumption (C) of these goods according to a Cobb-Douglass utility function.[2]

$$U = \frac{C_1^{\eta_1} C_2^{\eta_2}}{\eta_1^{\eta_1} \eta_2^{\eta_2}}, \quad \eta_1 + \eta_2 = 1 \tag{1}$$

The consumption in one sector and the price index are defined in (2). In these σ is the elasticity of substitution between varieties in one sector, which determines how interchangeable two goods in a sector are according to consumers.

$$C_i = \left[\int_{\omega \in \Omega_i} q_i(\omega)^{\rho} d\omega\right]^{\frac{1}{\rho}} \text{ and } P_i = \left[\int_{\omega \in \Omega_i} p_i(\omega)^{1-\sigma} d\omega\right]^{\frac{1}{1-\sigma}}, \text{ with } \rho \equiv \frac{\sigma-1}{\sigma} \tag{2}$$

Consumers minimise expenditures per unit of utility, which results in the following consumer demand for a single variety.[3] In this function R is the total revenue in the economy. η_i represents the share of income that is spend on sector i. Equation (3) shows that the demand for a variety depends negatively on the price of that variety.

$$q_i(\omega) = \eta_i R P_i^{\sigma-1} p_i(\omega)^{-\sigma} \tag{3}$$

3.2 Production

In both countries consumers inelastically supply a fixed amount of labour $(\bar{L})$ and capital $(\bar{K})$. *Without loss of generality I assume that the home country has relatively more labour than capital compared to the foreign country* $(\bar{L}/\bar{K})^H > (\bar{L}/\bar{K})^F$. The price of labour is the wage (w) and the price of capital is the interest rate (r). Furthermore, the government taxes emissions (Z) at rate (t). All tax revenue is given back to the consumers in the form of a lump sum payment.

[1] In the following sections the country indicator is ommited for notational clarity. It will only be stated when distinction is neccesary. Otherwise the equation holds for both countries.

[2] If one wants to analyse welfare implications in this model a utility loss as result of worldwide emissions can be added, which is common in the literature. This can be defined as f(Z) in the utility function and be subtracted from equation (1). As the utility function is separable in consumption and emissions, the demand for a variety does not depend on pollution, which is the reason why it is omitted in this paper.

[3] See for derivation appendix B.

Firms in both sectors use capital and labour to produce intermediate inputs (x_i) according to the production function (4).

$$x_i(k,l) = \frac{l^{1-\beta_i} k^{\beta_i}}{\beta_i^{\beta_i}(1-\beta_i)^{(1-\beta_i)}} \tag{4}$$

Cost minimisation per unit of this intermediate input implies that the price of one input results in the price for intermediate inputs $p_{xi}(w,i) = w^{1-\beta_i} r^{\beta_i}$.[4] Note that the price of the intermediate inputs used in production is independent of firm productivity. *Without loss of generality it is assumed that sector 2 is more capital intensive and sector 1 is more labour intensive ($\beta_2 > \beta_1$).*

Firms use intermediate inputs to produce potential output (y_i) according to $y_i(\varphi,k,l) = \varphi x_i(k,l)$. Potential output is the amount of net output (sellable goods) that a firm would be able to produce if it did not need emissions in production. More productive firms need less intermediate inputs to produce one unit of potential output. However, production of potential output generates emissions, which are taxed against price t. Firms have the possibility to abate these emissions by devoting a share of potential output (θ_i) to abatement.[5] The abatement function, which gives the emissions per unit of potential output is shown in (5). α_i $(0 < \alpha_i < 0.5)$ represents how emission intensive production is in a given sector. A higher level implies that a firm needs more emissions to produce. The parameter can be interpreted as the elasticity of substitution of the emission intensity with respect to the abatement intensity (Shapiro & Walker, 2018). *In this model it is assumed that the capital intensive sector is also the sector that uses the most emissions, which implies that $\alpha_1 < \alpha_2$.*

$$A_i(\theta_i) = \frac{(1-\theta_i)^{\frac{1}{\alpha_i}}}{\varphi}\ , with\ 0 \leq \theta_i < 1\ , 0 < \alpha_i < 1 \tag{5}$$

As firms have to use part of their potential output to reduce emissions, not all potential output will be available to sell and trade. When θ_i is the share of potential output that firms use for abatement, the share of output that is left to be sold is equal to $(1-\theta_i)$. Therefore, the net

[4] See for derivation appendix B.

[5] This method is used in several models intergrating environmental emission into trade models. The first to use this method are Copeland & Taylor (2003), who show that using this method, emissions can both be interpreted as being a result of production and being an input to production. This is usefull because it allows for a model without an assumption on this point.

output (q_i) and emissions (z_i) can be written as $q_i \equiv (1-\theta_i)y_i(\varphi, k, l)$ and $z_i = A_i(\theta_i)y_i(\varphi, k, l)$ respectively. Using the abatement, emissions and potential output functions, the net output function can be determined (6). This function shows that emissions can be interpreted as an input to production. The price for x_i is $p_{xi} = w^{1-\beta_i}r^{\beta_i}$.

$$q_i(z_i, x_i) = \varphi(z_i)^{\alpha_i}(x_i)^{(1-\alpha_i)} \tag{6}$$

Given the net production function and the prices of both emissions and intermediate inputs firms minimise their costs. The marginal costs of net output $c_{q_i} = \frac{1}{\varphi}\left(\frac{p_{xi}}{1-\alpha_i}\right)^{1-\alpha_i}\left(\frac{t}{\alpha_i}\right)^{\alpha_i}$ [6] depend on both the productivity of a firm and the prices of both emissions and intermediate inputs. The more emission intensive the sector the more the tax influences the marginal costs compared to the price of intermediate inputs.

Total costs for producing potential output are the sum of the costs for producing output and fixed costs. The fixed costs of production do not depend on the productivity of the firm.

$$C_{q_i} = \left(\frac{p_{xi}}{1-\alpha_i}\right)^{1-\alpha_i}\left(\frac{t}{\alpha_i}\right)^{\alpha_i}\left[\frac{q_i(\varphi)}{\varphi} + f\right] \tag{7}$$

3.3 Technology upgrade

In the model firms have the possibility to upgrade their production technology after entry. When a firm chooses to do so their productivity will increase with a constant factor ($\phi > 1$). More, specifically, $\varphi = \phi\varphi$ for a firm that upgrades. This element provides the main structural difference with the model by LaPlue (2019) and makes it possible the answer the main question of this thesis.

Considering the equations above firms that have done the upgrade have lower marginal costs. The reason for this is that firms that do the upgrade are both better at reducing emissions and in producing potential output. Besides variable production costs there are also fixed

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[6] These marginal costs are simplified from $c_{q_i} = \frac{p_{xi}}{\varphi(1-\alpha_i)(1-\theta_i)}$ in which $(1-\theta_i) = \left(\frac{\alpha_i}{1-\alpha_i}\frac{p_{xi}}{t}\right)^{\alpha_i}$. This last part is the share of potential output that is used in production. This shows that the share of potential output that goes to the production of net output does differ over industries but does not depend on the productivity of the firms or the technology upgrade. It shows that when the relative price of intermediate inputs as compared to the tax increases the amount of potential output that is used not net production as compared to abatement increases. Furthermore, the amount of potential output that is used for net output depends on how much the industry relies on emission for production.

production costs (f_D), which can be thought of as overhead costs and also uses intermediate inputs and emissions to produce. Furthermore, when a firm chooses to upgrade they have to make a fixed upgrade investment (δf_u), which implies that the fixed costs for an upgraded firm are $f = f_D + \delta f_u$. Delta represents the fact that the fixed investment is shared equally over all potential periods that the firms is active.

3.4 Pricing and profits

Firms within each sector compete on a monopolistically competitive market. This implies that firms can ask a price that is above marginal costs that depends on the elasticity of substitution between varieties. From this follows that prices differ among firms based on both their productivity whether or not they have done the upgrade.

$$p_i(\varphi) = \frac{\sigma}{\sigma - 1}\frac{1}{\varphi}\left(\frac{p_{xi}}{1 - \alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t}{\alpha_i}\right)^{\alpha_i} \tag{8}$$

Clearly, more productive firms have lower prices. Also firms that have done the upgrade can ask an even lower price. The price is lower in the sector in which the price of the intermediate inputs is lower. Given that α differs over sectors the effect of the price of intermediate inputs on the price of the final goods also depends on the intensity with which emissions are used in the industry. Prices in all industries will become larger when the tax in the country increases. However, the sector that pollutes more is more affected by it.

Revenues are the product of the price (8) and the consumer demand (3) for the specific variety. This function shows that for any given level of productivity the revenue increases when a larger share of expenditures is spend on the industry. Total revenue is larger when the price index increases.[7]

$$r_i(\varphi) = \eta_i R P_i^{\sigma-1} p_i(\varphi)^{1-\sigma} \tag{9}$$

The revenue function in combination with the costs function determines the profit of the firm. The profit function of a firm also depends on whether the firms has invested in the better technology or not. The profit in the industry depends on the revenue and the fixed costs. The fixed costs depend on whether or not the firm has done the upgrade.

[7] As is generally the case in these kind of models the ratio of the revenues of any two firms with different productivity levels only depends on the productivity levels. $r_i(\varphi'')/r_i(\varphi') = (\varphi''/\varphi')^{\sigma-1}$

$$\pi_i(\varphi) = \frac{r_i(\varphi)}{\sigma} - f\left(\frac{p_{xi}}{1-\alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t}{\alpha_i}\right)^{\alpha_i} \tag{10}$$

3.5 Entry and Exit

In order to enter the market firms have to pay the sunk market entry costs f_e. These costs use the same inputs as fixed costs. After entry firms take a random draw from the exogenous productivity distribution $G(\varphi) = \left[\underline{\varphi}, \overline{\varphi}\right]$. In this thesis a Pareto distribution is used for the productivity $\left(G(\varphi) = 1 - \left(\frac{\underline{\varphi}}{\varphi}\right)^k\right)$ to solve the different equilibrium values. Additionally there is a probability of exiting the market each period equal to δ. Firms that have high enough productivity to satisfy the zero profit condition will start to produce. Others will exit immediately. The productivity level for which the zero profit condition holds is the minimum productivity for which a firm stays in the market. In equilibrium firms enter the market until the expected profits of market entry are equal to the costs of entering.

4. Autarkic equilibrium

In this chapter the autarkic equilibrium is presented. It shows that the inclusion of pollution and environmental policy has an impact on the relative price of the sectors in absence of trade. Furthermore, it shows that in autarky the possibility to upgrade does not result in differences in average productivity across sectors. Moreover, differences across sectors in the use of factors of production does not result in differences in the share of firms that upgrade their technology.

4.1 Technology choice

In this model firms choose whether or not to invest in the technology of their firm. As a result firms will receive a productivity benefit. However, firms also pay the fixed upgrade cost (f_u), which require intermediate products to fulfil. This implies that the profit function is different for firms depending on their upgrade status[8].

$$\pi_i(\varphi) = \frac{r_i(\varphi)}{\sigma} - f_D\left(\frac{p_{xi}}{1-\alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t}{\alpha_i}\right)^{\alpha_i} \tag{11}$$

[8] The revenue function only differs in ϕ which makes it possible to express the profit function of an upgrading firm as a function of the same revenue function as the profit function without the upgrade, which allows for convenient comparison of the two.

$$\pi_i^U(\phi\varphi) = \frac{(\phi)^{\sigma-1} r_i(\varphi)}{\sigma} - f_D \left(\frac{p_{xi}}{1-\alpha}\right)^{(1-\alpha)} \left(\frac{t}{\alpha}\right)^{\alpha} - \delta f_U \left(\frac{p_{xi}}{1-\alpha_i}\right)^{(1-\alpha_i)} \left(\frac{t}{\alpha_i}\right)^{\alpha_i}$$

A firm will upgrade their production technology if it is profitable to do so i.e. when the additional profits from upgrading the technology ($\pi_i^{U_A}(\phi\varphi) = \pi_i^U(\phi\varphi) - \pi_i(\varphi)$) are larger than the additional costs. I assume that only a share of the firms are productive enough to do the upgrade ($\varphi_{iD}{}^* < \varphi_{iU}^*$) [9]. This implies that there are two cut-off conditions: one for the domestic market and one for doing the technology upgrade which are given by (12) and (13) respectively.

$$\frac{r_{iD}(\varphi_{iD}^*)}{\sigma} = f_D \left(\frac{p_{xi}}{1-\alpha_i}\right)^{(1-\alpha_i)} \left(\frac{t}{\alpha_i}\right)^{\alpha_i} \tag{12}$$

$$\frac{((\phi)^{\sigma-1} - 1) r_i(\varphi_{iU}^*)}{\sigma} = \delta f_U \left(\frac{p_{xi}}{1-\alpha_i}\right)^{(1-\alpha_i)} \left(\frac{t}{\alpha_i}\right)^{\alpha_i} \tag{13}$$

Dividing (13) by (12) results in the relationship between the two zero-profit productivity conditions (14). Immediately, this shows that the relationship is the same in both sectors. Furthermore, it shows that the amount of firms that upgrade their technology is smaller when the upgrade costs are higher. If the benefits of the upgrade are larger the minimum productivity for the upgrade is lower relative to the zero-profit productivity cut-off.

$$\left(\frac{\varphi_{iU}^*}{\varphi_{iD}^*}\right)^{\sigma-1} = \frac{\delta f_U}{((\phi)^{\sigma-1} - 1) f_D} \tag{14}$$

4.2. Equilibrium

The free entry condition is given by (15). This shows, on the left hand side, the probability of successful entry and the average profit in the market after entry. Firms will enter the market until the expected profits of market entry are equal to the entry costs. As this depends on the average profit in the entire sector it is necessary to determine the post-upgrade average productivity. For this I use the method used by Navas (2018). They conclude that it is possible to define the average productivity as the weighted average of the pre-upgrade average

[9] This requires assumptions on the costs structure in the economy which are discussed in appendix E.

productivity of upgraders ($\tilde{\varphi}_{iU}$) and non-upgraders ($\tilde{\varphi}_{iD}$), to determine the average productivity in the market after upgrading has taken place ($\tilde{\varphi}_{iDU}$).[10]

$$[1 - G(\varphi_{iD}^*)]\pi_i(\tilde{\varphi}_{iDU}) \geq f_e \left(\frac{p_{xi}}{1-\alpha_i}\right)^{(1-\alpha_i)} \left(\frac{t}{\alpha_i}\right)^{\alpha_i} \tag{15}$$

Interestingly, the possibility to upgrade increases the minimum productivity to survive in equilibrium as compared to a situation in which this possibility does not exist. The reason for this is that the upgrade increases the expected profits of market entry as some firms will draw a productivity level high enough to upgrade and receive the productivity benefits for this. However, this effect is the same across industries. Differences in both emission intensity and capital and labour intensity across sectors do not result in differences across industries. This result is also found by Navas (2018), who analyses a similar upgrade in a model without environmental pollution, and is similar to results found by for example Bernard et al. (2007). The explanation for this result lies in the fact that even though the marginal costs of production are lower in one sector because of differences in required emission use and relative factor use leading to lower prices and higher sales, the entry costs are also lower in that sector. This leads to more entry in the lower costs sector which drives up competition and makes it more difficult to survive which cancels the effect of lower marginal production costs. This results in the same equilibrium average and zero-profit cut-off productivity in both sectors.

