The circular economy, international trade, and the sectoral compositions of economies

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Abstract

There has been a recent trend in a number of major economies towards the introduction of large-scale recycling schemes. In this paper we explore how such initiatives affect the sectoral composition of economies throughout the world via global raw material markets and trade linkages. We build a multi-country multi-sector model of recycling and trade, which offers three key insights. First, changing recycling rates in one country alters that country's demand for raw material, and thus affects its trading partners by changing global raw material prices. Second, the exact qualitative effect on trading partners' economies is ambiguous and hinges on the elasticity of energy supply. Third, the quantitative effects themselves are sensitive to the convexity of recycling costs. Altogether, we conclude that large-scale recycling schemes have quantitatively significant effects on a global level as their impact is not limited to the domestic economy. Our paper, therefore, highlights the importance of taking the external effects of large-scale recycling initiatives into account.

Keywords: recycling, circular economy, manufacturing, mining, international trade, structural transformation
JEL classification: F16, F43, O40, Q53, Q56

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Introduction

In order to secure a steady supply of raw material, a number of major economies such as the European Union and China have been advancing legislation to introduce large-scale recycling programs in what has been framed as a "circular economy revolution". "Circular economy" refers to a "reduce-reuse-recycle" approach to waste management, as opposed to the "linear" system of "extract-consume-dump". A circular economy, therefore, ensures greater self-sufficiency through intelligent product design, and the recycling of materials embedded in final goods into the economic system. The reasons for this tendency towards a more circular approach are two-fold. First, there are obvious concerns about the sustainability of the current, mostly linear, system of resource use. There are huge externalities linked to waste disposal and most strategic raw materials are non-renewable. This is also coupled with policymakers' desire towards environmental protection, and combating climate change. Second, global upward trends in the consumption of critical raw materials such as oil, natural gas, or copper, sustained by strong growth in emerging economies, have accelerated depletion rates across the planet. Large-scale recycling programs are seen as practical solutions to supply uncertainty, especially in geographies that lack their own critical natural resources. For a review on recycling policy we refer the reader to Geng et al. (2017).

In addition to influencing policymakers, issues like fluctuating raw material prices, scarcity, and shifting consumer preferences are making a business case for the circular economy as well. Dobbs et al. (2015) argue that circular economy concepts can be a clever way to cut costs for corporations. But an increasing trend for consumers to care about environmental issues makes circular initiatives a good marketing tool too (Balch (2018)). For these reasons, we see many companies explore recycling models. Some examples include H&M recycling old clothes (The Economist (2015)), Coca Cola recycling the equivalent of its packaging by 2030, McDonald's making all its packaging from renewable and recyclable sources by 2025, Iceland (a UK grocer) eliminating all plastic packaging from its private label products by 2023 (Aglionby et al. (2018)), and Tata Steel experimenting with an innovative steelmaking technology that could lead to a 20% reduction in energy use and CO_2 emission in steel production (Pooler (2017)). These corporate initiatives show that even private businesses see merit in the circular economy concept making it ever more relevant to study its economic impact as it is poised to become more widespread.

In this paper we explore, from a theoretical point of view, how a large-scale shift towards higher recycling rates in the short run can impact international trade in raw materials, and the sectoral composition of economies trading with each other. Large-scale recycling can significantly reduce demand for raw material from advanced economies, which can produce downward pressure on prices. This question is interesting because dropping prices and decreasing demand can spell doom, but they may also encourage a shift towards manufacturing

– generally considered a way towards upper-middle income status (see e.g. Szirmai (2013)). We investigate which one of these forces prevails under what conditions.

To study this problem, we build a parsimonious but powerful general equilibrium multi-sector, multi-country model of recycling and trade. In the model, countries allocate energy between manufacturing, mining, and recycling, and they trade final goods and raw material with each other. Our model exhibits material balance, a general class of convex costs in the recycling rate, and elastic energy demand curves. We characterize our model in two ways. On the one hand, given the complexity of the baseline model, we resort to a numerical solution. On the other hand, under auxiliary assumptions, we reduce the complexity of the model and explore its behavior as an autarky and a small open economy.

Our analysis reveals three key insights. First, we show that changing recycling rates in a given country can reverberate globally and can affect the sectoral composition of other economies. Second, we show that the precise effects of changing recycling rates hinge greatly on the elasticity of energy supply. If energy is supplied inelastically, then increased recycling in one country incentivizes other countries reallocate resources from the mining to the manufacturing sector. If, however, energy is supplied elastically then the precise effects are less clear. Our simulations show that less and more raw-material-rich countries are affected differently. Third, we explore the role recycling cost convexity plays in our conclusions. We find that our conclusions are qualitatively robust to various levels of convexity. Nevertheless, there is substantial quantitative variation in our results, which underlines cost convexity as a key parameter for policymakers to pay attention to.

To the best of our knowledge our research question is novel in the resource economics literature. In general, however, our paper contributes to the steady state literature on recycling and international trade. Recycling and international trade have been explored in Kinnaman and Yokoo (2011), Shinkuma and Managi (2011), Sugeta and Shinkuma (2012), and, Bernard (2015). Kinnaman and Yokoo (2011) study the environmental impacts of re-use when waste can be traded and restorative policy is designed to ensure a first-best world equilibrium. Sugeta and Shinkuma (2012) consider the effects of international heterogeneity in the recovery rates and levels of trade liberalization on environmental quality. Optimal policy and extended producer responsibility schemes in the presence of convex recycling costs is explored in Shinkuma and Managi (2011) and Bernard (2015).

Our inquiry takes distance from the recent literature in two ways. First, we abstract away from inefficiencies and optimal taxation as well as from environmental issues. We focus mainly on the macroeconomic effects of recycling rates on the composition of the main sectors of the economy. Our objective is not, as a matter of fact, to explicitly determine the optimal levels of recycling, but rather to understand the impacts on the economy when those vary as policy parameters in the short run. Second, we consider a world in which trade is carried out in a non-cooperative way. Therefore, we understand that the relationship between the trading parties is purely economic and therefore selfish. Our model fits in an environment in which presumptions of global altruism are doubtful.

1 The model

We consider an economy in steady state with a single final good whose consumption preferences are captured by a strictly increasing utility function. This consumption good is produced with raw material and energy. Ready-to-be-used raw material needs to be produced. Raw material production requires energy as an input. There is also a possibility to recycle raw material that was previously used in final goods production. Recycling is also done by energy in a separate sector. We let the recycling intensity be exogenous, since it is our policy parameter of interest.[1] Finally, the economy can import and export final goods and raw material. We abstract away from energy accumulation and environmental considerations.

We consider the central planner's problem, which is

$$\max_{c,m,E,e_c,e_m,x_m,x_c,m_i,m_r} \quad c + \xi(T-E) \text{ s.t.}$$

$$c = A[m_i + m_r + x_m]^\beta e_c^{1-\beta} + x_c \tag{1}$$

$$m_i = \min\{m, Be_m^\gamma\} \tag{2}$$

$$m_r = \min\left\{\alpha(m_i + x_m), Ce_r^{\omega_1(1-\alpha)^{\omega_2}}\right\} \tag{3}$$

$$E = e_c + e_m + e_r$$

$$0 = x_c + px_m,$$

where c is consumption, $\xi > 0$ is a penalty parameter, m is virgin material, m_i is intermediary (or transformed) raw material production, m_r is recycled raw material, e_c is energy employed in manufacturing, e_m is energy in raw material extraction, e_r is energy in recycling, T is total energy endowment, E is the amount of energy effectively used, x_m is net raw material imports, x_c is net consumption good imports, $\alpha \in (0,1)$ is recycling intensity, $A > 0$ is a technology parameter for manufacturing, $\beta \in (0,1)$ is the share of raw material in manufacturing, $B > 0$ and $\gamma \in (0,1)$ are technology parameters for raw material extraction, $C > 0, \omega_1 \in (0,1)$, and $\omega_2 \geq 0$ are technology parameters for recycling, and $p > 0$ is the

[1] Exogenous increases in our model can be interpreted, for instance, as optimal responses to externalities. Examples of recycling intensities as policy instruments can be found in the European Union and the United States. For a discussion see Kinnaman (2006).

global market price of raw material with the global market price of the consumption good being normalized to 1. Figure 1 summarizes material flow in the model.

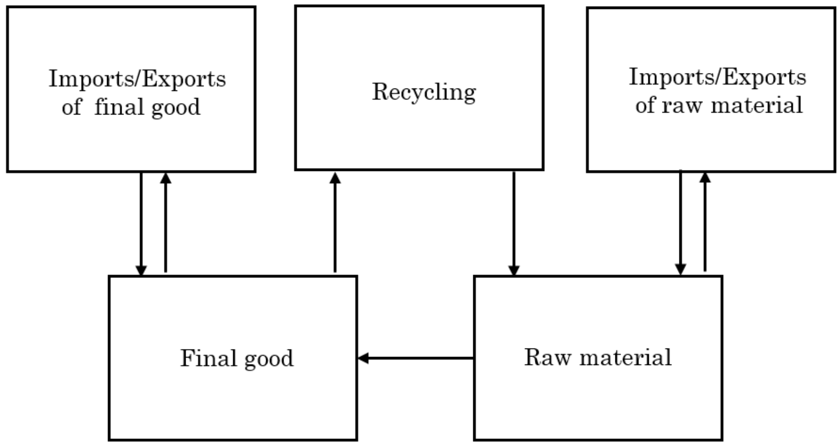


Figure 1: Material flow in the model

We close the model in world trade. To do so, we need a global market clearing condition for raw material, which will pin down p. Suppose we have N countries indexed by i, each behaving according to our model. Then global raw material market clearing requires $\sum_{i=1}^{N} x_m^i(p) = 0$; in other words, the sum of all countries' net raw material imports must be zero. The global final goods market will clear by Walras' law.