The Autarkic equilibrium determines the comparative advantage of both countries. The total revenue in a sector is equal to the total amount of firms in that sector times the average revenue of those firms, which is the same as the revenue of the average post-upgrade firm. Taking into account that the average productivity is the same across sectors in autarky, the relative amount of active firms in each sector can be given by (17), in which $\mathrm{A}_i = (1-\alpha_i)^{(1-\alpha_i)}\alpha_i^{\alpha_i}$.[11]

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[10] The average productivity represents the average productivity over all firms in the market including the benefit a share of these firms receives for their upgrade. The equilibrium relationship between the average and the cut-off condition for non-upgraders is given by: $\tilde{\varphi}_{iDU}^{\sigma-1} = \frac{k}{k-\sigma+1}\left(1 + (\phi^{\sigma-1}-1)^{\frac{k}{\sigma-1}}\left(\frac{f_d}{\delta f_u}\right)^{\frac{k-\sigma+1}{\sigma-1}}\right)\varphi_{iD}^{*\ \sigma-1}$ (using the specific productivity distribution). This method is explained in more detail in Appendix C.

[11] A_i is decreasing in α_i for values between 0 and 0.5 and increasing for the values between 0.5 and 1. Given that the amount of emissions used in production in realtive is in general smaller than half of total inputs, I'll assume that α_i is smaller than 0.5. This implies that if $\alpha_2 > \alpha_1$, $\mathrm{A}_2 < \mathrm{A}_1$.

$$\frac{M_1}{M_2} = \frac{\eta_1}{\eta_2}\frac{\mathrm{A}_1}{\mathrm{A}_2}\frac{p_{x2}^{(1-\alpha_2)}}{p_{x1}^{(1-\alpha_1)}}t^{\alpha_2-\alpha_1} = \frac{\eta_1}{\eta_2}\frac{\mathrm{A}_1}{\mathrm{A}_2}\left(\frac{r}{w}\right)^{\beta_2(1-\alpha_2)-\beta_1(1-\alpha_1)}\left(\frac{t}{w}\right)^{\alpha_2-\alpha_1} \quad (17)$$

The relative mass of firms in sector one depends both on the prices of intermediate inputs in both sectors and the country's emission tax. $\mathrm{A_i}$ is smaller in the sector in which α_i is larger. All else equal, there are less firms in the sector that relies more on emissions, which is sector 2. Also the relative mass of firms in the sector in which consumers spend a larger share of income is larger. An increase in the tax increases the relative mass of firms in the least emission intensive industry, which is assumed to be sector one. Additionally, the relative mass of firms in sector one depends on the ratio between the prices of intermediate inputs in both sectors. In order to determine how the relative mass of firms depends on the relative factor endowments and the tax rate, the wage is chosen as the numeraire in the model. This implies that both the interest rate and the tax rate are relative to the wage, which is normalised to one in each country. As a result (17) simplifies to the last part.

The (relative) emission tax has a negative influence on the relative mass of firms in sector two. If the government increases the tax rate sector two becomes relatively less attractive because it relies more on the now more expensive emissions for production. The relative price of capital[12] has an ambiguous effect on the relative mass of firms that depends on the extent to which sectors differ in their capital and emission intensity. An increase in the relative price of capital increases the relative mass of firms in sector one if $\frac{\beta_2}{\beta_1} > \frac{1-\alpha_1}{1-\alpha_2}$. Thus, the relationship between the relative price of capital and the relative mass of firms in sector one can be reversed based on how the relative difference between β_1 and β_2 and $1-\alpha_1$ and $1-\alpha_2$ relate to each other. If the emission intensities are closer together than the capital intensities, the relative price of capital decreases the relative mass of firms in the capital intensive industry. In the remainder of the analysis is assumed that the relationship does not flip due to parameters, such that a higher relative price of capital will always result in an increase in the relative price for the capital and emission intensive industry.

The relative mass of firms directly determines the relative prices (20). This is used to determine differences in relative prices across the countries based on environmental policy and factor endowments.

[12] See appendix E for derivation.

$$\frac{P_1}{P_2} = \frac{\eta_1}{\eta_2}\left(\frac{M_1}{M_2}\right)^{\frac{\sigma}{1-\sigma}} \tag{20}$$

Comparative advantage is determined based on these relative goods prices across countries which depends on the capital and labour endowments across countries and the emission taxes across countries. As $(\bar{L}/\bar{K})^H > (\bar{L}/\bar{K})^F$ the relative price of capital is relatively higher in the home country compared to the foreign country. Additionally, potential differences in the emission tax across countries will have an influence on the comparative advantage of a country. This will be discussed in more detail below.

5. Costly trade[13]

This chapter describes the impact of costly trade on the share of active firms in each sector that upgrades their production and abatement technology. The costly trade equilibrium assumes that firms have to pay fixed and variable trade costs, which are equal across countries and sectors. The variable trade costs are in the shape of iceberg transport costs $(\tau > 1)$. The fixed costs are f_x and require both intermediate inputs and emissions in production. These costs are equal in both the home and the foreign country. Given the variable trade costs the prices that result on the export market are higher with factor τ (21).

$$p_{iX}(\phi\varphi) = \tau p_i(\phi\varphi) = \tau \frac{\sigma}{\sigma - 1}\frac{1}{\varphi}\left(\frac{p_{xi}}{1-\alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t}{\alpha_i}\right)^{\alpha_i} \tag{21}$$

In this section the functions for the home country will be considered. However, the functions for the foreign country can be determined analogously.

5.1 Technology choice

It is assumed that only a share of the exporters is productive enough to do the upgrade $(\varphi_i^* < \varphi_{Xi}^* < \varphi_{Ui}^*)$[14]. Given this assumption firms will survive in the market when they are productive enough to cover fixed production costs. Firms will choose to export (and upgrade) if the additional profit of exporting (and upgrading their technology) is larger than the

[13] The discussion in this section is done from the point of view of the home country. The discussion is analogous for the foreign country.

[14] This assumption requires assumptions on the costs structure in the model which are discussed in appendix 4.

additional costs. The total profits for a firm that only serves the domestic market, an exporter, and an exporter that also upgrades their technology are given by (22).

$$\pi_i^H(\varphi) = \frac{r_i^H(\varphi)}{\sigma} - f_D\left(\frac{p_{xi}{}^H}{1-\alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t^H}{\alpha_i}\right)^{\alpha_i}$$

$$\pi_{Xi}^H(\varphi) = \left(1+\frac{R^F}{R^H}\left(\frac{P_i^F}{P_i^H}\right)^{\sigma-1}\tau^{1-\sigma}\right)\frac{r_i^H(\varphi)}{\sigma} - (f_D+f_X)\left(\frac{p_{xi}{}^H}{1-\alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t^H}{\alpha_i}\right)^{\alpha_i} \quad (22)$$

$$\pi_{UXi}^H(\varphi) = \left(1+\frac{R^F}{R^H}\left(\frac{P_i^F}{P_i^H}\right)^{\sigma-1}\tau^{1-\sigma}\right)\frac{(\phi)^{\sigma-1}r_i^H(\varphi)}{\sigma} - (f_D+f_X+\delta f_U)\left(\frac{p_{xi}{}^H}{1-\alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t^H}{\alpha_i}\right)^{\alpha_i}$$

These functions result in the zero-profit condition for the domestic market (which is the same as in autarky) and the cut-off productivity levels for both exporting and technology adoption (23). To determine these conditions, the additional profits from entering the export market and from doing the upgrade are determined (left hand side of 23)[15]. The additional costs are on the right hand side of (23). In the conditions the revenue function is always the same function.

$$\frac{r_i^H(\varphi_i^{*H})}{\sigma} = f_D\left(\frac{p_{xi}{}^H}{1-\alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t^H}{\alpha_i}\right)^{\alpha_i}$$

$$\left(\frac{R^F}{R^H}\left(\frac{P_i^F}{P_i^H}\right)^{\sigma-1}\tau^{1-\sigma}\right)\frac{r_i^H(\varphi_{Xi}^{*}{}^H)}{\sigma} = f_X\left(\frac{p_{xi}{}^H}{1-\alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t^H}{\alpha_i}\right)^{\alpha_i} \quad (23)$$

$$\left(1+\frac{R^F}{R^H}\left(\frac{P_i^F}{P_i^H}\right)^{\sigma-1}\tau^{1-\sigma}\right)\frac{((\phi)^{\sigma-1}-1)r_i^H(\varphi_{XUi}^{*}{}^H)}{\sigma} = \delta f_U\left(\frac{p_{xi}{}^H}{1-\alpha_i}\right)^{(1-\alpha_i)}\left(\frac{t^H}{\alpha_i}\right)^{\alpha_i}$$

Using these conditions it is possible to compare the zero-profit conditions for exporters and exporters that do the upgrade with the domestic cut-off, which sheds light on how model parameters influence these.

$$\left(\frac{\varphi_{Xi}^{*}{}^H}{\varphi_i^{*H}}\right)^{\sigma-1} = \tau^{\sigma-1}\frac{R^H(P_i^H)^{\sigma-1}}{R^F(P_i^F)^{\sigma-1}}\frac{f_X}{f} \quad (24)$$

[15] The additional profit function always denotes the difference between the profit function of the firm minus the profit function doing one activity less. This way it is possible to express total expected profits in the market as a function of the probability of drawing a productivity level above the cut-off level for that specific activity and the additional profit that a firm recieves for having a productivity level equal to or higher than that level.

The comparison of the domestic and the export productivity cut-off (24) is very similar to the model by Bernard et al. (2007). This shows that the difference between the export and domestic cut-off increases when the variable trade costs increase and when the foreign market is smaller as compared to the domestic market. Both higher variable trade costs and smaller foreign market potential make it less profitable to supply the export market, which implies that firms have to be more productive to be able to export. It also shows that the effect of trade liberalisation is larger in the comparative advantage sector. Furthermore, when the fixed costs of exporting are higher, the difference between the domestic and the export cut-off productivity level is smaller (firms have to be more productive to be able to cover these costs).

Next it is possible to compare the upgrade condition with the export condition (25) and the domestic cut-off level (26).

$$\left(\frac{{\varphi_{Ui}^*}^H}{{\varphi_{Xi}^*}^H}\right)^{\sigma-1} = \frac{1}{\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)\left((\phi)^{\sigma-1}-1\right)}\frac{\delta f_U}{f_X} \tag{25}$$

$$\left(\frac{{\varphi_{Ui}^*}^H}{\varphi_i^{*H}}\right)^{\sigma-1} = \frac{1}{\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)\left((\phi)^{\sigma-1}-1\right)}\frac{\delta f_U}{f_d} \tag{26}$$

This shows that the difference between the productivity cut-off for doing the upgrade compared to either the export or the domestic cut-off level becomes smaller when the total benefits of improving the technology increases (ϕ).

Proposition 1: Higher productivity benefits associated with the technology upgrade (ϕ) *results in a larger share of active firms that upgrade their technology independent of the sector.*[16]

5.2 Effect of trade on technology adoption

The effect of trade on the technology choice is determined by a decrease in the variable trade costs. If the variable trade costs decline (in 26), $\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)$ increases, which implies that the cut-off productivity level for adopting the better technology declines relative to the one for the domestic market. Therefore, trade liberalisation increases the share of upgraders in both sectors in both countries. The mechanism behind this result is that trade liberalisation increases the access to the export market in both countries, which increases the upgrade benefits because

[16] The proof of all propositions are explained in appendix A.

total production is larger while the costs remain unchanged, which allows a larger share of firms to innovate. This result is also found when considering one sector international trade models without environmental effects (Bustos, 2011).