Four features of our modeling are worth highlighting. First, note that the introduction of the penalty parameter ξ makes the supply of energy inelastic when $\xi = 0$ and elastic when $\xi > 0$. More technically, this happens since our central planner's program implies the existence of a shadow value attached to energy, that is to say a Lagrange multiplier λ^E, that ensures the existence of a supply function such that $\partial E^* / \partial \lambda^{E^*} \left[\lambda^{E^*}/E^*\right] \neq 0$. Second, the recycling technology in the model is parameterized in the exponent as $\omega_1(1-\alpha)^{\omega_2}$. This structure says that the marginal productivity of recycling is exponentially decreasing in the rate of recycling. This assumption is the counterpart to the monetary cost functions recently explored in Shinkuma and Managi (2011) and Bernard (2015). Our recycling function is also consistent with the restriction $\lim_{e_r \to \infty} \alpha(m_i^* + m_r^* + x_m^*) < m_r^*$ suggested by Eichner and Pethig (2001). We show the convex nature of recycling costs in Figure 2. It is apparent from the figure that ω_2 controls the extent of cost convexities in recycling. In general, a marginal productivity of recycling exponentially decreasing in α captures an increasing difficulty in the recovery of material embedded in final goods, associated with imperfect technologies, complex material mixing, and miniaturization of components. Third, our model is consistent with the principle of material balance in the sense that the amount of embedded raw material and the amount of recycled raw material do not exceed the amount of physical inputs involved in each process, respectively. In other words, $m_i \leq m$ and $m_r \leq \alpha(m_i +$

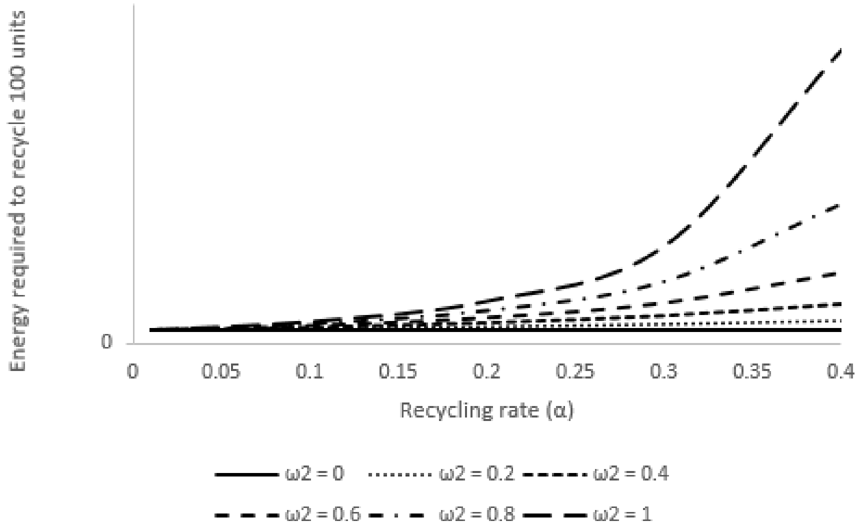


Figure 2: Energy required to recycle 100 units of raw material at different values of ω_2

x_m) hold. This treatment of material balance follows Anderson (1987) and Sugeta and Shinkuma (2012) by directly assuming Leontief technologies for these two processes. Fourth, we consider the Cobb-Douglas as a plausible technology *only in the short term*, where non-asymptotic substitution possibilities are reasonable. Our steady-state Cobb-Douglas world is therefore a plausible model structure, as far as our objective is to study the short term impact of abrupt changes in recovery rates on the sectoral composition of different economies when technological fundamentals, such as recycling efficiency, remain unaltered. Lemma 1 characterizes the optimal solution of the model.

Lemma 1. *To conserve space, let* $\omega \equiv \omega_1(1-\alpha)^{\omega_2}$. *The optimal solutions for* x_m, e_r, *and* E *are given by*

$$x_m^* = \frac{C}{\alpha} e_r^{\omega} - \left(\frac{p\gamma}{\xi B^{-1/\gamma}}\right)^{\frac{\gamma}{1-\gamma}}$$

$$e_r^* = \left(\frac{C\omega}{\alpha}\right)^{\frac{1}{1-\omega}} \left[\frac{\beta}{1-\beta}\left(\frac{A(1-\beta)}{\xi}\right)^{1/\beta}(1+\alpha) - \frac{p}{\xi}\right]^{\frac{1}{1-\omega}}$$

$$E^* = \left(\frac{A(1-\beta)}{\xi}\right)^{1/\beta} \frac{(1+\alpha)C}{\alpha} e_r^{\omega} + e_r + B^{-1/\gamma}\left(\frac{C}{\alpha} e_r^{\omega} - x_m\right)^{1/\gamma}$$

2 Two variations of the model

In Section 1, we have characterized a parsimonious and powerful model of the optimal allocation of material and energy in an economy that recycles, trades with the world, and is constrained by a rich class of convex recycling costs. These assumptions approach realistic scenarios. However, and as it should be expected, the stylized properties introduced are accompanied by a loss of algebraic tractability. Therefore, we appeal to a numerical treatment of our model in Section 3. To gain insight about the economic logic and to help us interpret the simulations, we follow a simple strategy in this section: by introducing auxiliary assumptions, we characterize how recycling affects trade, sectoral composition, raw material extraction, and final goods consumption in simplified scenarios, namely autarky, small open economy, and world trade.

2.1 Autarky

We start our algebraic analysis from the most tractable of the assumptions, namely, the economy is in autarky. To ensure tractability, we employ Assumptions 1, 2, and 3.

Assumption 1. *The economy is in autarky, namely,* $x_m = x_c = 0$.

Assumption 2. *The recycling technology is characterized by* $\omega_2 = 0$.

Assumption 3. *The recycling sector can be expressed as* $m_r = \min\left\{\alpha(m_i + x_m), Ce_r^{\omega_1(1-\alpha)^{\omega_2}}\right\}$.

Assumption 1 is just the definition of autarky. Assumption 2 is necessary to ensure algebraic tractability and to facilitate presentation. Assumption 3 says that the recycling activity of interest occurs only on previous period material. In steady state, however, this assumption is not necessarily damaging. Consider for instance the case in which there is a steady state flow of recycled material $\bar{\varphi} > 0$ returning into the production process from landfills. Note that the aggregate consumption function can be expressed as $A'[m_i + m_r + x_m]^\beta e_c^{1-\beta}$, with $A' = A\bar{\varphi}^\eta$ and $\eta \geq 0$. Thus, the effect of landfill mining can be modeled through the technology parameter. With these assumptions, we arrive at Proposition 1.

Proposition 1. *Let Assumptions 1-2 hold. If* $\xi = 0$ *then* $\partial e_r/\partial\alpha > 0, \partial e_c^*/\partial\alpha < 0, \partial e_m^*/\partial\alpha > 0, \partial m^*/\partial\alpha > 0, \partial c^*/\partial\alpha \gtreqless 0$ *holds. If* $\xi \neq 0$ *then* $\partial e_r/\partial\alpha \gtreqless 0, \partial e_c^*/\partial\alpha \gtreqless 0, \partial e_m^*/\partial\alpha \gtreqless 0, \partial m^*/\partial\alpha \gtreqless 0, \partial c^*/\partial\alpha \gtreqless 0$ *holds.*

Proposition 1 says that in the autarky model, when the energy is inelastic, if the economy decides to recycle more, it is optimal to reallocate energy from final goods production towards recycling and raw material extraction. This makes intuitive sense as more recycling requires more energy, but a higher recycling rate also makes raw material extraction more attractive as more of the extracted raw material can be reused later through recycling. The ambiguous effect on consumption encompasses the inherent trade-off between recycling and productive activities: the more the economy recycles, the more material it will have, *ceteris paribus*, to use in final goods production, but more recycling also requires the economy to divert energy from final goods production to recycling. When the energy is elastic then the effects are ambiguous.

2.2 Small open economy

In our second variation, we consider what happens to a small open economy if we open up the world to trade. By small open economy we refer to a country that is too small to have an effect on global market price p, and thus takes p as given. To guarantee algebraic tractability, we shall make the following assumptions.

Assumption 4. *The material extraction and recycling sectors are merged and represented by the same technology. Therefore, they collapse into one constraint of the form* $m_i + m_r = \min\{m + \alpha(m + x_m), B[e_m + e_r]^\gamma\}$ *with* $\gamma \equiv \omega_1(1-\alpha)^{\omega_2}$.

Assumption 5. *The recycling technology is characterized by* $\omega_2 = 1$.

Assumption 4 for us is merely a technical assumption that is necessary to derive sensible comparative static results. While it is possible to derive comparative statics with respect to α without Assumption 4, the resulting expressions are too complex to interpret without numerical analysis. We consider numerical examples in Section 3. Assumption 5 says that recycling becomes exponentially harder at higher intensities. With this, we depart from the simple case of Assumption 2 considered in autarky, and thus work with a more realistic set-up. We restrict our attention to $\omega_2 = 1$, because this parameter choice facilitates presentation while delivering the same qualitative insights as any $\omega_2 > 0$.

We can now establish Lemma 2 and Proposition 2.

Lemma 2. *Let Assumption 4 hold. The optimal solutions for* E, x_m, *and* e_c *are*

$$E^* = \left(\frac{p}{\xi}\frac{1-\beta}{\beta}\right)^{\frac{1}{1-\beta}} \left(\frac{A\beta}{p}\right)^{\frac{1}{1+\beta^2}} + \left(\frac{\beta}{1-\beta}B\gamma\right)^{\frac{1}{1-\gamma}} \left(\frac{p}{A\beta}\right)^{\frac{1}{(1-\beta)(1-\gamma)}}$$

$$x_m^* = \left(\frac{p}{A\beta}\right)^{\frac{1}{\beta-1}} \left(\frac{p}{\xi}\frac{1-\beta}{\beta}\right)^{\frac{1}{1-\beta}} \left(\frac{A\beta}{p}\right)^{\frac{1}{1+\beta^2}} - B\left[\left(\left[\frac{p}{A\beta}\right]^{1/(\beta-1)} \frac{1-\beta}{\beta}\frac{1}{B\gamma}\right)^{\frac{1}{\gamma-1}}\right]^{\gamma}$$

$$e_c^* = \left(\frac{p}{\xi}\frac{1-\beta}{\beta}\right)^{\frac{1}{1-\beta}} \left(\frac{A\beta}{p}\right)^{\frac{1}{1+\beta^2}}$$

Lemma 2 allows us now to analyze what happens to the small open economy if it increases its recycling rate, α. The findings are summarized in Proposition 2.