Proposition 2: A reduction in variable trade costs (τ) *increases the share of active firms that has done a technology upgrade in each sector.*

Besides that, (25-26) show that the share of exporters that upgrades their technology depends on the relative price indices in both countries. This implies that there can be differences over the two sectors regarding the share of firms that innovates. More specifically, the difference depends on comparative advantage. In (27) the ratio of the share of firms that upgrades their technology over the two sectors is given for the home country.

$$\frac{\frac{{\varphi_{1UX}^{*}}^{H}}{{\varphi_{1}^{*}}^{H}}}{\frac{{\varphi_{2UX}^{*}}^{H}}{{\varphi_{2}^{*}}^{H}}} = \left(\frac{1 + \frac{R^F}{R^H}\left(\frac{P_2^F}{P_2^H}\right)\tau^{1-\sigma}}{1 + \frac{R^F}{R^H}\left(\frac{P_1^F}{P_1^H}\right)\tau^{1-\sigma}} \right)^{\frac{1}{\sigma-1}} \tag{27}$$

The ratio shows that the level of variable trade costs and the relative country size do not lead to differences across sectors. The reason for this is that both sectors are affected by them in the same way. If home has a comparative advantage in sector one $P_1^H/P_2^H < P_1^F/P_2^F$. This can be rearranged to $P_2^F/P_2^H < P_1^F/P_1^H$, which implies that more firms are able to upgrade in the comparative advantage sector. This is due to the fact that the benefits of the upgrade are larger because firms in the comparative advantage sector have better export opportunities. This result is similar to that found by Navas (2018), who shows the effect of trade on the adoption of a productivity enhancing technology in a setting without environmental policy and pollution.

Proposition 3: For each level of the variable trade costs (for $\tau > 1$) *the share of active firms that upgrades their technology is larger in the comparative advantage industry.*

Besides the fact that there is a difference in the share of active firms that have adopted to the new technology in each sector based on comparative advantage, comparative advantage also induces differences in the effect of trade. Initially, the effect of trade is larger in the comparative advantage industry because the export potential is larger in that sector. However, when trade costs decline and trade becomes more open the relative prices across countries converges which reduces the relative difference in export potential across sectors. This implies that the effect of trade on the relative share of active firms that improves their technology depends on the height of the variable trade costs. In the comparative advantage (disadvantage) industry the effect of trade on innovation is relatively lower (higher) when the variable trade costs are low as compared to high. The intuition behind this result is that the goods price convergence reduces the difference in foreign market potential across sectors.

Proposition 4: A reduction in the variable trade costs will increase the share of active firms that upgrade their technology more (less) in the comparative advantage industry (comparative disadvantage industry) when variable trade costs are high. When variable trade costs are low the share of active firms that improves their technology increases more (less) in the comparative disadvantage industry (comparative advantage industry).

This section shows that even though this paper includes emissions as a third factor of production, this does not change the general result found by Navas (2018). However, due to the addition of the environment in this paper the comparative advantage depends on environmental taxes as well as the relative factor endowments of a country, which has an influence on the effect of trade on the environment. Therefore, the implications are analysed in more detail in the next section.

6. Effect of comparative advantage on relative technology upgrading

The previous chapter shows that the effect of trade on the share of firms that upgrades their technology depends on the comparative advantage, which makes it interesting to analyse the differential impact trade has on technology upgrading across sectors for the different sources of comparative advantage. The differential effects over the range of variable trade costs are analysed by looking at a change when variable trade costs are either large or a change when variable trade costs are close to one. The in-between behaviour can be non-linear based on how the relative factor and goods prices behave for different levels of the variable trade costs and how these interact with both the effects of environmental taxes and the upgrade possibility. Given the scope of this thesis such analysis is omitted but analysing these effects in more detail is interesting for future research.

The home country has a comparative advantage in sector one if (28) holds.

$$\frac{p_{x2}^{H(1-\alpha_2)}}{p_{x1}^{H(1-\alpha_1)}} t^{H^{\alpha_2-\alpha_1}} > \frac{p_{x2}^{F(1-\alpha_2)}}{p_{x1}^{F(1-\alpha_1)}} t^{F^{\alpha_2-\alpha_1}}$$

$$\Leftrightarrow \left(\frac{w^H}{w^F}\right)^{(1-\beta_2)(1-\alpha_2)-(1-\beta_1)(1-\alpha_1)} \left(\frac{r^H}{r^F}\right)^{\beta_2(1-\alpha_2)-\beta_1(1-\alpha_1)} > \left(\frac{t^F}{t^H}\right)^{\alpha_2-\alpha_1} \quad (28)$$

In order to interpret this result again the wage rate is used as the numeraire in both countries and substituting (19) for the relative price of capital which gives an expression that relates the relative factor endowments across countries to the relative taxes across countries (29). If this inequality holds the home country has a comparative advantage in the labour intensive sector one. If the opposite holds, the home country has a comparative advantage in the capital and emission intensive sector two.

$$\left(\frac{\left(\bar{L}/\bar{K}\right)^{H}}{\left(\bar{L}/\bar{K}\right)^{F}}\right)^{\beta_2(1-\alpha_2)-\beta_1(1-\alpha_1)} > \left(\frac{t^F}{t^H}\right)^{\alpha_2-\alpha_1} \qquad (29)$$

Differences across countries in environmental policy as well as differences in relative factor endowments can result in comparative advantage. Therefore, several situations can be determined, which are explained in the following sections.

6.1 Comparative advantage based on factor endowments

This section describes the situation in which relative capital endowments are the only source of comparative advantage. Since the introduction of emissions and environmental policy only has an influence on the technology choice through comparative advantage these results closely follow Navas (2018). In the absence of differences in environmental policy across countries, the right hand side of (29) is equal to one. Thus, the home country has a comparative advantage in the labour intensive sector one if $\left(\bar{L}/\bar{K}\right)^{H} > \left(\bar{L}/\bar{K}\right)^{F}$. For this analysis it is have assumed that home is labour abundant, and has a comparative advantage in the labour intensive industry.

A change from autarky to costly trade results in a larger share of upgraders in the labour intensive industry i.e at each level of τ the share is larger in the labour intensive industry. The intuition behind this result is that the comparative advantage industry benefits relatively more from the export market. This implies that the benefits of the technology upgrade are larger in the labour intensive sector because production is larger. Declining trade costs result in a relatively larger increase in the demand for labour as compared to capital in the home country compared to foreign. As the relative goods prices converge, the difference between the shares of active firms with the improved technology across sectors declines. Thus, for small values of the variable trade costs, the difference in the relative share of upgrading across sectors firms is smaller than when variable trade costs are large.

Following the general conclusions of chapter 5, the increase in the share of upgraders as a result of a change in variable trade costs is larger (smaller) in the labour intensive sector compared to the capital intensive industry for high (low) levels of the variable trade costs. Navas (2018) shows that the behaviour of the relative innovation cut-offs between a high level of variable trade costs and a low level is slightly non-linear.

6.2 Comparative advantage based on emission taxes

To focus on the effect of differential environmental policy it is assumed in this section that the (relative) factor endowments are equal across countries. In this case the left hand side of (29) is equal to 1, which implies that the home country has a comparative advantage in the labour intensive industry if $(t)^H > (t)^F$. In general, the share of incumbent firms that has improved their technology is larger in the labour (capital) intensive industry if the home country has a more (less) stringent policy than foreign. This effect of taxes on comparative advantage is the result of the difference in α across sectors. An emission tax has more impact on the price of the goods in the capital and emission intensive industry, which has an influence on the relative price and comparative advantage.

Assume without loss of generality that home has a higher tax than foreign. This implies that there is a relatively larger share of upgrading firms in the labour (capital) intensive industry in the home (foreign) country. Policy induced comparative advantage implies that the low tax country specialises in the emission intensive industry, which is a result found in previous research. The share of firms that improves their technology is larger in the comparative advantage industry. This shows that, in the high tax country, the interaction of policy with trade effects result in a larger share of active firms with improved technology in the clean sector. This result might seem counterintuitive since one might assume that the more emission intensive sector invests more to counteract the negative effects of the higher tax. The difference relies on the fact that the technology upgrade considered here improves both the abatement and the production technology in the same way. Therefore, the better technology has no influence on the relative use of emissions versus intermediate inputs. As a result the firms' decision is driven by the export potential of the industry, which is larger in the clean sector of the high tax country.

As in the previous case, the difference in the share of upgraders depends on the height of the variable trade costs. When trade liberates, the difference between relative goods prices across countries becomes smaller. Since the high tax (low tax) country specialises in the labour (capital) intensive industry, the relative demand for labour will increase (decrease) which results in a decrease (increase) in the relative price of capital. This implies that even though relative goods prices converge in equilibrium the relative price of capital in each country diverges. As in the former section the convergence of relative goods prices results in a smaller difference in the share of active firms that upgrade their technology across sectors when variable trade costs are small compared to when they are large.

The interaction of environmental policy differences and trade result in across sector differences in the effect of trade on the share of firms that updates their technology. For high values of the variable trade costs in the high tax (low tax) country the trade induced increase is relatively larger in the labour (capital) intensive industry. However, for low values of variable trade costs in the high tax (low tax) country the increase in the share upgraders is larger in the capital (labour) intensive industry. This shows that the relative impact of tax differences across countries on technology adoption depends on the level of the variable trade costs.

The fact that environmental policy differences create comparative advantage which changes the relative share of firms that adopts the better technology in each sector, implies that unilateral tax changes have an influence on this depending on the initial tax difference and the direction of the change. Independent of the initial comparative advantage of the home country, assuming that the change does not reverse the countries tax difference, a unilateral increase (decrease) in home's tax relatively encourages (discourages) innovation in the labour intensive industry and relatively discourages (encourages) innovation in the capital intensive industry as a result of the change in relative export potential of both sectors. The reason for this is that a relative tax increase always reduces the foreign market potential of the capital intensive industry.

6.3 Comparative advantage based on factor endowments and taxes

It is interesting to see how the differences in environmental policy affect the comparative advantage induced by differences in factor endowments. The inequality (29) shows that differences in environmental policy across countries either enhances or diminishes the initial comparative advantage[17]. Continue to assume that the home country is labour abundant, which

[17] Theoretically, the difference in taxes can also make the inequality in (29) invalid, which would imply that the differences in environmental policy result in the fact that the home country has a comparative advantage in the capital intensive industry even in the country is relatively more labour abundant. In this paper I assume that this does not happen.

implies that the left hand side of (29) is larger than one. Whether the home country has a comparative advantage in the labour intensive industry depends on the difference in environmental policy across countries. If $(t^H > t^F)$, (29) always holds which implies that the home country has a comparative advantage in the labour intensive industry, which is enhanced by the difference in emission taxes. However, if $(t^H < t^F)$, the difference in environmental policy across countries works in the opposite direction compared to the difference in factor endowments, reducing the initial comparative advantage. This shows that differences in emission policy across countries can change comparative advantage.

If the relatively more labour abundant home country has a relatively higher (lower) emission tax compared to foreign, the initial comparative advantage is larger (smaller) as compared to a situation with equal taxes. This implies that in the home country for a high level of variable trade costs the share of active firms that improved their technology in the labour intensive industry is larger (smaller) when the emission tax in home is higher (lower) than the foreign tax. The opposite holds for the capital intensive industry in the home country. In the relatively capital abundant foreign country the share of active firms that has upgraded their technology in the capital intensive industry is relatively larger (smaller) when the emission tax in foreign is lower (higher) than the tax in the home country. Consequently, the interaction of policy with international trade results in a reduction or an increase in the differences in the share of active firms with improved technology across sectors as compared to a situation in which taxes are equal.

Environmental policy also interacts with the effects of trade liberalisation on the size of the increase in the share of active firms that upgrades their technology. In general the difference in the effect of trade across sectors is smaller (larger) when the difference in emission taxes benefits the opposite (same) industry as the relative factor endowments. The larger the initial comparative advantage (disadvantage) the larger (smaller) the impact of a decrease in variable trade costs on the share of firms that improves their technology in the comparative advantage (disadvantage industry) for smaller levels over trade openness. For lower levels of trade openness the opposite holds.

Besides the impact of trade itself, tax changes can also have an influence on technology updating through its effect on comparative advantage for a given level of trade openness. Assume that in absence of a difference in environmental taxes the home (foreign) country has a comparative advantage in the labour (capital) intensive industry. If the home country increases their tax, the comparative advantage of the labour intensive industry increases, which relatively encourages (discourages) technology upgrading in the labour (capital) intensive industry caused by a change in export potential that benefits the labour intensive industry in the home country. In the foreign country, it relatively encourages (discourages) technology updates in the capital (labour) intensive industry due to an improvement of the relative export potential of the capital intensive industry. The same reasoning holds when the foreign country would unilaterally reduce their environmental tax. If the home country unilaterally reduces their tax, which reduces (increases) the comparative advantage of the labour (capital) intensive industry, the relative difference between the share of firms that updates their technology across sectors becomes smaller since it relatively discourages (encourages) technological change in the labour (capital) intensive industry. Thus, increasing the emission tax never increases the relative share of active firms that improves their technology in the emission intensive industry because it always decreases the relative foreign market potential of the polluting industry. The foreign market potential provides the incentive to upgrade technology in this model.