Proposition 2. *Let Assumptions 4-5 hold. If $\xi = 0$ and $p > A\beta^{\beta}(1-\beta/B)^{1-\beta}$ holds, then $\partial e_c^*/\partial\alpha > 0$, $\partial e_m^*/\partial\alpha < 0$, $\partial x_m^*/\partial\alpha > 0$, $\partial m^*/\partial\alpha > 0$, $\partial c^*/\partial\alpha \gtreqless 0$. If $\xi \neq 0$, then $\partial e_c^*/\partial\alpha \gtreqless 0$, $\partial e_m^*/\partial\alpha \gtreqless 0$, $\partial x_m^*/\partial\alpha \gtreqless 0$, $\partial m^*/\partial\alpha \gtreqless 0$, $\partial c^*/\partial\alpha \gtreqless 0$.*

Proposition 2 says that, when energy is supplied inelastically, increased recycling triggers a transition towards final goods production and away from raw material extraction if p is sufficiently high, and vice versa if p is low. On the one hand, the level of p at which this switch in the direction of recycling's effect happens is decreasing in the productivity of the raw material sector. This indicates that countries with more productive raw material sectors are more likely to transition towards manufacturing if recycling increases. On the other hand, the threshold p is increasing in manufacturing productivity A, which indicates that countries that are more productive in manufacturing are less likely to further transition towards manufacturing in response to higher recycling.

We may also solve the condition on p for A/B, the productivity of manufacturing relative to raw material production. We can then conclude that in places that are relatively better at raw material production, energy will migrate away from raw material production if α increases and imports will increase, and vice versa.

These results hint at two interesting considerations. First, we see that increased recycling has heterogeneous effects depending on country fundamentals such as A, B, and β. Second, it is apparent that increased recycling leads to convergence in sectoral composition between countries, and in particular it triggers a transition towards manufacturing in raw material-rich countries. The second part of Proposition 2 says that, when the supply of energy is elastic, directions are ambiguous.

To conclude this section, we compare our results in autarky to the small open economy when energy is supplied inelastically. In this case, our results in autarky show the somewhat mechanical result that increased recycling requires the diversion of energy from manufacturing to recycling. We concluded that if we open up this economy to trade, then these changes may help its trade partners transition out of raw material production and into manufacturing to fill the gap. The small open economy results confirm this intuition. They indicate that raw material-rich countries indeed transition out of raw material extraction and into manufacturing. Of course, we still only considered a single country changing its own recycling rate. In the next section, we continue our analysis in a multi-country framework.

3 Identical countries with inelastic supply of energy

After having exhausted the practical limits of what can be analytically done with our model, we turn to numerical simulations. We consider three cases. First, we explore what happens if the world consists of two hypothetical identical countries. This is a natural benchmark case from a theoretical perspective as studying two identical countries ensures that any results we observe is entirely due to our variable of interest: the recycling rate, α. Second, we explore the role that the convexity of recycling costs plays in our results. For this two-country experiment, we keep the assumption of inelastic energy supply. Third, in Section 4, we relax the assumption of inelastic energy supply, and consider a set-up with five countries resembling five regions in the world. This is a more empirically relevant scenario as it allows us to more precisely characterize what happens to poor resource-rich economies when rich resource-poor economies are increasing their rates of recycling.

As a first case, we consider two identical countries, which we label Country 1 and Country 2. We examine what happens as Country 1 changes its recycling rate, α, gradually from 0.01 to 0.99. The parameters used in our simulations are summarized in Table 1.

Table 1: Parameters in the identical-country simulations

A	B	C	T	α	β	γ	ω_1	ω_2	ξ
1.00	1.00	1.00	100	0.01	0.33	0.67	0.67	1.00	0

Note that the small open economy results from Proposition 2 are valid in a multi-country framework, and what remains to be pinned down by our numerical treatment of the model is what the market-clearing global raw material price is and how it moves as the recycling rate of Country 1 changes. The only other difference of our treatment here relative to the results in Proposition 2 is that we no longer need the somewhat restrictive Assumption 4, which merged the mining and recycling sectors into one. In light of this, it is natural to begin with interpreting the results of our simulations through the lens of Proposition 2.

As Figure 3 shows, the share of manufacturing employment in Country 1 initially increases as α gets higher. This indicates that raw material price is above a threshold similar to the one identified in Proposition 2. This initial increase in manufacturing share tapers off and reverses as α gets higher. This indicates that raw material prices presumably dropped below the threshold. Reassuringly, we find in Figure 4 that this is indeed the case: there is clear downward pressure on raw material prices after an initial bump. Similarly to energy in manufacturing, the behavior of energy in mining in Country 1 also obeys the rules set forth in Proposition 2: after decreasing at first, we see a mining revival in Country 1 as raw material prices drop. Appendix Figures B.9 and B.11 show that the behavior of trade and mining output in Country 1 are also consistent with the predictions of Proposition 2.

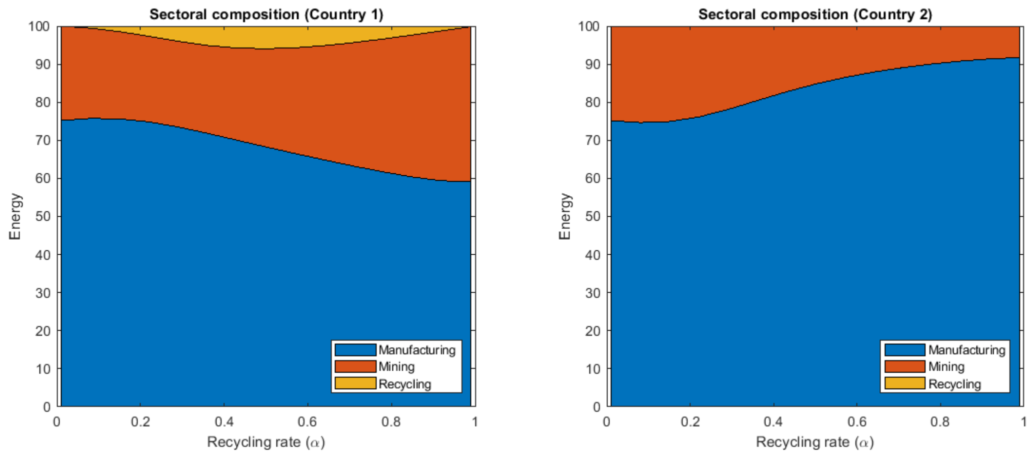


Figure 3: Sectoral composition in the identical country simulations

It is apparent in Figure 3 that the general qualitative insights of Proposition 2 also carry over to the behavior of Country 2. We see that consistent with our expectations, Country 2 sees a boom in its manufacturing sector at the expense of mining. This underlines the main result of our paper: that increased recycling can help trade partners transition out of mining and into manufacturing. As Figure B.9 shows trade responds accordingly: Country 2 becomes a net exporter of manufactured goods as Country 1's recycling rate grows.

Raw material prices themselves also exhibit interesting behavior as illustrated in Figure 4. As consistent with intuition, at very high rates of recycling, raw material prices are depressed. This negative force is exerted by lower demand due to higher recycling, and by the revival of the mining sector in Country 1. This revival of Country 1's mining sector at higher levels of α (as evident in Figures 3 and B.10) is itself an interesting phenomenon. It shows that due to the fact that marginal recycling output is diminishing in the recycling rate, very high levels of recycling incentivize Country 1 to revive its mining sector as further energy allocated to recycling would produce little additional output.

Finally, Figures B.11-B.12 illustrate the potential welfare implications of increased recycling. Figure B.11 shows that Country 2 benefits greatly from Country 1's increased recycling. Country 1's welfare, however, peaks around a recycling rate of 20%. This figure of course is not to be interpreted too literally, our point is merely qualitative: welfare may be diminishing in recycling at high recycling rates.

3.1 The convexity of recycling costs

As we have noted before, the recycling literature generally considers recycling costs to be convex. That is to say, the cost of an additional unit of material recycled is increasing in the recycling rate. This is equivalent to saying that the marginal output of additional energy

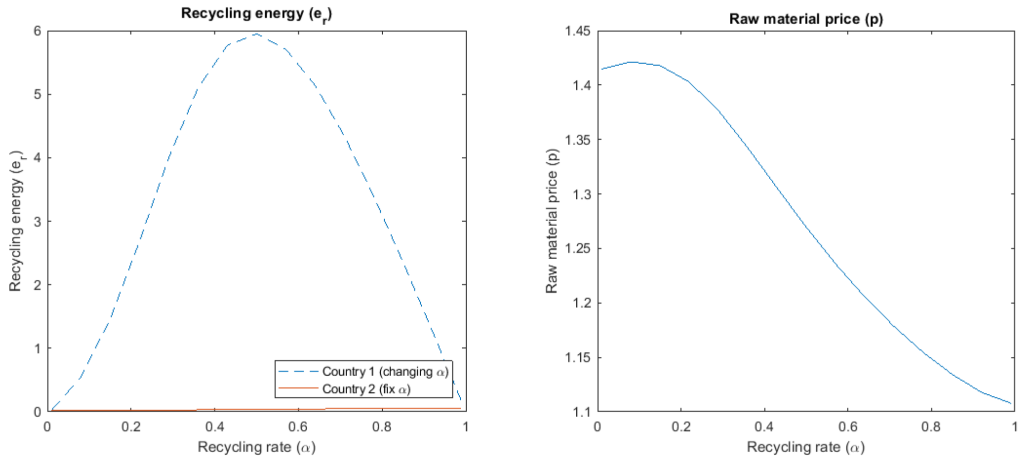


Figure 4: Recycling energy and raw material price in the identical country simulations

spent on recycling is diminishing as the recycling rate increases. The magnitude of these diminishing returns is captured by our parameter ω_2. Figure 5 illustrates this for several values of ω_2.