7. Environmental effects

Technology upgrading can be seen as part of the technique effect of international trade (Najjar & Cherniwchan, 2020), which makes it interesting to analyse how the possibility to upgrade technology has an influence on the emission intensity of firms. Previous research shows that 2/3 of the change in emission intensity in empirical trends is due to the technique effect, that results from within-plant level changes in emission intensity (Cherniwchan, 2017). The model in this thesis allows to analyse the same mechanisms as Najjar and Cherniwchan (2020) focussing on the effect of trade in the presence of policy instead of the effect of policy. In this thesis is focused on the within-firm change in emission intensity, by Najjar and Cherniwchan (2020) defined as the process effect, that is influenced by the possibility to upgrade technology through its impact on productivity.

Given the structure of the model the amount of emissions per unit of net output (emission intensity, e) is optimally chosen by each firm and depends negatively on the productivity of the firm (which includes the upgrade status of the firm) and positively on the relative price of intermediate inputs and emissions. As in the previous sections it is assumed that for a small change in trade openness the factor prices are constant, which implies that the ratio of the relative price of intermediate inputs to the emission tax is assumed to stay constant for a small change in variable trade costs. This assumption potentially overstates the effect of trade on the emission intensity in the presence of an endogenous technology choice since it ignores the increase in demand for capital and labour that leads to an increase in factor prices. This puts an upward pressure on the emission intensity as intermediate inputs become relatively more expensive compared to emissions.

The effect on emission intensity is compared for a high and a low level of variable trade costs. The average emission intensity in sector i of the home country is given by (30).[18]

$$e_i{}^H(\tilde{\varphi}_{iu}^H) = \frac{1}{\tilde{\varphi}_{iu}^H}\left(\frac{\alpha_i}{1-\alpha_i}\frac{p_{xi}^H}{t^H}\right)^{1-\alpha_i} \tag{30}$$

Higher post-upgrade productivity leads to lower demand for emissions because firms not only become more productive in producing potential output but also become equally more efficient in abatement. This results in a decline in emission intensity. As productivity has an equal impact on both production and emissions, productivity changes do not directly change the relative composition of intermediate input and emissions of a firm.

Proposition 5: All else equal an increase in the average industry productivity leads to a decrease in the emission intensity.

The possibility to upgrade adds two additional effects of trade on emission intensity to the model. First, the endogenous choice to improve the production and abatement increases the pre-upgrade average productivity in the market as compared to a situation in which it is not possible. Besides that, the firms that actually upgrade receive benefits which implies that the possibility to upgrade technology introduces a difference between the post- and pre-upgrade average productivity in the market.

Proposition 6: The possibility to upgrade technology enhances the effect of trade on the environment via its effect on average productivity.

Furthermore, both the effect of technology adoption on pre-upgrade average productivity and the difference between the pre- and post-upgrade average productivity depend on the level of trade and comparative advantage. Trade liberalisation increases the average

[18] This is defined as the amount of emissions used in production divided by the total amount of production of a firm ($z_i(\varphi)/q_i(\varphi)$). In order to analyse this it is important to determine the average productivity in a sector. These are discussed in Appendix C.

benefits of the improved technology because firms are able to export more, which has a positive effect on the share of firms that upgrades their technology.

Proposition 7: Trade decreases emission intensity in both sectors through an increase in the pre- and post-upgrade average productivity. Both changes are larger (smaller) in the comparative advantage (disadvantage) industry when variable trade costs are high and become smaller (larger) in the comparative advantage (disadvantage) industry when variable trade costs are small.

This analysis shows that technology improvements provide a mechanism through which trade has an influence on the environmental technique effect. Trade liberalisation increases the share of active firms that improves their technology and the associated productivity benefits, which increases the average sector productivity. Both the share of firms that upgrade their technology and the upgrade benefits are larger in the comparative advantage industry. Therefore, the reduction in emission intensity as a result of the existence of an endogenous technology choice, because of within-firm productivity improvements, is larger in the comparative advantage industry. Furthermore, the downward pressure of trade liberalisation on emission intensity is enhanced due to the possibility to adopt a better technology.

8. Abatement upgrade

In this section the case is explored in which the technology upgrade does not influence the production of potential output but only has an influence on the abatement efficiency, which implies that the technology improvement can be considered a green improvement instead of a general improvement. The main difference as compared to the general upgrade is that it leads to the fact that the upgrade benefits (ϕ) will be to the power α_i for each sector, which results in differences in the average and the cut-off productivity level across sectors in autarky. To see this it is assumed that the upgrade only improves the abatement efficiency of the firm and therefore only improves φ in the abatement function (5). As a result the net output function for a firm that upgrades their technology becomes (30).

$$q_i(z_i, x_i) = \varphi(\phi z_i)^{\alpha_i}(x_i)^{(1-\alpha_i)} \tag{30}$$

Given this net output function the cost function of a firm is given by (7). However, for a firm that does the upgrade the productivity is now $\phi^{\alpha_i}\varphi$ instead of $\phi\varphi$. This results in the following relationship (31) between the zero profit cut-off productivity level and the minimum productivity level for doing the abatement technology upgrade in autarky.

$$\left(\frac{\varphi_{iU}^*}{\varphi_{iD}^*}\right)^{\sigma-1} = \frac{\delta f_U}{((\phi^{\alpha_i})^{\sigma-1}-1)f_D} \tag{31}$$

This shows that if the technology upgrade only has an influence on abatement efficiency, the minimum productivity for doing the upgrade differs across sectors. More specifically, a larger share of firms will do the upgrade in the sector that relies more on emissions. The reason for this is that the benefits of the upgrade are larger in the more emission intensive sector, which results in less productive firms to find it optimal to invest. In the free trade equilibrium all firms are able to export, which implies that there is no change in the relative share of active firms that improves their technology.

When considering the costly trade equilibrium there cannot be any differences in average productivity across sectors in autarky. Therefore, it is assumed that alpha is equal across sectors in both countries. In the previous sections the impact of the technology upgrading is the same across sectors even though alpha is different because both the abatement efficiency and the productivity for producing potential output are affected in the same way. If only abatement efficiency is affected and alpha equal is equal across sectors, the impact of the upgrade is the same across industries because there is no difference in upgrade benefits across sectors.

Given this assumption on alpha, comparative advantage is only the result of differences in relative factor endowments and cannot be the result of taxes since both sectors are affected by the tax in the same way. In autarky the relative prices are given by (31), which implies that a country has a comparative advantage in the sector that is intensive in the production factor the country is abundant in.

$$\frac{P_1}{P_2} = \left(\frac{\eta_1}{\eta_2}\right)^{\frac{1}{1-\sigma}} \left(\left(\frac{r}{w}\right)^{(1-\alpha)(\beta_1-\beta_2)}\right)^{\frac{\sigma}{1-\sigma}} \tag{31}$$

The share of active firms that has improved technology is determined in the same way as in chapter 5 and is given by (32). Following the same reasoning as in chapter 5, (32) shows that a decline in the variable trade costs leads to an increase in the share of upgrading firms in each sector. Again, this result is similar to the results found by Navas (2018). The impact of comparative advantage on the result is the same as before. If the home country has a comparative advantage in the labour intensive industry the share of active firms that upgrades their abatement technology is larger in this industry. However, the effect is smaller as compared to the situation in which the improvement affects production of potential output as well.

$$\left(\frac{{\varphi_{Ui}^{*}}^{H}}{{\varphi_{i}^{*}}^{H}}\right)^{\sigma-1} = \frac{1}{\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)((\phi^{\alpha})^{\sigma-1}-1)}\frac{\delta f_U}{f_d} \tag{32}$$

Whereas, relative emission intensity across firms depended on the difference between alpha in the previous case, now firms in each sector pollute an unequal amount per unit of production across sectors only because of comparative advantage. Differences in the relative emission intensity across sectors (33) in this case are determined by the differences in post-upgrade average productivity and the relative price of intermediate inputs, which can be expressed as the relative price of production factors. It can be concluded that the average emission intensity is smaller in the comparative advantage industry because the post-upgrade average productivity is larger.

$$\frac{{e_{1DU}}^{H}(\tilde{\varphi}_1^H)}{{e_{2DU}}^{H}(\tilde{\varphi}_2^H)} = \frac{\frac{1}{\tilde{\varphi}_{1DU}^H}\left(\frac{\alpha}{1-\alpha}\frac{p_{x1}^H}{t^H}\right)^{1-\alpha}}{\frac{1}{\tilde{\varphi}_{2DU}^H}\left(\frac{\alpha}{1-\alpha}\frac{p_{x2}^H}{t^H}\right)^{1-\alpha}} = \frac{\tilde{\varphi}_{2DU}^H}{\tilde{\varphi}_{1DU}^H}\left(\frac{i^H}{w^H}\right)^{(1-\alpha)(\beta_1-\beta_2)} \tag{33}$$

This explorative section shows that even when sectors in countries have equally emission intensive technologies, trade can still have a differential impact on technology upgrading across sectors because of the comparative advantage resulting from factor endowments. However, the difference is that now the benefits of the upgrade are smaller and depend on the parameter alpha. It could be interesting to explore this result in future research by making a costly trade model with heterogeneous firms that can both include endogenous abatement efficiency upgrades and comparative advantage as a result of environmental policy.

9. Evidence

This chapter compares the theoretical results found in the model with observations in data. For this purpose three hypotheses derived from the model's results are compared with evidence from the revealed comparative advantage sectors in The Netherlands. Although The Netherlands has the largest comparative advantage in service sectors like transport and storage, finance and insurance and R&D (Oomes et al., 2017), the sectors that will be considered in this chapter are three sectors that export goods in order to make a clear comparison with the models' results. These sectors are agro-food, chemicals and petroleum products (respectively 12%, 8% and 6% of value added exports in 2011). When considering energy use, the chemical industry uses the most with 63% of the total use in the industrial sector (in 2018) (CBS, 2019). The chemical industry is followed by the other two that both also use a considerable amount of energy in production. However, when considering emission intensity, data shows that the petroleum industry is leading (CBS,2019). Furthermore, over years the emission intensity has declined in all these industries.

The nature of these sectors makes them useful to analyse the impact of environmental policy on their comparative advantage and how productivity enhancing innovation in relationship to trade might have an influence on the decline in emissions. The comparisons made in this chapter are not causal in nature but try to provide some insights in whether the theoretical mechanisms from the model are present in reality. The hypotheses derived from the model are discussed in the next subsection followed by a short review of information the sectors and some concluding remarks.

9.1 Hypotheses.

This section provides three hypotheses derived from the theoretical model. First, the results of the model shows that environmental policy differences across countries have an impact on (initial) comparative advantage, which in turn has an influence on the share of firms that upgrades their technology in each sector. If environmental policy differences affect comparative advantage one would assume that it has an influence on trade patterns via changes in relative production costs across sectors and countries. Empirical research shows that environmental regulation creates relative differences in production costs across sectors i.e. sectors can be affected differently by a policy (Dechezleprête & Sato, 2017).

Hypothesis 1: Differences in environmental stringency across countries has an influence on comparative advantage.

Second, the model predicts that independent of the type of technology upgrade that is available (improving general productivity or abatement efficiency), more firms choose to improve their technology upgrade in the comparative advantage industry of a country. This implies that it is expected that the comparative advantage industries are the leaders in environmental technology adoption and production process improvements. It is important to note that the technology improvement considered in the model does not directly have an influence on the tax burden per emission which makes that firms cannot reduce it by making the decision to update their technology. This results in the second hypothesis.

Hypothesis 2: The comparative advantage sectors are leading in the adoption of more productive (environmental) technologies.

Lastly, the model makes predictions on emission intensity of firms. In general, the results suggest that trade liberalisation puts a downward pressure on the average emission intensity of firms in a sector. This result is also found in empirical research using data on the emissions of single plants in the United States in relation to changes in trade between the United States and Mexico due to changes in tariffs (Cherniwchan, 2017). In general these results show that an increase in the tariff preferences, decreases the emissions of firms in the United States on the plant level. According to the predictions in this thesis the effect is stronger in the comparative advantage sector, which would imply that industries that export relatively more have a relatively lower emission intensity than a similar sector (in emission use) with a smaller export share. Since, making comparisons is difficult without controlling for other differences across sectors, the following hypothesis has been formulated.

Hypothesis 3: Emission intensity is on average lower in comparative advantage sectors and can be affected by productivity enhancing technology improvements.

9.2 Agro-food sector

The agro-food sector is named as the largest goods exporting comparative advantage sector in the Netherlands (Oomes et al., 2017). The sector includes everything that has to do with the production of food products and agriculture. Over the period 2011-2019 exports of the sector has been growing with 45% and in 2019 72,5% of these exports was Dutch production (Jukema, Ramaekers & Berkhout, 2020). However, there are concerns that comparative advantage is affected by unequal environmental policy and laws across countries. Environmental costs have to be, for at least to some extent, passed on in prices, which puts a downward pressure on the position of the Dutch firms on the world market if environmental costs are unequal. Several examples of environmental policy that seemed to have an influence on the comparative advantage of firms in the agro-food sector can be named. For example, a EU policy that forces firms to use 10% biofuel in their energy increased both the prices of Dutch firms and had an influence on imports and emissions elsewhere (Silvis et al., 2009). Furthermore, the introduction of the CO_2 permit trading system specifically for the greenhouse horticulture part of the agro-food sector did reduce the production for those firms because of the increased production costs.

The Dutch agro-food sector is leading internationally regarding the production technologies that are used (Jukema, Ramaekers & Berkhout, 2020). Furthermore, the plans of the sector for the period 2019-2030, as stated in the “kennis en innovatie agenda” of the “Ministerie of landbouw, natuur en voedselkwaliteit”, show high ambition for innovation both productivity enhancing and sustainable. Technology improvements using the knowledge that is present in the country are executed which allows the sector to maintain their position on the world market. Besides that firms of the same size in this sector export larger volumes as compared to in other sectors. The high export levels go hand in hand with higher investments in R&D for these firms. These facts seem to be in line with hypotheses two.

Additionally, there have been large investments in the greenhouse horticulture sub-sector to reduce the use of energy use after that it became subject to the CO_2 permit trading system of the EU (Silvis et al., 2009). Since, the increase of the emission price increased production prices it reduced the comparative advantage of the sector. In contrast to the predictions of the theoretical model that a reduction in comparative advantage results in less innovation in the sector, firms responded to this by doing large investments in green production processes. However, these investments were directly focussed on the reduction of the impact that the permit trading system has, which is different from the productivity enhancing technology that was modelled, which can explain this difference.

The growth of the Dutch Agro-Food sector in the last 25 years has been accompanied with significant progress environmentally (Jukema, Ramaekers & Berkhout, 2020). Data on both factor productivity and exports show an increase of 60% and 24-28% respectively over the period 1995 to 2019. Over the same period the emission intensity of firms in the sector has declined. This can be attributed to a 50% increase in the energy efficiency and a decline in emissions of greenhouse gasses (15%) and of acidifying substances (45%). Furthermore, within the agro-food sector a larger increase in production volumes has been observed in the relatively cleaner non-animal sectors as compared to the subsectors that produce animal products.

All in all the Agro-food sector in the Netherlands shows the effects that are found in the model. This comparative advantage sector has seen an increase in export and production accompanied with innovative developments that have improved the processes and productivity. At the same time there have been improvements environmentally.

9.3 Chemicals

The chemical industry is the second comparative advantage sector of the Netherlands (Oomes et al., 2017). The export of chemical products grew over the period 2002 to 2017 (CBS, 2018b). However, the share of the total Dutch exports of products made in the Netherlands has stayed around the same level. The chemical industry has the largest environmental burden of all sectors in the Netherlands (CLO, 2020a). In 2013 the Dutch chemical industry had on average a trade intensity of around 30% with countries that do not fall under the ETS (Emission Trading System) (Triple, 2013) Estimates show that an emission price of €20 per ton CO_2 would result in significant changes in production costs and prices. Additionally, it will affect their comparative position with respect to the countries that are not affected by the ETS.

Starting from 1995 the production efficiency has increased the most in the chemical sector out of the wider industrial sector in the Netherlands (CBS, 2008). Indeed over the period since 1995 the reduction of the emission intensity in the chemical sector can be linked to an improvement of processes that increase the efficiency of production (CLO, 2020b). The share of innovative companies in the chemical industry (including the petroleum industry) in the period 2016 to 2018 is 73%, which is significantly larger than the average of 55% in the industrial sector and 37% in the country (CBS, 2020). These innovations are largely process innovations or a combination of process and product innovations. Additionally, plans within the sector for the period until 2050 name among other things improvements in the production technology as a way to increase both productivity and sustainability, by making use of less inputs for the same amount of production (ChemistryNL, 2020). This supports the idea that process improvements can lower emission intensity.

In the 10 years prior to 2016 the Dutch chemical sector saw a larger decrease in emission intensity as compared to other emission intensive sectors (Joosse, 2019). Furthermore, over the same period there has been a decline in the total emissions of the sector whereas the output has increased (De Thouars, 2018). This seems to be in line with the models' results that find that the comparative advantage sector has a relatively lower emission intensity as similar sectors that do not have a comparative advantage in the Netherlands. However, the chemical industry's emission intensity, based on CO_2 per unit of output, is slightly larger when comparing the Dutch sector to the rest of the European Union (CBS, 2018a).

9.4 Petroleum Products

Over the period 2002 to 2017 the export of petroleum products produced in The Netherlands has increased and the sector exports increased from 11% to 14% of total export (CBS, 2018b). Several studies on the effects of CO_2-pricing show that it can affect the comparative and competitive position of refineries (de Bruyn et al., 2018). These studies show that the complex refineries are affected less as compared to other refineries within one country. However, investments that improve environmental quality do not seem to provide productivity improvements (de Bruyn et al., 2018). Furthermore, if investments are needed to comply with environmental restrictions the comparative position is reduced even more. This shows that for this sector environmental policy has an influence on the international position of the sector mainly through the large investments that have to be done to improve environmental quality which puts pressure on the margins in the industry. However, a lot of countries seem to be affected by environmental policy in a similar way as compared to The Netherlands (Plomp et al., 2015). This can be attributed to the fact that the most trading partners of the Netherlands are in Europe (Triple, 2013). However, the Dutch trade with countries outside the EU is larger compared to other European countries.

As compared to the rest of Europe the Dutch refineries have a relatively high productivity in their production process (Triple, 2013). Also in comparison with other (industrial) sectors the petroleum industry has a relatively larger share of innovative firms over the period 2016 to 2018 (CBS, 2020). Again as in the chemical industry, these innovations are largely process innovations. This seems to be in line with the theoretical prediction that the comparative advantage industry has a relatively larger share of innovative firms as compared to other sectors.

The petroleum industry is the sector that has the highest emission intensity of the sectors that are considered in this chapter (CBS, 2019). However, in comparison to other countries the Dutch sector is leading in productivity and has lower emissions as compared to other countries (Plomp et al., 2015). The Dutch sector has a relatively lower emission intensity as compared to the average in the EU-21 (CBS, 2018a). This is based on a comparison of the amount of emissions per unit of product. These facts, a higher productivity and lower emission, seem to comply with the results found in the model of this thesis.

9.5 Conclusion

In general the comparison of the model's results with empirical data and information on the three main goods exporting Dutch industries shows similar results as the model in this thesis.

The comparative advantage industries considered in this chapter can be affected by differences in environmental policy. Therefore, the first hypothesis brought forward by the theoretical model is similar to observations of reality. In the agro-food sector, specific environmental restrictions or CO_2-pricing result in an upward pressure on production costs and export prices. Estimates on the effect of an emission trading system on the chemical industry shows that it can increase prices relative to non-affected firms in other countries. Additionally, evidence from the petroleum industry shows that environmental policy has to be unequal across countries in order to affect comparative advantage.

The second hypothesis stating that the comparative advantage sectors are leading in their used technologies can also be seen when looking at developments in the considered sectors. More specifically, data on the agro-food sector shows that firms of the same size in other sectors export less and invest less in R&D. In the chemical industry production efficiency has increased the most within the wider Dutch industrial sector. Furthermore, the share of innovative firms is larger in the chemical and petroleum industry compared to the Dutch average.

The third hypothesis stating that the emission intensity is lower in sectors that invest more in productivity enhancing technologies can also be observed. In the agro-food sector there can be seen an increasing trend in factor productivity as well as a decreasing trend on emission intensity. Also in the chemical industry productivity improvements go hand in hand with a decreasing emission intensity. Additionally, the highly innovative Dutch petroleum sector has relatively lower emission intensity as compared to other countries.

10. Conclusion

In this thesis a two-country two-sector international trade model with heterogeneous polluting firms that are able to upgrade their (abatement) technology is presented in order to analyse the effects of trade on technology upgrades in the presence of taxed emission. The following main conclusions arise.

Trade liberalisation increases the share of active firms that improves their production and/or abatement technology in all industries. The introduction of taxed pollution in the model does not change the mechanism behind this effect also found in previous research on the impact of trade on endogenous technology adoption by Navas (2018), Bustos (2011) and Cui (2017). Trade liberalisation increases the access to the foreign market which increases the benefits of improved production technology and abatement efficiency while leaving the costs constant. In addition, comparative advantage leads to differences across sectors. The export potential is better in the comparative advantage industry, which results in the fact that a larger share of active firms has adopted the more productive technology in that sector. Additionally, the model predicts that the effect of trade liberalisation differs based on comparative advantage. Trade liberalisation results in a larger (smaller) increase in the share of firms that has improved technology in the comparative advantage industry when variable trade costs are initially high (low).

As opposed to the result found using a one-sector trade model (Cui, 2017), this thesis shows that a technology update does not have to be clean to be affected by environmental policy when two-sectors are considered. Indeed, the model in this thesis shows that environmental policy can create comparative advantage as found by Cole et al, (2010), Millimet & Roy (2016) and Ollivier (2016), and results in compositional changes as found by Cole & Elliott (2003) and Broner et al. (2012). Furthermore, the results show that environmental policy interacts with comparative advantage based on factor endownmets and has an influence on the effect of trade on technology adoption in both countries. In accordance with the mechanism proposed by Gong et al. (2020), this thesis shows that higher relative emission taxes in a country can reduce a pre-existing comparative advantage of the country's polluting industry. However, the model in this thesis predicts that this will reduce the share of active firms that improves their technology and the impact that trade has on this instead of an increase as they propose. In general, the difference in the effect of trade on technology adoption across sectors is smaller (larger) when the difference in the emission taxes across countries benefits the opposite (same) industry as the relative factor endowments. This difference is the result of the fact that in this thesis a general technology improvement is considered instead of a green upgrade. Since the technology improvements in this thesis do not reduce use of emissions as compared to intermediate inputs policy changes do not have an influence on the share of firms that adopt the better technology.

Technology improvements provide a mechanism through which trade has an influence on environmental outcomes (emission intensity) through the technique effect via its influence on average sector productivity. This mechanism could be a potential explanation for the empirical finding that emissions declined because of within-firm changes in emission intensity instead of the reallocation of resources across firms within sectors as a result of trade (Cherniwchan, 2017; Levinson, 2009; Forslid et al., 2018; Richter & Schiersch, 2017). The model in this thesis shows that the existence of an improved technology enhances the effect of trade on the average sector emission intensity via the technique effect because of both the interaction with the reallocation effect and an additional effect that is generated by the upgrade. This result could provide insights for empirical research on the effect of international trade on environmental outcomes. The relatively larger additional effect of trade on emission intensity via the upgrade benefits in the comparative advantage industry could hide a composition effect of trade even more if it is not controlled for.

Due to the focus of this thesis on the technique effect, the effects of an available better technology on environmental outcomes via the scale and composition effects are not considered. However, considering these would provide insights on the extent to which the technology choice has an influence on aggregate pollution. The possibility to upgrade has an influence on the pace at which relative factor prices change as a result of trade liberalisation as found by Navas (2018). For simplicity, in this thesis the impact of trade on technology choice and emission intensity is analysed at two levels of trade openness. However, considering the behaviour of the share of upgraders over an entire range of variable trade costs would make it possible to elaborate on the interaction of environmental policy and other sources of comparative advantage.

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Appendix A

Proofs of propositions.

Effect on technology upgrades

The share of active firms that does the technology upgrade in equilibrium (S_1^H) is given by (using the productivity distribution).

$$S_1^H = \left(\frac{\varphi_{Ui}^{*\,H}}{\varphi_i^{*H}}\right)^{-k} = \left(\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)((\phi)^{\sigma-1}-1)\frac{f_d}{\delta f_u}\right)^{\frac{k}{\sigma-1}} \quad (1)$$

The equilibrium zero-profit productivity cut-off level is given by (2).

$$\varphi_i^{*H} = \left[\frac{\underline{\varphi}^k}{\delta f_e}\frac{\sigma-1}{k-\sigma+1}\left(f_D+\left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{-k} f_X\right.\right.$$
$$\left.\left. + (\delta f_U)^{1-k}\left(1+\left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{1-\sigma}\frac{f_x}{f}\right)^k\left((\phi^{(\sigma-1)}-1)f_D\right)^k\right)\right]^{\frac{1}{k}} \quad (2)$$

The minimum productivity cut-off level for improving the technology is given by (3).

$$\varphi_{Ui}^{*\,H} = \left(\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)((\phi)^{\sigma-1}-1)\frac{f_d}{\delta f_u}\right)^{-\frac{1}{\sigma-1}}\left[\frac{\underline{\varphi}^k}{\delta f_e}\frac{\sigma-1}{k-\sigma+1}\left(f_D+\left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{-k} f_X\right.\right.$$
$$\left.\left. + (\delta f_U)^{1-k}\left(1+\left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{1-\sigma}\frac{f_x}{f}\right)^k\left((\phi^{(\sigma-1)}-1)f_D\right)^k\right)\right]^{\frac{1}{k}} \quad (3)$$

Proposition 1: In order to proof that the productivity benefits have a positive effect on the share of active firms that upgrades, the derivative to $((\phi)^{\sigma-1}-1)$ is taken (4). If the benefits of the upgrade increase, $((\phi)^{\sigma-1}-1)$ increases. This derivative is positive which implies that all else equal an increase in the productivity benefits of the improved technology leads to an increase of the share of upgrading firms.

$$\frac{\partial S_1^H}{\partial((\phi)^{\sigma-1}-1)} = \frac{k}{\sigma-1}\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)\frac{f_d}{\delta f_u}\left(\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)((\phi)^{\sigma-1}-1)\frac{f_d}{\delta f_u}\right)^{\frac{k-\sigma+1}{\sigma-1}} \quad (4)$$

This effect is result of an increase in the zero profit cut-off level $\partial\varphi_i^{*H}/\partial((\phi)^{\sigma-1}-1) > 0$ and a reduction in the minimum productivity level for doing the upgrade $\partial\varphi_{iU}^{*H}/\partial((\phi)^{\sigma-1}-1) < 0$. This implies that an increase in the upgrade benefits both results in the fact that firms have to be more productive in order to be active in the market but firms have to be less productive to be able to upgrade.