In this section we explore how important this cost convexity is. Our analysis here is motivated by two facts. First, if cost convexity significantly affects our results, then there is a case for policymakers to better measure and monitor the cost structure of recycling activities. Second, regardless of the current levels of convexity, it is not inconceivable that technological progress will make the recycling industry more efficient over time thereby reducing the degree of convexity and lowering ω_2. It is therefore natural to ask whether such forces dampen or reinforce our main insights.

To proceed, we conduct the same identical-country simulations as above. Now, however, we consider three separate values of ω_2. At $\omega_2 = 0$ we effectively remove convexity from recycling costs: the output of additional energy deployed in recycling is independent of the recycling rate α. This is the natural lower bound for the level of convexity, and essentially the upper bound for technological progress. At $\omega_2 = 0.33$, we consider a case where the cost structure exhibits an intermediate level of convexity. Finally, at $\omega_2 = 1$, we consider a case with a high level of convexity. This is equivalent to the case simulated above.

Figures B.19-B.21 show sectoral composition changes differ at different levels of cost convexity. Two broad conclusions can be drawn from these figures. First, the transition from mining to manufacturing for Country 2 is dampened by lower cost convexity. Second, the mining revival in Country 1 is less pronounced as more energy can be deployed profitably in the recycling sector when diminishing returns there are not so prevalent.

One factor that might explain this is raw material prices shown in Figure 6a. The drop in raw material prices is more severe at higher levels of convexity. This implies that if recycling costs are more convex, then Country 2 will have more incentives to switch out of mining

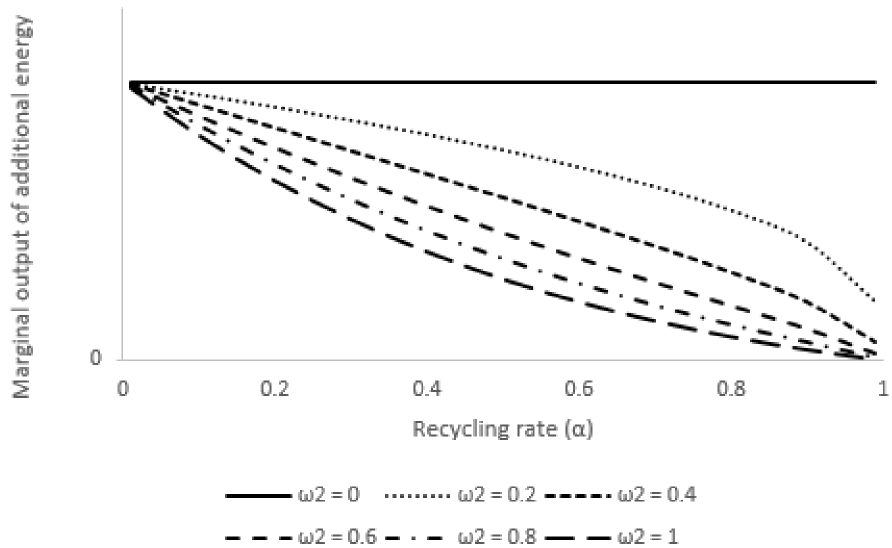
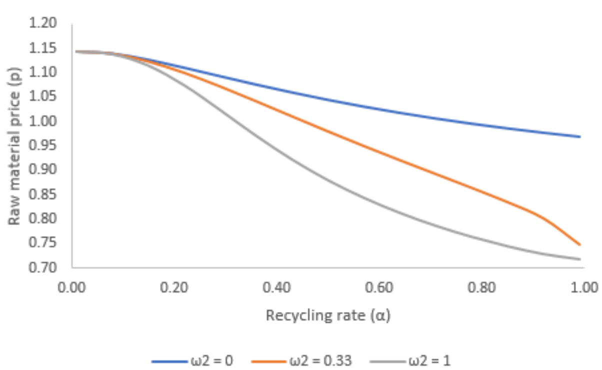
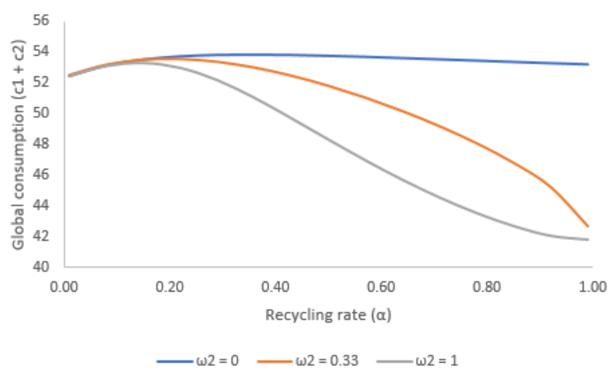


Figure 5: Recycling cost convexity



(a) Raw material prices



(b) Global consumption

Figure 6: The effect of recycling cost convexity

and into manufacturing. Figures B.13-B.15 show that this lower incentive for Country 2 to switch to manufacturing also manifests itself in trading patterns. Lower convexity delays the switch Country 2 to be a net exporter of manufactured goods.

Finally, Figure 6b shows that lower levels of convexity allow for higher final good consumption on a global level. This is intuitive as a lower ω_2 is effectively an improvement in recycling production technology. The recycling rate α that maximizes global consumption increases as convexity decreases. This means that technological progress in the form of lower ω_2 would allow a welfare-maximizing government to optimally recycle more. Interestingly, at lower levels of convexity the quantitative effects of the recycling rate on welfare start to diminish. In fact, at $\omega_2 = 0$, the relationship between global consumption and the recycling rate is increasing allowing for 100% recycling with no loss of welfare.

4 Non-identical countries with elastic supply of energy

In this section, we relax the assumption of inelastic energy supply ($\xi = 0$) in order to investigate how the model behaves when the signs of the derivatives are ambiguous – as established in Proposition 2. To make our simulation more interesting, and given that signs are ambiguous, we use some empirically-estimated set of parameters. We run our model on five hypothetical world regions that only trade physical goods, namely Western Offshoots, Europe, BRIC+, East Asia, and the rest of the world ("RoW"). As will be apparent in our calibration method, these names are simply chosen because real data in these regions of the world are used to estimate key parameters. The exact composition of these regions is detailed in Figure 7. We first outline the calibration procedure, and then discuss the implications of the calibrated model below.

4.1 Method of calibration

To calibrate our multi-regional model, we use the World Input-Output Table built by Timmer et al. (2014) and data provided by Eurostat and the World Bank for the year 2014. We now discuss how we calibrate each parameter. All parameters from our calibration are summarized in Table 2.

Recycling rate (α)

For European countries, we have a Circular Economy Indicator computed by the Eurostat. However, for countries not covered by the Eurostat data set, to the best of our knowledge, there is no official data on the circular recycling rate. In order to get around this, we regress the Eurostat's Circular Economy Indicator for EU countries on GDP per capita. We use

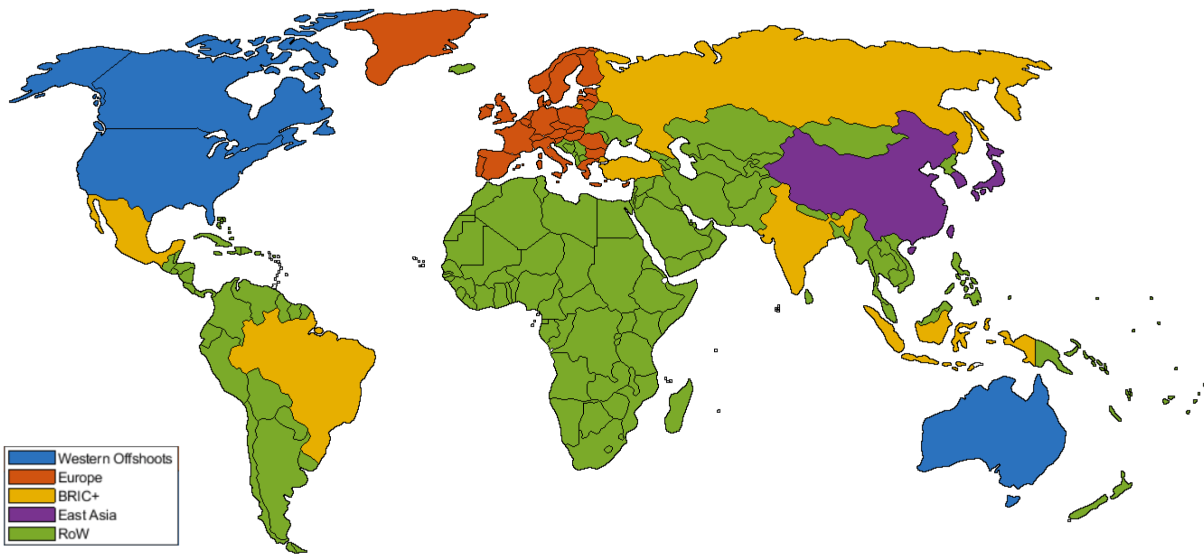


Figure 7: (1) Regions and members. Western Offshots: Australia, Canada, United States. (2) Europe: Austria, Belgium, Bulgaria, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, Great Britain, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden. (3) BRIC+: Brazil, Indonesia, India, Mexico, Russia, Turkey (4) East Asia: Japan, Korea, Taiwan, China. (5) Rest of the World: All others.

this regression to predict α for all countries in the Western Offshoots, Europe, and East Asia regions given their GDP per capita. Then we take the GDP-weighted average of these country-level predicted recycling rates to aggregate them op to the regional level. For the BRIC+ and RoW regions, for which recycling activities are small or absent, we simply pick the smallest predicted Circular Economy Indicator observed across European countries.