Proposition 2: The derivative of (1) to τ is given by (5). This derivative is negative which implies that all else equal a decrease in the variable trade costs (an increase in the trade openness) results in an increase in the share of active firms (note: this method omits the effect that a small change in τ leads to a change in the relative prices and the relative revenues).

$$\frac{\partial S_i^H}{\partial \tau} = -k\left((\phi)^{\sigma-1}-1\right)\frac{f_d}{\delta f_u}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}\tau^{\sigma}\left(\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)\left((\phi)^{\sigma-1}-1\right)\frac{f_d}{\delta f_u}\right)^{\frac{k-\sigma+1}{\sigma-1}} \quad (5)$$

Again this effect results from an increase in the zero-profit productivity cut-off level $(\partial \varphi_i^{*H}/\partial \tau > 0)$ and a decrease in the cut-off level for the upgrade $\left(\partial \varphi_{iU}^{*H}/\partial \tau < 0\right)$.

Proposition 3: To show that the share of upgrading firms is larger in the comparative advantage industry it needs to be that if $S_i^H > S_j^H$, that the home country has a comparative advantage is sector i. Comparing the shares gives (6).

$$\left(\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)\left((\phi)^{\sigma-1}-1\right)\frac{f_d}{\delta f_u}\right)^{\frac{k}{\sigma-1}} > \left(\left(\tau^{1-\sigma}\frac{R^F\left(P_j^F\right)^{\sigma-1}}{R^H\left(P_j^H\right)^{\sigma-1}}+1\right)\left((\phi)^{\sigma-1}-1\right)\frac{f_d}{\delta f_u}\right)^{\frac{k}{\sigma-1}} \quad (6)$$

Simplification of this expression shows that this holds when $P_i^F/P_i^H > P_j^F/P_j^H$, which is equal to $P_i^F/P_j^F > P_i^H/P_j^H$. This implies that the share of upgrading firms is larger in the comparative advantage industry.

Proposition 4: The effect of a decrease in variable trade costs is larger in the comparative advantage industry when $\partial S_i^H/\partial \tau > \partial S_j^H/\partial \tau$.

$$-k\left((\phi)^{\sigma-1}-1\right)\frac{f_d}{\delta f_u}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}\tau^{\sigma}\left(\left(\tau^{1-\sigma}\frac{R^F(P_i^F)^{\sigma-1}}{R^H(P_i^H)^{\sigma-1}}+1\right)\left((\phi)^{\sigma-1}-1\right)\frac{f_d}{\delta f_u}\right)^{\frac{k-\sigma+1}{\sigma-1}}$$
$$> -k\left((\phi)^{\sigma-1}-1\right)\frac{f_d}{\delta f_u}\frac{R^F\left(P_j^F\right)^{\sigma-1}}{R^H\left(P_j^H\right)^{\sigma-1}}\tau^{\sigma}\left(\left(\tau^{1-\sigma}\frac{R^F\left(P_j^F\right)^{\sigma-1}}{R^H\left(P_j^H\right)^{\sigma-1}}+1\right)\left((\phi)^{\sigma-1}-1\right)\frac{f_d}{\delta f_u}\right)^{\frac{k-\sigma+1}{\sigma-1}}$$

$$\frac{P_i^F}{P_i^H}\left(\tau^{1-\sigma}\frac{R^F\left(P_i^F\right)^{\sigma-1}}{R^H\left(P_i^H\right)^{\sigma-1}}+1\right)^{k-\sigma+1} > \frac{P_j^F}{P_j^H}\left(\tau^{1-\sigma}\frac{R^F\left(P_j^F\right)^{\sigma-1}}{R^H\left(P_j^H\right)^{\sigma-1}}+1\right)^{k-\sigma+1}$$

This shows that the impact of a change in the comparative advantage industry is larger since the above inequality only holds true when $P_i^F/P_i^H > P_j^F/P_j^H$. The effect of a change in τ depends on the level of τ and the relative goods prices at that level of trade openness. Since $P_i^F/P_i^H > 1$ for each level of $\tau > 1$ in the comparative advantage sector and the relative goods prices are closer to one for smaller levels of τ in this sector, the effect of a decrease in the variable trade costs is smaller when trade is more open. This implies that the increase in the share of firms that upgrades their technology as a result of trade liberalisation is smaller for smaller levels of variable trade costs. In the comparative disadvantage sector the relative goods prices across countries are smaller than one ($P_i^F/P_i^H < 1$) and converge in the direction of one when variable trade costs decline. This implies that the effect of trade increases in the comparative disadvantage sector when variable trade costs decline.

Effect of trade via upgrade possibility on emission intensity

Proposition 5: To show that the emission intensity depends negatively on the average productivity in the industry the partial derivative of the emission intensity (30).

$$\frac{\partial e_i{}^H(\tilde{\varphi}_{iDU}^H)}{\partial \tilde{\varphi}_{iDU}^H} = -\frac{\left(\frac{\alpha_i \ p_{xi}^H}{1-\alpha_i \, t^H}\right)^{1-\alpha_i}}{\left(\tilde{\varphi}_{iDU}^H\right)^2} < 0 \tag{6}$$

The derivative (6) is negative which implies that, all else equal, an increase in the average productivity reduces the emission intensity.

Proposition 6: To show that the possibility to upgrade increases both the pre- and post-upgrade average productivity ($\tilde{\varphi}_{iDU}^H, \tilde{\varphi}_{iD}^H$), the situation $\phi = 1$ (upgrade has no benefits) is compared with $\phi > 1$. The pre- and post- upgrade productivity are given by (7) and (8) respectively.

$$\tilde{\varphi}_{iDU}^H = \left[1 + \left[\left(\frac{\varphi_{iU}^*}{\varphi_{iD}^*}\right)^{-k} (\phi^{\sigma-1} - 1)\right]^{\frac{1}{\sigma-1}} \left(\tau^{1-\sigma} \frac{R^F}{R^H} \left(\frac{P_i^F}{P_i^H}\right)^{\sigma-1} + 1\right) (\phi^{\sigma-1} - 1) \frac{\delta f_u}{f_d}\right] \tilde{\varphi}_{iD}^H \tag{7}$$

$$\tilde{\varphi}_{iD}^H = \left(\frac{k}{k-\sigma+1}\right)^{\frac{1}{\sigma-1}} \left[\frac{\underline{\varphi}^k}{\delta f_e} \frac{\sigma-1}{k-\sigma+1} \left(f_D + \left(\tau \frac{P_i^H}{P_i^F} \left(\frac{R^H}{R^F} \frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{-k} f_X\right.\right.$$
$$\left.\left. + (\delta f_U)^{1-k} \left(1 + \left(\tau \frac{P_i^H}{P_i^F} \left(\frac{R^H}{R^F} \frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{1-\sigma} \frac{f_x}{f}\right)^k \left(\left(\phi^{(\sigma-1)} - 1\right) f_D\right)^k\right)\right]^{\frac{1}{k}} \tag{8}$$

If $\phi = 1$, (7) becomes $\tilde{\varphi}_{iDU}^{H} = \tilde{\varphi}_{iD}^{H}$, which implies that there is no difference between the average pre- and post-upgrade. When the upgrade does not have benefits the share of firms that upgrade is zero. Additionally, the pre-upgrade average productivity is lower if $\phi = 1$, because the third term between the squared brackets is zero. Since emission intensity and average productivity are negatively related this implies that all else equal the emission intensity is lower.

Proposition 7:

$$\frac{\partial \tilde{\varphi}_{iDU}^{H}/\tilde{\varphi}_{iD}^{H}}{\partial \tau} = -(\phi^{\sigma-1}-1)\frac{\delta f_u}{f_d}\left[\left((\sigma-1)\tau^{-\sigma}\frac{R^F}{R^H}\left(\frac{P_i^F}{P_i^H}\right)^{\sigma-1}\right)\left(\left(\frac{\varphi_{iU}^{*\;H}}{\varphi_i^{*H}}\right)^{-k}(\phi^{\sigma-1}-1)\right)^{\frac{1}{\sigma-1}} + k(\phi^{\sigma-1} - 1)\left(\frac{\varphi_{iU}^{*\;H}}{\varphi_i^{*H}}\right)^{-(k+1)}\left(\tau^{1-\sigma}\frac{R^F}{R^H}\left(\frac{P_i^F}{P_i^H}\right)^{\sigma-1}+1\right)\left(\left(\frac{\varphi_{iU}^{*\;H}}{\varphi_i^{*H}}\right)^{-k}(\phi^{\sigma-1}-1)\right)^{\frac{-\sigma}{\sigma-1}}\frac{\partial\left(\varphi_{Ui}^{*\;H}/\varphi_i^{*H}\right)}{\partial\tau}\right]$$

The derivative of (7) divided by (8), is negative which implies that a decline in the variable trade costs, increases the difference between the pre- and post-upgrade productivity. This implies that the interaction between international trade and technology upgrades is able to reduce emission intensity.

$$\frac{\partial \tilde{\varphi}_{iD}^{H}}{\partial \tau} = -\left(\frac{k}{k-\sigma+1}\right)^{\frac{1}{\sigma-1}}\frac{1}{k}\left(k\tau^{-(k+1)}\left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{-k} f_X + k\,(\sigma-1)\,(\delta f_u)^{1-k}\left((\phi^{\sigma-1}-1)f_d\right)^k\frac{f_X}{f}\left(1+\left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{1-\sigma}\frac{f_x}{f}\right)^{k-1}\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\tau^{-\sigma}\right)$$

$$\left[\frac{\underline{\varphi}^k}{\delta f_e}\frac{\sigma-1}{k-\sigma+1}\left(f_D+\left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{-k} f_X + (\delta f_U)^{1-k}\left(1+\left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{1-\sigma}\frac{f_x}{f}\right)^k\left((\phi^{(\sigma-1)}-1)f_D\right)^k\right)\right]^{\frac{1-k}{k}}$$

The derivative of (8) is negative which implies that the pre-upgrade productivity increases when the variable trade costs decline. Since both P_i^F/P_i^H and $\left(\frac{\varphi_{iU}^{*\;H}}{\varphi_i^{*H}}\right)^{-k}$ are larger in the comparative advantage industry, the effect is larger in the comparative advantage industry.

Appendix B

Derivation of consumption and production

Derivation of the consumer demand for a single variety: The consumers minimise their costs per unit of utility (U). The optimisation problem looks the following:

$$\Lambda = C_1 P_1 + C_2 P_2 + \lambda \left(1 - \frac{C_1^{\eta_1} C_2^{\eta_2}}{\eta_1^{\eta_1} \eta_2^{\eta_2}}\right)$$

The first order conditions are:

$$\frac{\partial \Lambda}{\partial C_1} = P_1 - \lambda \frac{\eta_1 C_1^{\eta_1 - 1} C_2^{\eta_2}}{\eta_1^{\eta_1} \eta_2^{\eta_2}} = 0$$

$$\frac{\partial \Lambda}{\partial C_2} = P_2 - \lambda \frac{\eta_2 C_2^{\eta_2 - 1} C_1^{\eta_1}}{\eta_1^{\eta_1} \eta_2^{\eta_2}} = 0$$

From this follows the following relationship between C_1 and C_2.

$$\frac{P_1}{P_2} = \frac{\eta_1 C_1^{\eta_1 - 1} C_2^{\eta_2}}{\eta_2 C_2^{\eta_2 - 1} C_1^{\eta_1}} = \frac{\eta_1 C_2}{\eta_2 C_1}$$

$$C_2 = \frac{\eta_2}{\eta_1} \frac{P_1}{P_2} C_1$$

Combining this with the side constraint $\left(1 = \frac{C_1^{\eta_1} C_2^{\eta_2}}{\eta_1^{\eta_1} \eta_2^{\eta_2}}\right)$ gives the consumption of each variety per unit of utility.

$$C_1 = \eta_1 \left(\frac{P_2}{P_1}\right)^{\eta_2}$$

$$C_2 = \eta_2 \left(\frac{P_1}{P_2}\right)^{\eta_1}$$

P_u is the price per unit of utility. R/ P_u is the total amount of utility that a consumer can get for the revenue (R).

$$P_U = P_1 \eta_1 \left(\frac{P_2}{P_1}\right)^{\eta_2} + P_2 \eta_2 \left(\frac{P_1}{P_2}\right)^{\eta_1} = P_1^{\eta_1} P_2^{\eta_2}$$

The demand per unit C_i can be determined by using sheppard's lemma.

$$\frac{\partial P_i}{\partial p_i(\omega)} = \left(\frac{p_i(\omega)}{P_i}\right)^{-\sigma}$$

This implies that the total demand for a single variety is.

$$q_1(\omega) = \eta_1 \left(\frac{P_2}{P_1}\right)^{\eta_2} \left(\frac{p_1(\omega)}{P_1}\right)^{-\sigma} \frac{R}{P_u} = \eta_1 R p_1(\omega)^{-\sigma} {P_1}^{\sigma-1}$$

$$q_2(\omega) = \eta_2 \left(\frac{P_1}{P_2}\right)^{\eta_1} \left(\frac{p_2(\omega)}{P_2}\right)^{-\sigma} \frac{R}{P_u} = \eta_2 R p_2(\omega)^{-\sigma} {P_2}^{\sigma-1}$$

Derivation of the production side: The first step of the derivation is minimising the costs of intermediate inputs by choosing the optimal amounts of inputs to use in production of it.

$$c^p{}_i(i, w) = \underset{\{k,l\}}{min} \{ik + wl : \ x_i(k, l) = 1\}$$

Optimisation problem:

$$\Lambda = ik + wl + \lambda \left(1 - \frac{l^{1-\beta_i} k^{\beta_i}}{\beta^{\beta_i}(1-\beta)^{(1-\beta_i)}}\right)$$

FOC:

$$\frac{\partial \Lambda}{\partial k} = \ i - \lambda \frac{\beta_i l^{1-\beta_i} k^{\beta_i - 1}}{\beta^{\beta_i}(1-\beta_i)^{(1-\beta_i)}} = 0$$

$$\frac{\partial \Lambda}{\partial l} = \ w - \lambda \frac{(1-\beta_i) l^{1-\beta_i-1} k^{\beta_i}}{{\beta_i}^{\beta_i}(1-\beta_i)^{(1-\beta_i)}} = 0$$

$$\frac{i}{w} = \frac{\lambda}{\lambda} \frac{\beta_i l^{1-\beta_i} k^{\beta_i - 1}}{\beta^{\beta_i}(1-\beta_i)^{(1-\beta_i)}} = \frac{\beta_i}{1-\beta_i} \frac{l}{k}$$

$$l = \frac{1-\beta_i}{\beta_i} \frac{r}{w} k$$

Using the side constraint this gives the following relatiosnhips between the amount of capital and labour used as compared to the relative price on the factor:

$$k = \beta_i \left(\frac{w}{r}\right)^{(1-\beta_i)}$$

$$l = (1-\beta_i) \left(\frac{r}{w}\right)^{\beta_i}$$

This implies that the price of one unit of intermediate inputs is:

$$p_{xi}(r,w) = r\left(\beta_i\left(\frac{w}{r}\right)^{(1-\beta_i)}\right) + w\left((1-\beta_i)\left(\frac{r}{w}\right)^{\beta_i}\right) = w^{1-\beta_i}r^{\beta_i}$$

The second step of the costs minimisation process is to determine the costs of one unit of net output. Given the price of intermediate inputs and the net output fucntion.

$$c^p(r,w,t) = \underset{\{z_i, x_i\}}{min}\left\{tz_i + p_{xi}(r,w)x_i :\ \varphi(z_i)^{\alpha_i}(x_i)^{(1-\alpha_i)} = 1\right\}$$

This results in the following optimisation problem:

$$\Lambda = tz_i + p_{xi}(r,w)x_i + \lambda\left(1 - \varphi(z_i)^{\alpha_i}(x_i)^{(1-\alpha_i)}\right)$$

FOC:

$$\frac{\partial\Lambda}{\partial z_i} = t - \lambda\left(\alpha_i\varphi(z_i)^{\alpha_i-1}(x_i)^{(1-\alpha_i)}\right) = 0$$

$$\frac{\partial\Lambda}{\partial} = p_{xi} - \lambda\left((1-\alpha_i)\varphi(z_i)^{\alpha_i}(x_i)^{(1-\alpha_i)-1}\right) = 0$$

$$\frac{t}{p_{xi}} = \frac{\lambda}{\lambda}\frac{\alpha_i\varphi(z_i)^{\alpha_i-1}(x_i)^{(1-\alpha_i)}}{(1-\alpha_i)\varphi(z_i)^{\alpha_i}(x_i)^{(1-\alpha_i)-1}} = \frac{\alpha_i}{1-\alpha_i}\varphi\frac{x_i}{\varphi z_i} = \frac{\alpha_i}{1-\alpha_i}\frac{x_i}{z_i}$$

$$x_i = \frac{t}{p_{xi}}\frac{1-\alpha_i}{\alpha_i}z_i$$

Using the side constraint this gives the following factor input coefficients for net output:

$$x_i = \frac{1}{\varphi}\left(\frac{t}{p_{xi}}\frac{1-\alpha_i}{\alpha_i}\right)^{\alpha_i}$$

$$z_i = \frac{1}{\varphi}\left(\frac{p_{xi}}{t}\frac{\alpha_i}{1-\alpha_i}\right)^{1-\alpha_i}$$

This implies that costs of producing one unit of net output is:

$$c^q(t,w,i) = t\left(\frac{1}{\varphi}\left(\frac{p_{xi}}{t}\frac{\alpha_i}{1-\alpha_i}\right)^{1-\alpha_i}\right) + p_{xi}\left(\frac{1}{\varphi}\left(\frac{t}{p_{xi}}\frac{1-\alpha_i}{\alpha_i}\right)^{\alpha_i}\right)$$

$$c^q{}_i(t,w,i) = \frac{p_{xi}}{\varphi(1-\alpha_i)\left(\frac{p_{xi}}{t}\frac{\alpha_i}{1-\alpha_i}\right)^{\alpha_i}}$$

Given these the following factor input demands can be identified for a firm.

$$k_i(\varphi) = \beta_i \left(\frac{w}{r}\right)^{(1-\beta_i)} \left(\frac{t}{p_{xi}} \frac{1-\alpha_i}{\alpha_i}\right)^{\alpha_i} \frac{q_i(\varphi)}{\varphi}$$

$$l_i(\varphi) = (1-\beta_i) \left(\frac{w}{r}\right)^{\beta_i} \left(\frac{t}{p_{xi}} \frac{1-\alpha_i}{\alpha_i}\right)^{\alpha_i} \frac{q_i(\varphi)}{\varphi}$$

$$z_i(\varphi) = \left(\frac{p_{xi}}{t} \frac{\alpha_i}{1-\alpha_i}\right)^{1-\alpha_i} \frac{q_i(\varphi)}{\varphi}$$

$$x_i(\varphi) = \left(\frac{t}{p_{xi}} \frac{1-\alpha_i}{\alpha_i}\right)^{\alpha_i} \frac{q_i(\varphi)}{\varphi}$$

Appendix C

Productivity distribution and average productivity and aggregation

The productivity upgrade results in the fact that some increase their productivity level with a constant factor through the possibility to upgrade. As stated in the main text the cut-off level for the upgrade depends on the pre-upgrade productivity drawn by a firm from the productivity distribution $G(\varphi)$ with density function $g(\varphi)$. The specific function used for the ex-ante productivity distribution is a Pareto distribution with shape parameter k.

$$g(\varphi) = \frac{k\varphi^k}{\varphi^{k+1}}$$

$$G(\varphi) = 1 - \left(\frac{\varphi}{\varphi^*}\right)^k$$

The constant factor (ϕ), that increases the productivity of firms that upgrade leads to a difference between the ex-ante and ex-post productivity distribution as there do not exist firms with a productivity level between φ_{iu}^* and $\phi\varphi_{iu}^*$. The model allows that the average productivity after the upgrade is implemented can be expressed as a weighted average of the before upgrade average productivity levels for both non-upgraders and upgraders. This method is also used by Navas (2018), and explained in this appendix. Note that for the trade situation in which a share of exporters will upgrade their technology $\varphi_{iU} > \varphi_{iX}$.

The ex-ante (before the upgrade is done) distributions for firms with a productivity level above the zero-cut-off condition for the domestic market, the export market and the upgrade respectively are given by the following functions respectively.

$$\mu_{iD}(\varphi) = \begin{Bmatrix} \dfrac{g(\varphi)}{1 - G(\varphi_{iD})} & if\ \varphi > \varphi_{iD}^* \\ 0 & otherwise \end{Bmatrix}$$

$$\mu_{iX}(\varphi) = \begin{Bmatrix} \dfrac{g(\varphi)}{1 - G(\varphi_{iX})} & if\ \varphi > \varphi_{iX}^* \\ 0 & otherwise \end{Bmatrix}$$

$$\mu_{iU}(\varphi) = \begin{Bmatrix} \dfrac{g(\varphi)}{1 - G(\varphi_{iU})} & if\ \varphi > \varphi_{iU}^* \\ 0 & otherwise \end{Bmatrix}$$

Given these distributions the averages in these sectors are given by the following three expressions. These averages represent the average productivity in each group before the upgrade.

$$(\tilde{\varphi}_{iD})^{\sigma-1} = \int_{\varphi_{iD}^*}^{\infty} \varphi^{\sigma-1}\mu_{iD}(\varphi)d\varphi$$

$$(\tilde{\varphi}_{iX})^{\sigma-1} = \int_{\varphi_{iX}^*}^{\infty} \varphi^{\sigma-1}\mu_{iX}(\varphi)d\varphi$$

$$(\tilde{\varphi}_{iU})^{\sigma-1} = \int_{\varphi_{iU}^*}^{\infty} \varphi^{\sigma-1}\mu_{iU}(\varphi)d\varphi$$

The averages above can be used to determine the post-upgrade average productivity on the domestic $(\tilde{\varphi}_{iDU})$ and the export market $(\tilde{\varphi}_{iXU})$. Since all active firms serve the domestic market, some of them will have the upgraded technology i.e. the firms for which $\tilde{\varphi}_{iU} > \varphi$. The probability that a firm belongs to that category is $pr(\tilde{\varphi}_{iU} > \varphi) = 1 - G(\varphi_{iU}^*)/1 - G(\varphi_{iD}^*)$. Therefore, the post-upgrade average productivity level for the domestic market is equal to the following. Given the Pareto distribution the probability that a firm does the upgrade is given it is active on the domestic market $(\varphi_{iU}^*/\varphi_{iD}^*)^{-k}$.

$$\tilde{\varphi}_{iDU} = \tilde{\varphi}_{iD} + \left[\left(\frac{\varphi_{iU}^*}{\varphi_{iD}^*}\right)^{-k} (\phi^{\sigma-1} - 1)\right]^{\frac{1}{\sigma-1}} \tilde{\varphi}_{iU}$$

Similarly, post-upgrade the average productivity on the export market can be defined using the probability that that an exporter also does the upgrade $pr(\tilde{\varphi}_{iU} > \varphi|\varphi_{iX}^*) = 1 - G(\varphi_{iU}^*)/1 - G(\varphi_{iX}^*) = (\varphi_{iU}^*/\varphi_{iX}^*)^{-k}$.

$$\tilde{\varphi}_{iXU} = \tilde{\varphi}_{iX} + \left[\left(\frac{\varphi_{iU}^*}{\varphi_{iX}^*}\right)^{-k} (\phi^{\sigma-1} - 1)\right]^{\frac{1}{\sigma-1}} \tilde{\varphi}_{iU}$$

These averages show that the post-upgrade average productivity on the domestic and the export market depends both on the pre-upgrade average productivity for either the domestic or the export market the market (first term) and the additional benefits of the upgrade for the firms that do the upgrade (second term). If there would be zero benefits from the upgrade $(\phi = 1)$ the second term would be zero, which implies that the pre and post-upgrade average productivity levels are the same.

Consequently aggregate variables can be written as a function of these average productivity levels that result after upgrades have taken place. This implies that a common property of models of this kind, that the average of each variable in the model is the same as the value of the variable at the average productivity in the market, still holds (Melitz, 2003). This property is applied for aggregation in this paper. In the Autarkic equilibrium the relationship between the post-upgrade industry average and the pre-upgrade industry cut-off level is given by (1).

$$\tilde{\varphi}_{iDU} = \left(\frac{k}{k-\sigma+1}\right)^{\frac{1}{\sigma-1}} \left(1 + (\phi^{\sigma-1} - 1)^{\frac{k}{\sigma-1}} \left(\frac{f_d}{\delta f_u}\right)^{\frac{k-\sigma+1}{\sigma-1}}\right)^{\frac{1}{\sigma-1}} \varphi^*_{iD} \quad (1)$$

In the costly trade equilibrium the post-upgrade average productivity in the market is given by (2). This is determined using the above expressions for the post-upgrade average productivity, the cut-off conditions from the main text and the property of the distribution function that $\tilde{\varphi} = \left(\frac{k}{k-\sigma+1}\right)^{\frac{1}{\sigma-1}} \varphi^*$ for the pre-upgrade values. This shows that the possibility to upgrade introduces an endogenous difference between the average and the cut-off productivity level that depends on the foreign market potential.

$$\tilde{\varphi}^H_{iDU} = \left(\frac{k}{k-\sigma+1}\right)^{\frac{1}{\sigma-1}} \left[1 + \left[(\phi^{\sigma-1} - 1)^{\frac{k}{\sigma-1}} \left(\left(\tau^{1-\sigma} \frac{R^F}{R^H} \frac{(P^F_i)^{\sigma-1}}{(P^H_i)^{\sigma-1}} + 1\right) \frac{f_D}{\delta f_U}\right)^{\frac{k-\sigma+1}{\sigma-1}}\right]\right]^{\frac{1}{\sigma-1}} \varphi^{*H}_i \quad (2)$$

This is different as compared to Autarky. Although in Autarky the relationship between the industry average and the cut-off level is different as compared to a situation in which there is no upgrade possibility the relationship only depends on model parameters. If variable trade costs become extremely large ($\tau \rightarrow \infty$), $\left(\tau^{1-\sigma} \frac{R^F}{R^H} \frac{(P^F_i)^{\sigma-1}}{(P^H_i)^{\sigma-1}}\right)$ goes to zero, which makes the result the same as the Autarky case.