Manufacturing TFP (A) and factor shares (β)

To calibrate the TFP of the manufacturing sector and the remuneration shares β and $(1-\beta)$, we use the World Input-Output Table. For each region, we regress the total remuneration of raw material and electricity in logs on the value of raw materials and electricity in logs for all sectors classified as manufacturing.[2]

[2] We consider manufacture of wood and of products of wood and cork, except furniture, articles of straw and plaiting materials, food products, beverages and tobacco products, paper and paper products, coke and refined petroleum products, chemicals and chemical products, basic pharmaceutical products and pharmaceutical preparations, rubber and plastic products, other non-metallic mineral products, basic metals, fabricated metal products, except machinery and equipment, computer, electronic and optical products, electrical equipment, machinery and equipment, motor vehicles, trailers and semi-trailers, other transport equipment, and other manufacturing.

Table 2: Calibrated parameter values

Region	A	B	C	T	α	β	γ	ω_1	ω_2	ξ
Western Offshoots	1.9700	1.00	1.9700	100	0.2103	0.5699	0.67	1	0.9893	1
Europe	1.9972	0.33	1.9972	100	0.1475	0.4635	0.67	1	0.9164	1
BRIC+	1.9980	1.82	1.9980	100	0.0150	0.4790	0.67	1	0.7931	1
East Asia	2.0004	1.51	2.0004	100	0.1379	0.4948	0.67	1	0.9061	1
RoW	1.7485	2.84	1.7485	100	0.0150	0.3260	0.67	1	0.7931	1

Cost of recycling parameters (ω_1, ω_2)

We start by estimating $\omega = \omega_1(1-\alpha)^{\omega_2}$, with the World Input-Output Table. To do this, we regress the value of electricity used in recovery on the total the value of recovery for each country. Given that the regression is performed on a global level, we assume the estimated parameter is the same for all regions. We use each α to recover ω_2 according to the equation $\omega = \omega_1(1-\alpha)^{\omega_2}$, assuming $\omega_1 = 1$.

Recycling and mining TFP (C, B)

We assume that the TFP of the recycling sector equals the TFP of the manufacturing sector in each region, that is $C = A$. Finally, to calibrate the TFP of the raw material-producing sector, B, we turn to the data on natural resource rents as a % of GDP by the World Bank. We calculate the GDP-weighted average of this figure within each group, and then normalize B for the US to 1, and scale the other regions' B accordingly.

Remaining parameters (γ, T, ξ)

Finally, to illustrate the ambiguous effects of an elastic suppply of energy in our model, we set $\gamma = 0.67$, $T = 100$, and $\xi = 1$ for all regions.

4.2 Results of the calibrated model

We simulate the calibrated model by increasing the recycling rate, α of Europe from 14.5% (close to our current estimate) to 99.5% in 1 percentage point increments. We thus evaluate the effect of increased recycling in Europe on the other regions.

Figures B.22-B.26 show how the allocation of energy across sectors changes in the five regions. As the recycling rate increases, Europe predictably ramps up energy devoted to recycling, but this tapers off later due to the convex costs of recycling. Energy devoted to manufacturing also enjoys a boom initially, then later on decreases. This seems consistent with the version of Proposition 2 that says that energy devoted to manufacturing is increasing in α as long as the raw material price is above a threshold. Indeed, as visible in the left

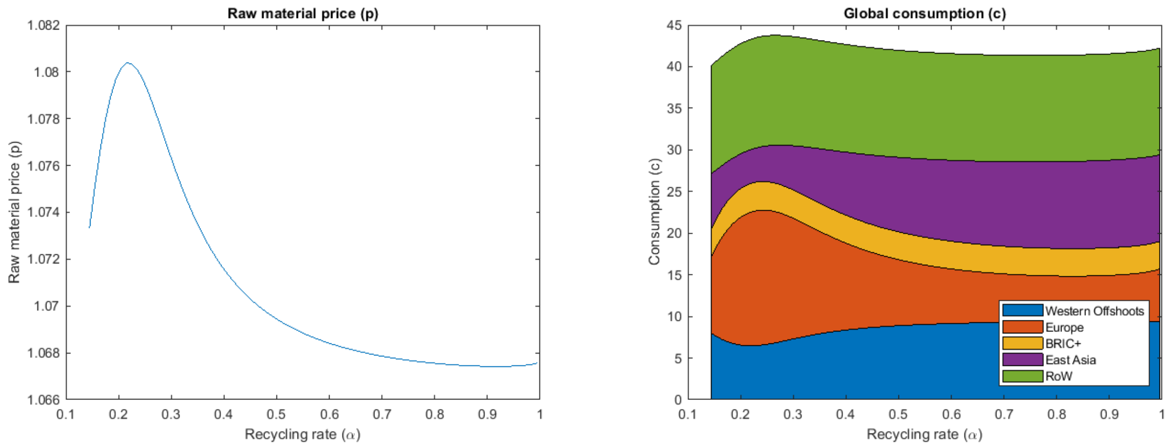


Figure 8: Raw material prices and consumption in the calibrated model

panel of Figure 8, raw material prices initially increase with Europe's α, but then take a dive. This behavior is consistent with the simulations in Section 3.

As a response to Europe's increasing α, different regions react differently. Initially, the Western Offshoots and East Asia significantly decrease energy devoted to manufacturing and recycling, while the BRIC+ and the Rest of the World ramp up mining activities somewhat. These initial reactions reverse as Europe winds down energy devoted to manufacturing at higher levels of α.

Why does Europe increase manufacturing initially as α increases? It is possible that a higher α makes manufacturing more efficient as more of the embedded raw material can be recycled and reused. This rise in efficiency also spurs Europe to import more raw material, as visible in Figure B.27. This increased raw material demand pushes up raw material price, and forces the Western Offshoots and East Asia to import less raw material and thus reduce manufacturing. The increase in raw material exports from the BRIC+ countries and the Rest of the World does not increase by much, because the extra raw material Europe imports is mostly rerouted from the Western Offshoots and East Asia. As Figure B.28 shows this increased final good production in Europe increases Europe's net exports in the final good. Some of this goes to the BRIC+ countries and the Rest of the World, who are able to afford more final goods due to a slightly increased mining output and a higher raw material price. But most of the extra exports merely displace the exports of the Western Offshoots and East Asia, thereby increasing Europe's market share in the global final goods exports market. These changes of course reverse as Europe starts to wind down manufacturing at higher levels of α.

It is apparent from these simulations that the effects of increasing α in Europe are highly heterogeneous. The Western Offshoots and East Asia are initially adversely affected by increased recycling in Europe both in terms of losing final goods production and in terms of losing consumption – as the right panel of Figure 8 shows.

At the same time, the BRIC+ and the Rest of the World groups enjoy an initial surge in mining activity and a corresponding increase in consumption. Global consumption on the whole increases initially, mostly driven by Europe.

However, once Europe's recycling rate goes over a tipping point, which is around 25%, raw material prices are depressed enough that the directions of a lot of the changes are reversed. This reversal of effects was also noted in our simulations in Section 3, and is consistent with what we see in Proposition 2 about the threshold level of raw material price at which the directions of the derivatives flip. While in the $\xi \neq 0$ case, we cannot ascertain analytically that such a reversal occurs, this calibration exercise shows that currently the world is in such a state where a form of Proposition 2 still holds.

5 Conclusion

In this paper we have presented a multi-country model of an economy with manufacturing, mining and recycling sectors. The countries are connected through trade in manufactured goods and raw material. In this set-up, we considered the effects of an increase in recycling rates. While our model can be applied more generally, our message focuses on short-run changes in the recycling rates of economies such as the European Union on its trading partners. Our primary goal was to investigate the effects of increased recycling on the sectoral composition of all regions involved.

Our main insight is that increased recycling in one trading partner can trigger a general reallocation of resources among economic sectors in the remaining partners. We proved that the directions of the changes heavily depend on the fundamentals of each region, and that general rules with respect to the directions of changes cannot be derived. We have shown that the elasticity of energy supply plays a major role in the ambiguity of the directions. Our mathematical insights are consistent with the results of our calibrated exercise.

In addition, we do document substantial quantitative variation in our conclusions depending on the state of technology. A key parameter here is the extent of diminishing returns in the recycling industry. We find that the stronger diminishing returns are in recycling, the higher the potential drop in raw material prices are, which in turn leads to a faster and more extensive transition to manufacturing in poor countries. On the other hand, stronger diminishing returns also lead to lower global welfare. Thus we call policymakers for special attention on the structure and estimation of this parameter.

One limitation of our analysis is that we do not explicitly take environmental concerns such as landfill capacity or pollution into account. We also do not model dynamics and raw material stock depletion. However, our model is primarily concerned with the short-term, that is, on the order of years to decades, where abstracting away from such considerations is arguably reasonable. We leave the incorporation of our insights into more complex frameworks to future work. Given the parsimony of our model, expansions incorporating these issues as well as multiple manufacturing or raw material sectors are possible avenues for future research.

References

Aglionby, J., Nicolaou, A., and Daneshkhu, S. (2018). Consumer goods groups join war on plastic. *Financial Times.* 22 January.

Anderson, C. (1987). The production process: Inputs and wastes. *Journal of Environmental Economics and Managment*, 14:1–12.

Balch, O. (2018). Is the circular economy an untapped business opportunity? *The Telegraph.* 23 January.

Bernard, S. (2015). North-south trade in reusable goods: Green design meets illegal shipments of waste. *Journal of Environmental Economics and Management*, 69:22–35.

Dobbs, R., Manyika, J., and Woetzel, J. (2015). *No Ordinary Disruption: The Four Global Forces Breaking All the Trends.* PublicAffairs, New York.

Eichner, T. and Pethig, R. (2001). Product design and efficient management of recycling and waste treatment. *Journal of Environmental Economics and Management*, 41(1):109–134.

Geng, W., Huang, B., Bartekova, E., Bleischwitz, R., Turkeli, S., Kemp, R., and Domenech, T. (2017). Circular economy policies in China and Europe. *Journal of Industrial Ecology*, 21(3):651–661.

Kinnaman, T. (2006). Examining the justification for residential recycling. *Journal of Economic Perspectives*, 20(3):4–14.