The average equilibrium post-upgrade productivity on the export market as a function of the zero-profit productivity level is given by (3).

$$\tilde{\varphi}^H_{iXU} = \left(\frac{k}{k-\sigma+1}\right)^{\frac{1}{\sigma-1}} \left(\tau^{\sigma-1} \frac{R^H (P^H_i)^{\sigma-1}}{R^F (P^F_i)^{\sigma-1}} \frac{f_X}{f}\right)^{\frac{1}{\sigma-1}} \left[1 + \left[(\phi^{\sigma-1} - 1)^{\frac{k}{\sigma-1}} \left(\left(\tau^{1-\sigma} \frac{R^F}{R^H} \frac{(P^F_i)^{\sigma-1}}{(P^H_i)^{\sigma-1}} + 1\right) \frac{f_x}{\delta f_U}\right)^{\frac{k-\sigma+1}{\sigma-1}}\right]\right]^{\frac{1}{\sigma-1}} \varphi^{*H}_i \quad (3)$$

The equilibrium cut-off productivity level based on the free-entry condition is the other determinant of the equilibrium average productivity and depends in the costly trade equilibrium on the variable trade costs. In Autarky the zero-profit cut-off level is given by (4). This is determined by using the free entry condition (15, main text) combined with the equilibrium relationship between the zero-profit productivity cut-off level for non-upgraders and upgraders (14, main text) leads to an expression of the cut-off productivity as a function of the model parameters.

$$\varphi_i^{*H} = \left[\frac{\underline{\varphi}^k}{\delta f_e}\frac{\sigma-1}{k-\sigma+1}\left(f_D + (\delta f_U)^{1-k}\left(\left(\phi^{(\sigma-1)}-1\right)f_D\right)^k\right)\right]^{\frac{1}{k}} \tag{4}$$

For costly trade the zero-profit cut-off level is given by (5). This shows that if the possibility of technology improvement does increase the zero cut-off productivity level as compared to a situation in which there is no possibility to upgrade.

$$\varphi_i^{*H} = \left[\frac{\underline{\varphi}^k}{\delta f_e}\frac{\sigma-1}{k-\sigma+1}\left(f_D + \left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{-k} f_X \right.\right.$$
$$\left.\left. + (\delta f_U)^{1-k}\left(1+\left(\left(\tau\frac{P_i^H}{P_i^F}\left(\frac{R^H}{R^F}\frac{f_X}{f}\right)^{\frac{1}{\sigma-1}}\right)^{1-\sigma}\frac{f_x}{f}\right)^k\left(\left(\phi^{(\sigma-1)}-1\right)f_D\right)^k\right)\right)\right]^{\frac{1}{k}} \tag{5}$$

Appendix D

Goods and factor price behaviour

The relative goods prices determine the foreign market potential in equilibrium and determine which country has a comparative advantage. In this appendix the relative prices in different situations are derived and explained in a similar fashion as for example (Navas, 2018) and (Bernard, Redding, & Schott, 2007). Given the average post-upgrade productivity the relative prices in Autarky are expressed as follows.

$$\frac{P_1}{P_2} = \left(\frac{M_1}{M_2}\right)^{\frac{1}{1-\sigma}} \frac{p_1(\tilde{\varphi}_{1DU})}{p_2(\tilde{\varphi}_{2DU})}$$

In Autarky the average productivity is the same across sectors such that this ratio only depends on the factor prices, environmental tax and the model parameters. The relative price of capital (with the wage as the nummeraire in both countries) is determined by model parameters in Autarky. This is explained in the main text.

For costly trade and free trade the relative prices are determined by both the price in the home country and in the foreign country as well as the trade costs.

$$\frac{P_1^H}{P_2^H} = \left[\frac{M_1^H\left(p(\tilde{\varphi}_{1DU}^H)\right)^{1-\sigma} + \tau^{1-\sigma}\left(\frac{\varphi_{1X}^{F*}}{\varphi_{1D}^{F*}}\right)^{-k} M_1^F\left(p(\tilde{\varphi}_{1XU}^F)\right)^{1-\sigma}}{M_2^H\left(p(\tilde{\varphi}_{2DU}^H)\right)^{1-\sigma} + \tau^{1-\sigma}\left(\frac{\varphi_{2X}^{F*}}{\varphi_{2D}^{F*}}\right)^{-k} M_2^F\left(p(\tilde{\varphi}_{2XU}^F)\right)^{1-\sigma}}\right]^{\frac{1}{1-\sigma}}$$

When the variable trade costs become extremely large ($\tau \rightarrow$ infinity) the share of exporters in foreign becomes zero which implies that the Autarkic average prices hold. When there are no fixed and variable trade costs (τ=1 and fx=0), the probability of exporting is one which implies that in both countries the prices count equally towards the price index (depending on the amount of firms). This implies that $P_1^H/P_2^H = P_1^F/P_2^F$. The reason behind this is that because all firms are able the export the amount of firms that serve the export market is equal to the amount of firms that serves the domestic market. Furthermore, the average productivity is the same for the domestic and export market which implies that in each county there is one price for both the export and the domestic market. As a result, the relative prices in the costless trade equilibrium are equal across countries. It also shows that differences in emission taxes do not change this result.

Appendix E

Cost structure

In order for the assumed order of the productivity cut-off levels to hold the costs structure in de model is assumed to rely on some restrictions. These are explained in this appendix.

For autarky it should be the case that $\varphi_{iU}^* > \varphi_i^*$. This is the case when:

$$\frac{\delta f_U}{((\phi)^{\sigma-1} - 1) f_D} > 1$$

For the costly trade equilibrium it should be the case that $\varphi_{iU}^* > \varphi_{Xi}^* > \varphi_i^*$. First, it needs that the threshold productivity level for an exporter is larger than the zero-profit cut-off productivity level in the market.

$$\tau^{\sigma-1} \frac{R^H (P_i^H)^{\sigma-1}}{R^F (P_i^F)^{\sigma-1}} \frac{f_X}{f} > 1$$

$$\frac{1}{\left(\tau^{1-\sigma} \frac{R^F (P_i^F)^{\sigma-1}}{R^H (P_i^H)^{\sigma-1}} + 1\right) ((\phi)^{\sigma-1} - 1)} \frac{\delta f_U}{f_X} > 1$$

This leads to the following assumptions on the costs structure that has to hold.

$$\tau^{1-\sigma} \frac{R^F (P_i^F)^{\sigma-1}}{R^H (P_i^H)^{\sigma-1}} f < f_X < \frac{\delta f_U}{\left(\tau^{1-\sigma} \frac{R^F (P_i^F)^{\sigma-1}}{R^H (P_i^H)^{\sigma-1}} + 1\right) ((\phi)^{\sigma-1} - 1)}$$

Appendix F

Aggregate revenue properties and factor use in autarky

Total revenue in the model is equal to the payments to all factors of production, which are labour, capital and emissions.

$$R = r\bar{K} + w\bar{L} + t(Z_1 + Z_2)$$

For each industry holds that the total revenue in the industry has to be equal to the total payments of that industry to the factors of production. This comes from the fact that all payments to the factors of production used for all net output and fixed costs are equal to the total revenue minus the total profits in the industry. Given the free entry condition it can be concluded that all expenses that firms have when entering are equal to the total profits in the country. Therefore, the total payments to the factors of production for the production of goods and for entry together are equal to total country revenue. Furthermore, the total payments to capital and labour in a sector are equal to the total expense of making intermediate inputs.

$$R_i = rK_i + wL_i + tZ_i = p_{xi}X_i + tZ_i$$

$$p_{xi}X_i = rK_i + wL_i$$

As the production function is Cobb-Douglas and all of the costs in the industry are made with the same factor intensities, the payments to capital and labour are a constant share of the total costs of intermediate inputs of the size of the factor intensity (Bernard, Redding, & Schott, 2007).

$$wL_i = (1 - \beta_i)p_{xi}X_i$$

$$rK_i = \beta_i p_{xi}X_i$$

The net production function is also Cobb-Douglas which implies that the share of total sector revenue that is spend on intermediate inputs versus emissions can be expressed as a function of parameters. These show that depending on how emission intensive the sector is the more emissions a firm uses in production. These functions show that in Autarkic equilibrium total emission demand is only function of the tax, the emission intensitivity, factor endowments and factor prices.

$$p_{xi}X_i = (1-\alpha_i)R_i$$

$$tZ_i = \alpha_i R_i$$

In total the amount of a factor that is used in an industry can be expressed as follows:

$$L_i = \frac{(1-\beta_i)(1-\alpha_i)R_i}{w}$$

$$K_i = \frac{\beta_i(1-\alpha_i)R_i}{r}$$

$$Z_i = \frac{\alpha_i R_i}{t}$$

The aggregate revenue in an industry can be expressed as the average revenue in the industry times the amount of firms that are active in that industry. Given that the average equilibrium productivity in Autarky is equal in both industries (see Appendix C), even when taking into account that some firms are able to upgrade their technology and others are not, the relative amount of firms in each sector in equilibrium can be expressed as.

$$\frac{R_1}{R_2} = \frac{\eta_1}{\eta_2}\frac{R}{R} = \frac{M_1}{M_2}\frac{r_i(\tilde{\varphi}_1)}{r_i(\tilde{\varphi}_2)}$$

$$\frac{M_1}{M_2} = \frac{\eta_1}{\eta_2}\left(\frac{p_{x2}}{1-\alpha_2}\right)^{1-\alpha_2}\left(\frac{1-\alpha_1}{p_{x1}}\right)^{1-\alpha_1}\left(\frac{t}{\alpha_2}\right)^{\alpha_2}\left(\frac{\alpha_1}{t}\right)^{\alpha_1}$$

Aside from the relative mass of firms in each sector it is also possible to look at the relative use of emissions and intermediate inputs across sectors in autarky. The relative amount of intermediate inputs depends on the relative price of intermediate inputs that are being used in production. All else equal the relative amount of intermediate inputs in sector 1 increases when consumers spend a larger share of their income on sector one; when sector one is less emission intensive (lower alpha); and when the relative price of capital changes. For emissions holds that the relative amount over industries does only depend on the relative intensity in which production of net output uses emissions. The relative amount of emissions does not depend on the tax, which is a result from the fact that both industries have the same tax rate.

$$\frac{X_1}{X_2} = \frac{\eta_1}{\eta_2}\frac{1-\alpha_1}{1-\alpha_2}\frac{p_{x1}}{p_{x2}} = \frac{\eta_1}{\eta_2}\frac{1-\alpha_1}{1-\alpha_2}\left(\frac{r}{w}\right)^{\beta_2-\beta_1}$$

$$\frac{Z_1}{Z_2} = \frac{\eta_1}{\eta_2}\frac{\alpha_1}{\alpha_2}\frac{t}{t} = \frac{\eta_1}{\eta_2}\frac{\alpha_1}{\alpha_2}$$

The total demand for labour and capital can be expressed as a function of model parameters (factor input coefficients for intermediate input) and the amount of intermediate inputs in each industry.

$$\frac{\bar{K}}{\bar{L}} = \frac{\beta_1\left(\frac{w}{r}\right)^{1-\beta_1} X_1 + \beta_2\left(\frac{w}{r}\right)^{1-\beta_2} X_2}{(1-\beta_1)\left(\frac{r}{w}\right)^{\beta_1} X_1 + (1-\beta_2)\left(\frac{r}{w}\right)^{\beta_2} X_2} = \frac{\beta_1\left(\frac{w}{r}\right)^{1-\beta_1} \frac{X_1}{X_2} + \beta_2\left(\frac{w}{r}\right)^{1-\beta_2}}{(1-\beta_1)\left(\frac{r}{w}\right)^{\beta_1} \frac{X_1}{X_2} + (1-\beta_2)\left(\frac{r}{w}\right)^{\beta_2}}$$

$$\frac{\bar{K}}{\bar{L}} = \frac{\beta_1 \frac{\eta_1}{\eta_2}\frac{1-\alpha_1}{1-\alpha_2} + \ \beta_2}{(1-\beta_1)\frac{\eta_1}{\eta_2}\frac{1-\alpha_1}{1-\alpha_2} + \beta_1}\frac{w}{r}$$

This result is very similar to results found in other models of the same type (Bernard, Redding, & Schott, 2007). It shows that in equilibrium, when all parameters in the model are held constant, an increase in the relative amount of capital in the country as compared to labour leads to an increase decrease in the return to capital compared to the return to labour. i.e. when capital becomes more abundant the return of capital will become lower simply because there is more available. The same holds for labour. The tax does not directly influence the relative demand for capital and labour in autarky, which is a similar result as in Copeland and Taylor (2003) and LaPlue (2019). The reason for this is that even though the tax has an influence on the relative amount of intermediate inputs versus emissions used in production, it does not influence the relative intensity of labour and capital that is used in the production of these intermediate inputs.

The relative amount of intermediate inputs and emissions in a country can be expressed as a function of the tax and the price of intermediate inputs in both industries.

$$\frac{Z}{X} = \frac{\eta_1\alpha_1 + \eta_2\alpha_2}{t\left(\frac{\eta_1(1-\alpha_1)}{p_{x1}} + \frac{\eta_2(1-\alpha_2)}{p_{x2}}\right)}$$

This shows that when the tax increases the total amount of emissions decreases in the country. The reason for this is that for both industries emissions become more expensive relative to intermediate inputs.