Kinnaman, T. and Yokoo, H. (2011). The environmental consequences of global reuse. *American Economic Review*, 101(3):71–76.

Pooler, M. (2017). Tata Steel makes progress with emission-cutting technology. *Financial Times.* 19 December.

Shinkuma, T. and Managi, S. (2011). *Waste and recycling: Theory and empirics.* Routledge, New York.

Sugeta, H. and Shinkuma, T. (2012). International trade in recycled materials in vertically related markets. *Environ Econ Policy Stud*, 14:357–382.

Szirmai, A. (2013). Chapter 2 - Manufacturing and economic development. In Szirmai, A., Naude, W., and Alcorta, L., editors, *Pathways to Industrialization in the Twenty-First Century*, pages 53–75. Oxford University Press.

The Economist (2015). Greening of business. 15 February.

Timmer, M., Dietzenbacher, E., Los, B., Stehrer, R., and Vries, G. (2014). An illustrated user guide to the world inputoutput database: the case of global automotive production. *Review of International Economics*, 23:575–605.

Appendix

A Proofs

Proof of Lemma 1

To prove Lemma 1 it suffices to note that in equilibrium $m_i^* = Be_m^{*\gamma} = m^*$ and $m_r^* = \alpha(m_i^* + x_m^*) = Ce_r^{*\omega}$, and therefore the constraints can be written as $c = A[(1+\alpha)(m+x_m)]^\beta e^{1-\beta} + x_c$, $Be_m^\gamma = m$, $Ce_r^\omega = \alpha(m+x_m)$, $E = e_c + e_m + e_r$, $0 = x_c + px_m$. Thus the FOCs with respect to e_r and x_m are given by $(C/\alpha)^\beta e_r^{\omega\beta}(1-\beta)e_c^{-\beta}B^\gamma/\gamma\,(C/\alpha e_r^\omega - x_m)^{1/\gamma-1} = p/A(1+\alpha)^\beta$ and $(1-\beta)/\beta\left[e_r + C/\alpha B^\gamma/\gamma\,(C/\alpha e_r^\omega - x_m)^{1/\gamma-1}\omega e_r^\omega\right] = \omega\left[E - e_r - B^\gamma\,(C/\alpha e_r^\omega - x_m)^{\frac{1}{\gamma}}\right]$, therefore Lemma 1 follows from optimization.

Proof of Lemma 2

To prove Lemma 2, note that the model can be reduced to

$$\max_{x_m, e_c, \ell} A\,[B(\ell - e_c)^\gamma + x_m]^\beta\, e_c^{1-\beta} - px_m - \xi\ell.$$

The first-order conditions with respect to e_c, x_m, and E are given by

$$\begin{aligned}
\frac{\beta}{1-\beta} e_c B\gamma(E-e_c)^{\gamma-1} &= B(E-e_c)^\gamma + x_m \\
x_m &= \left[\frac{p}{A\beta}\right]^{1/(\beta-1)} e_c - B(E-e_c)^\gamma \\
\xi &= A\beta[B(E-e_c)^\gamma + x_m]^{\beta-1}B\gamma(E-e_c)^{\gamma-1}.
\end{aligned} \tag{4}$$

We depart from (4), and then plug in for x_m and for the second term $E - e_c$. This gets us to the condition $\xi = pe_c^{\beta-1}[(1-\beta)/\beta]\,(p/A\beta)^{1/(\beta-1)}$. Finally we plug in for e_c and solve for E.

Proof of Proposition 1

To prove Proposition 1, note that for the case $\xi = 0$, there is an equation that defines the optimal e_r as an implicit function

$$g(e_r;\alpha) \equiv \omega\left[E - e_r - B^\gamma\left(\frac{C}{\alpha}e_r^\omega - x_m\right)^{\frac{1}{\gamma}}\right] - \frac{1-\beta}{\beta}\left[e_r + \omega\left(\frac{C}{\alpha}\right)^{\frac{1}{\gamma}}\frac{B^\gamma}{\gamma}e_r^{\frac{\omega(1-\gamma)}{\gamma}}\right] = 0.$$

Using the Implicit Function Theorem, we can derive that

$$\begin{aligned}\frac{\partial e_r}{\partial \alpha} &= -\frac{\partial g(e_r;\alpha)/\partial\alpha}{\partial g(e_r;\alpha)/\partial e_r} \\ &= \frac{\frac{\omega B^\gamma c^{1/\gamma}}{\gamma\alpha^{(1+\gamma)/\gamma}} e_r^\omega \left[1+\frac{1-\beta}{\beta\gamma} e_r^{\omega(1-2\gamma)/\gamma}\right]}{\frac{\omega^2 B^\gamma}{\gamma}\left(\frac{C}{\alpha}\right)^{\frac{1}{\gamma}} e_r^{\frac{\omega-\gamma}{\gamma}}\left[1+\frac{1-\beta}{\beta}\frac{1-\gamma}{\gamma}e_r^{-\omega}\right]+\omega+\frac{1-\beta}{\beta}} > 0.\end{aligned}$$

Then, it follows that

$$\begin{aligned}\frac{\partial e}{\partial \alpha} &= -\frac{\partial e_r}{\partial \alpha}\left[1+\frac{B^\gamma\omega}{\gamma}\left(\frac{C}{\alpha}\right)^{\frac{1}{\gamma}} e_r^{\frac{\omega-\gamma}{\gamma}}\right] < 0 \\ \frac{\partial e_m}{\partial \alpha} &= \frac{\partial e_r}{\partial \alpha}\left[1+\frac{B^\gamma\omega}{\gamma}\left(\frac{C}{\alpha}\right)^{\frac{1}{\gamma}} e_r^{\frac{\omega-\gamma}{\gamma}}\right] - \frac{\partial e_r}{\partial \alpha} > 0 \\ \frac{\partial m}{\partial \alpha} &= \frac{B}{\gamma} e_m^{\gamma-1}\frac{\partial e_m}{\partial \alpha} > 0 \\ \frac{\partial \ln c}{\partial \alpha} &= \frac{\beta}{1+\alpha}+\frac{\beta}{m}\frac{\partial m}{\partial \alpha}+\frac{1-\beta}{e}\frac{\partial e}{\partial \alpha} \gtreqless 0,\end{aligned}$$

where for c, the derivative of the logarithm is shown for computational simplicity. When $\xi \neq 0$, note that after plugging in for E^* in the FOC for e_r we have

$$\frac{1-\beta}{\beta}\left[e_r+\left(\frac{C}{\alpha}\right)^{1/\gamma}\frac{B^{-1/\gamma}}{\gamma}\omega e_r^{\omega/\gamma}\right] = \omega\left(\frac{A(1-\beta)}{\xi}\right)^{1/\beta}\frac{C(1+\alpha)}{\alpha}e_r^\omega,$$

and thus results follow from the Implicit Function Theorem.

Proof of Proposition 2

To prove Proposition 2, if $\xi = 0$, note that

$$\begin{aligned}\frac{\partial e}{\partial \alpha} &= \frac{\beta^{\frac{\beta}{\alpha(\beta-1)}}\left(\frac{A}{p}\right)^{\frac{1}{\alpha(\beta-1)}}\left(-\frac{B}{\beta-1}\right)^{1/\alpha}\left(\ln(B)-\ln(1-\beta)+\ln(\beta)+\frac{\ln(A)+\ln(\beta)-\ln(p)}{\beta-1}\right)}{\alpha^2} > 0 \\ \frac{\partial x_m}{\partial \alpha} &= B^{1/\alpha}\left(\frac{\left(\frac{p}{A}\right)^{\frac{\alpha-1}{\alpha(\beta-1)}}(1-\beta)^{\frac{\alpha-1}{\alpha}}}{\beta^{\frac{\beta(\alpha-1)}{\alpha(\beta-1)}}}+\frac{\beta^{\frac{\alpha+\beta}{\alpha(\beta-1)}}\left(\frac{A}{p}\right)^{\frac{\alpha+1}{\alpha(\beta-1)}}}{(1-\beta)^{1/\alpha}}\right)\cdot \\ &\quad \frac{(\ln(1-\beta)+\ln(A)-\ln(B)-\ln(p)-\beta\ln(1-\beta)+\beta\ln(B)+\beta\ln(\beta))}{\alpha^2(\beta-1)} > 0\end{aligned}$$

if and only if $p > A\beta^{\beta}\left(1-\beta/B\right)^{1-\beta}$ holds. The rest of the results then follow from differentiation with respect to α. The case $\xi \neq 0$ is similar to the proof of Proposition 1.

B Figures

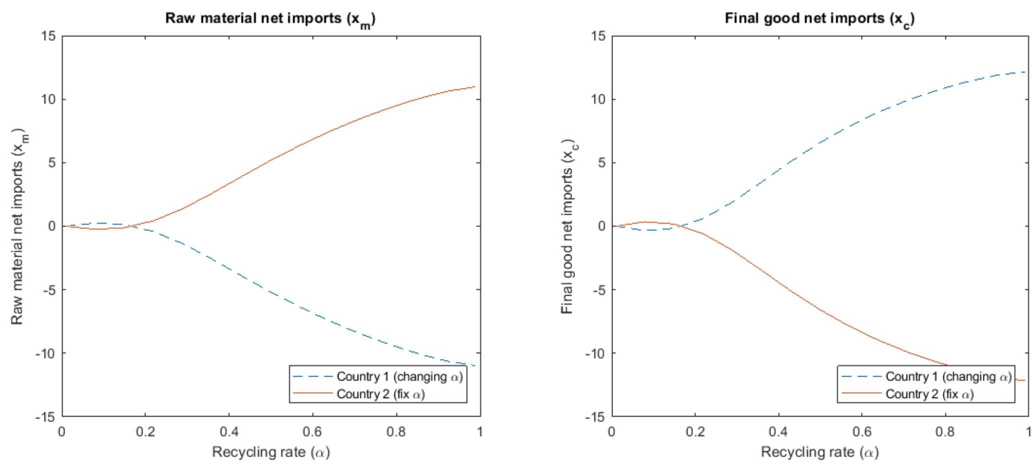


Figure B.9: Trade in the identical country simulations

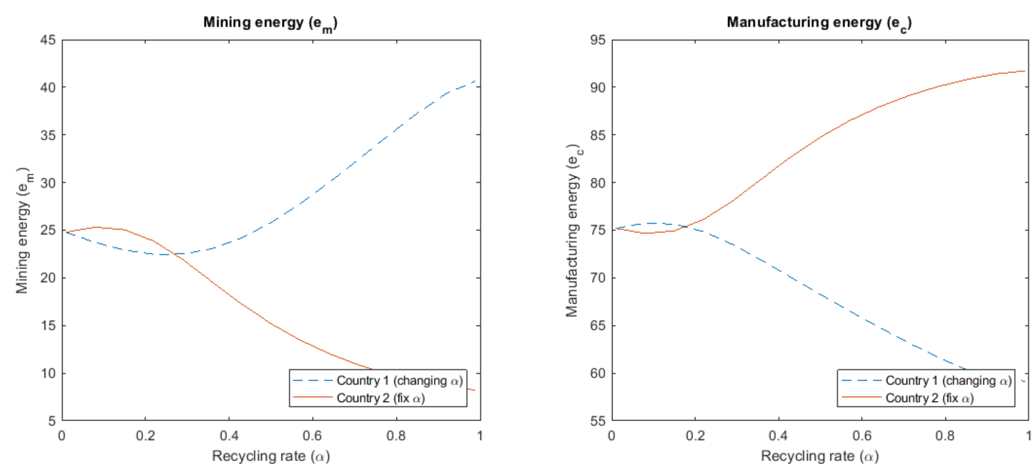


Figure B.10: Mining and manufacturing energy in the identical country simulations

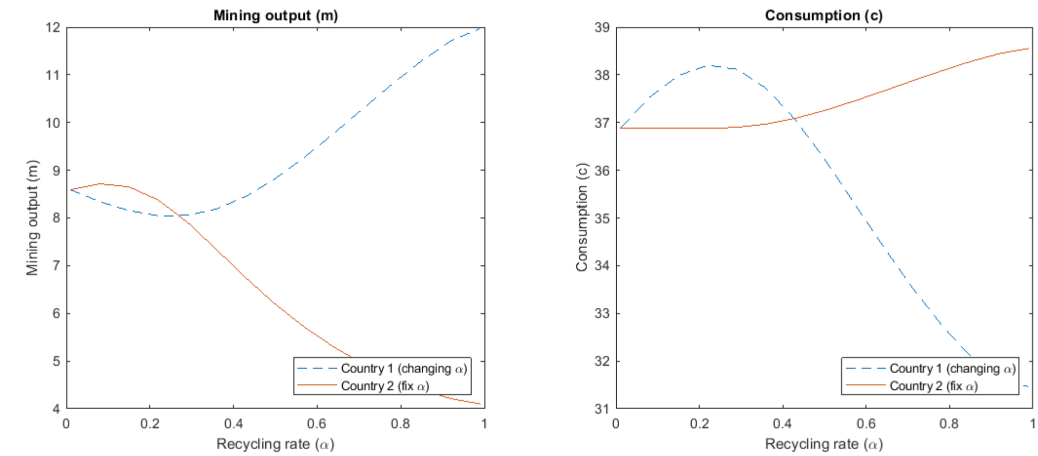


Figure B.11: Mining and manufacturing output in the identical country simulations

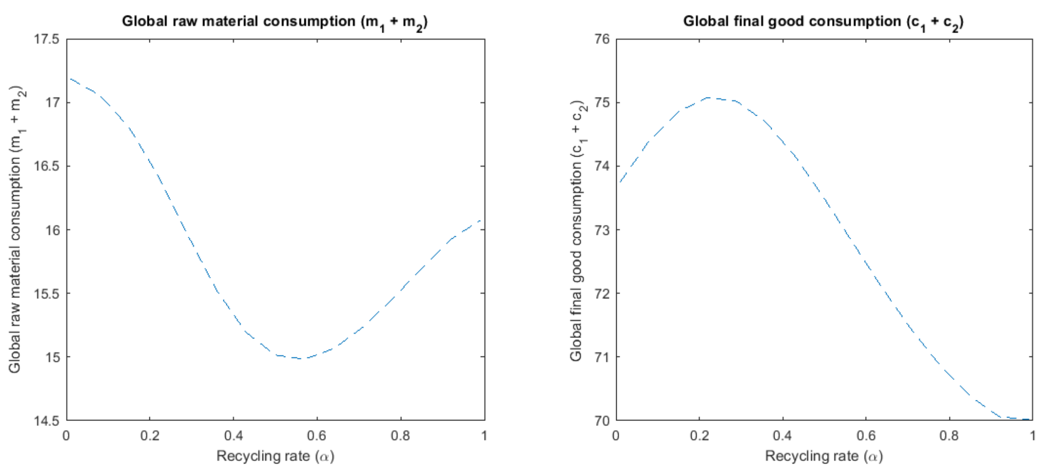


Figure B.12: Global raw material and final good consumption in the identical country simulations

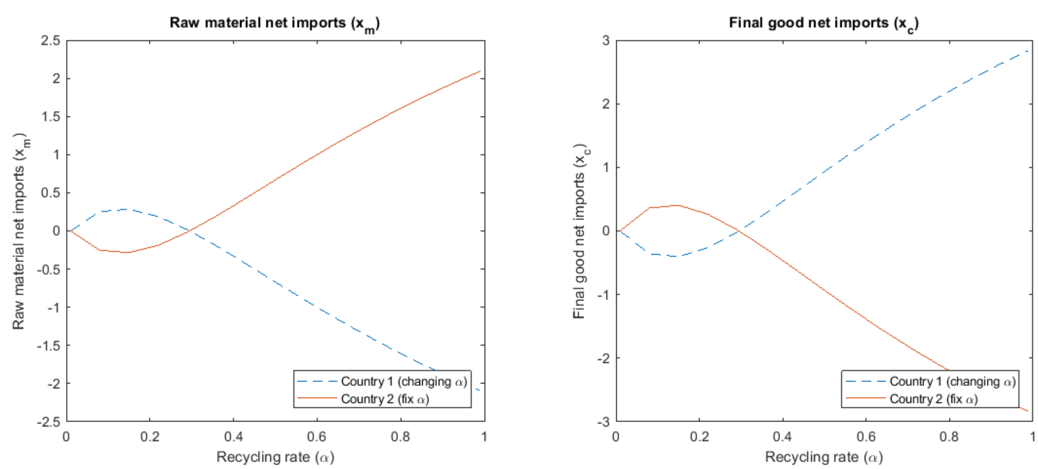


Figure B.13: Trade in the non-identical country simulations with $\omega_2 = 0$

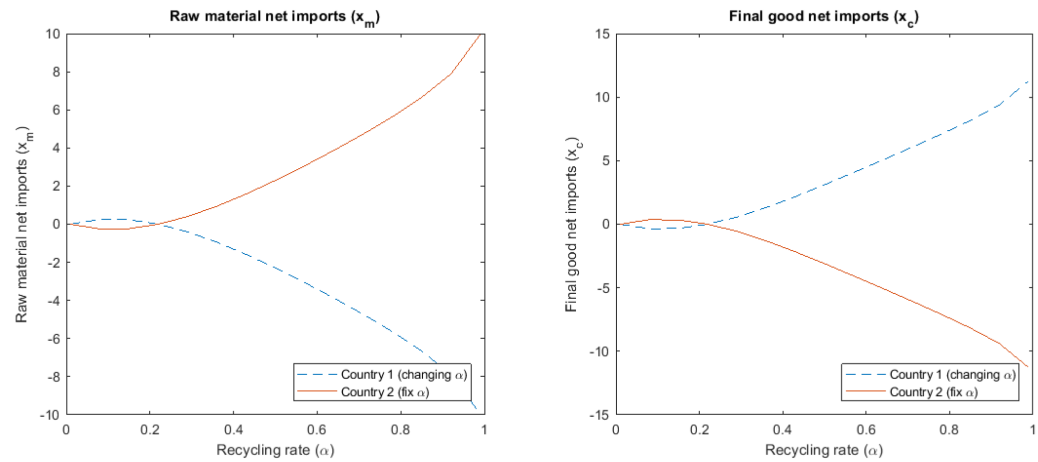


Figure B.14: Trade in the non-identical country simulations with $\omega_2 = 0.33$

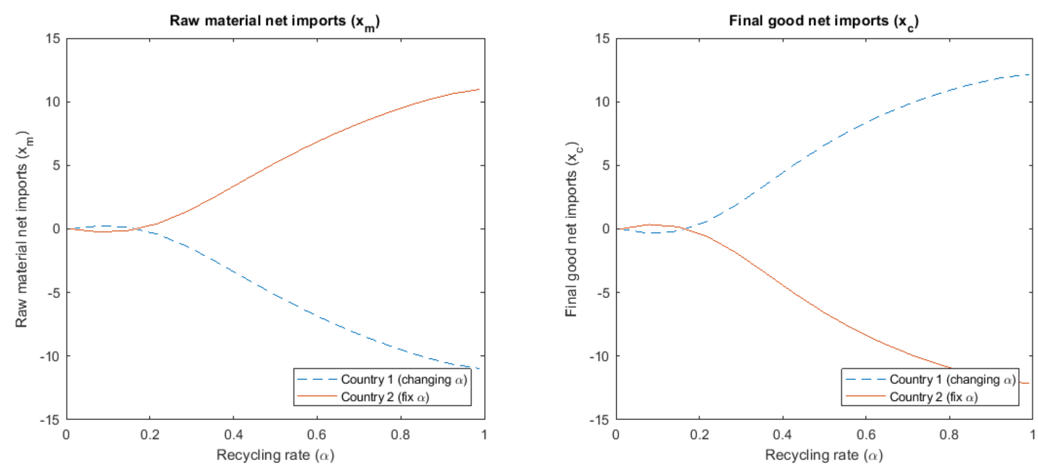


Figure B.15: Trade in the non-identical country simulations with $\omega_2 = 1$

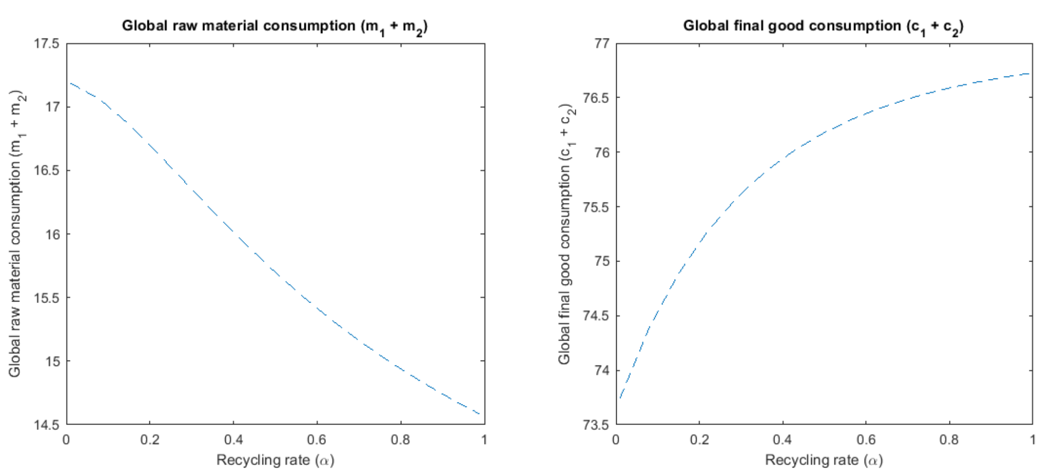


Figure B.16: Global raw material and final good consumption with $\omega_2 = 0$

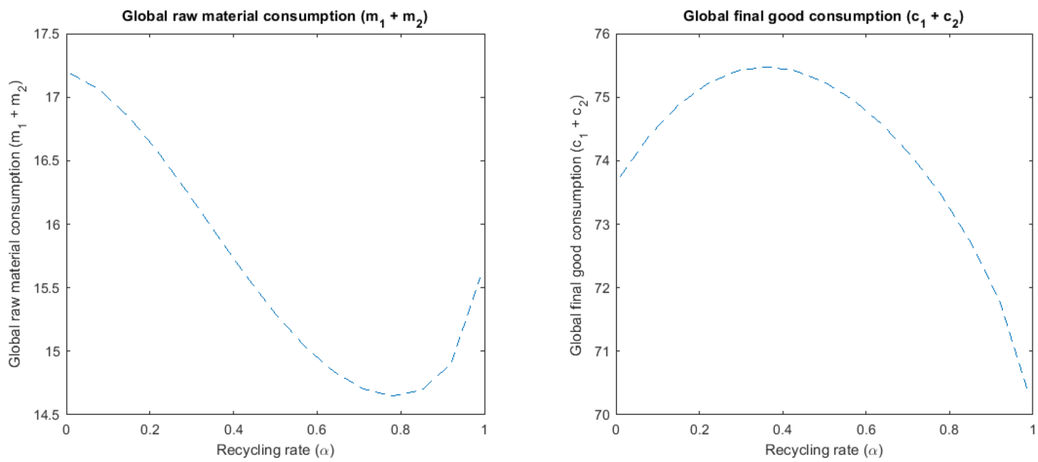


Figure B.17: Global raw material and final good consumption with $\omega_2 = 0.33$

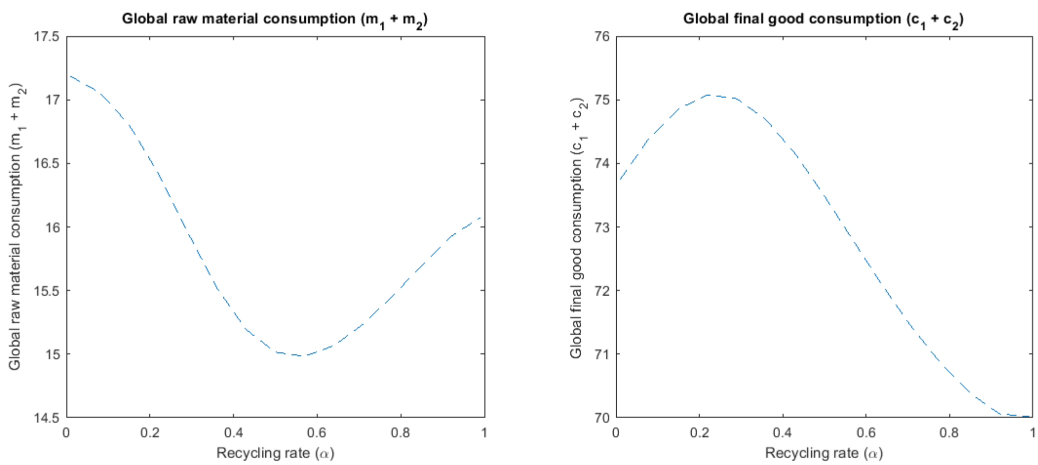


Figure B.18: Global raw material and final good consumption with $\omega_2 = 1$

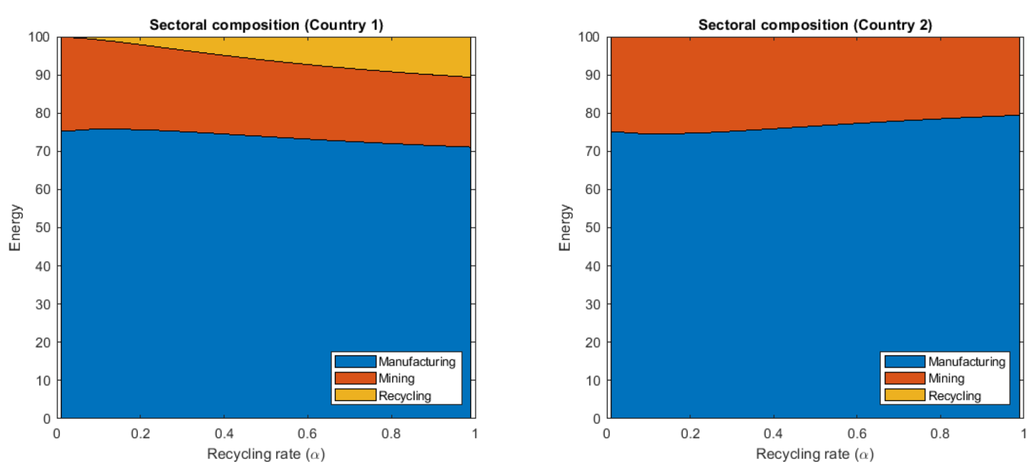


Figure B.19: Sectoral composition with $\omega_2 = 0$

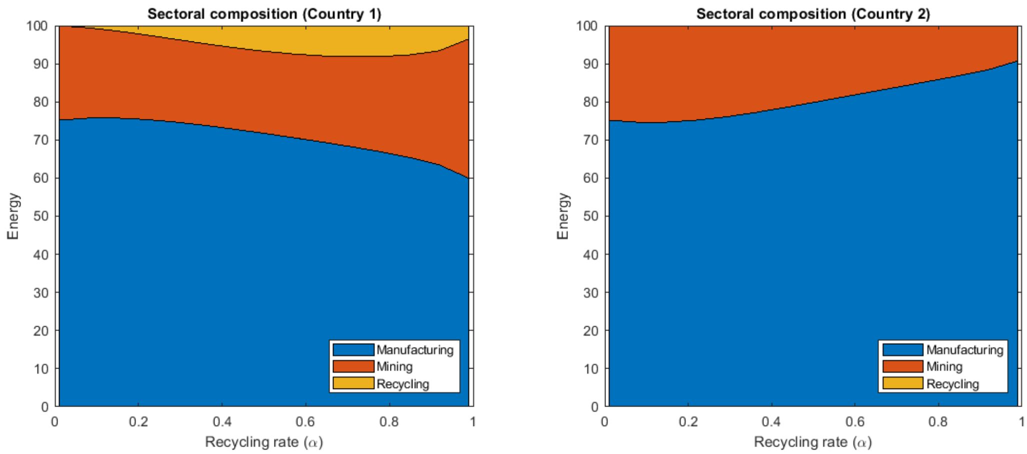


Figure B.20: Sectoral composition with $\omega_2 = 0.33$

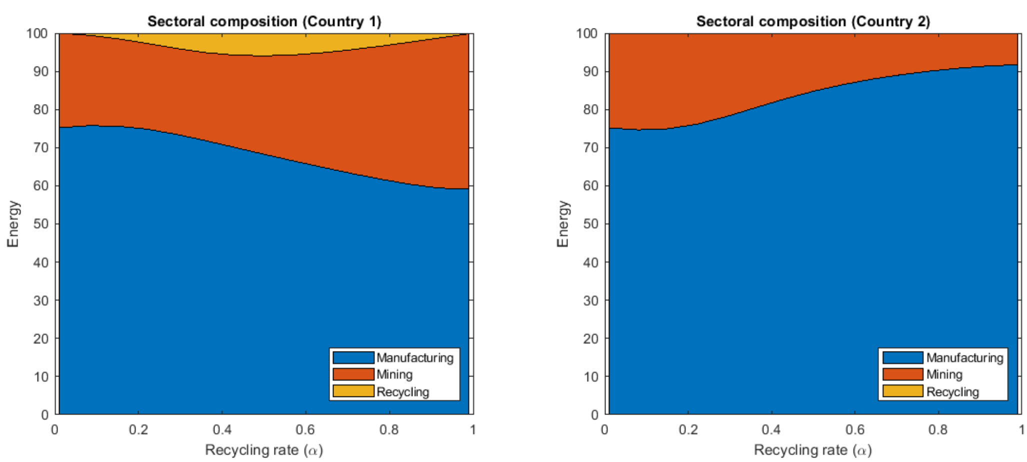


Figure B.21: Sectoral composition with $\omega_2 = 1$

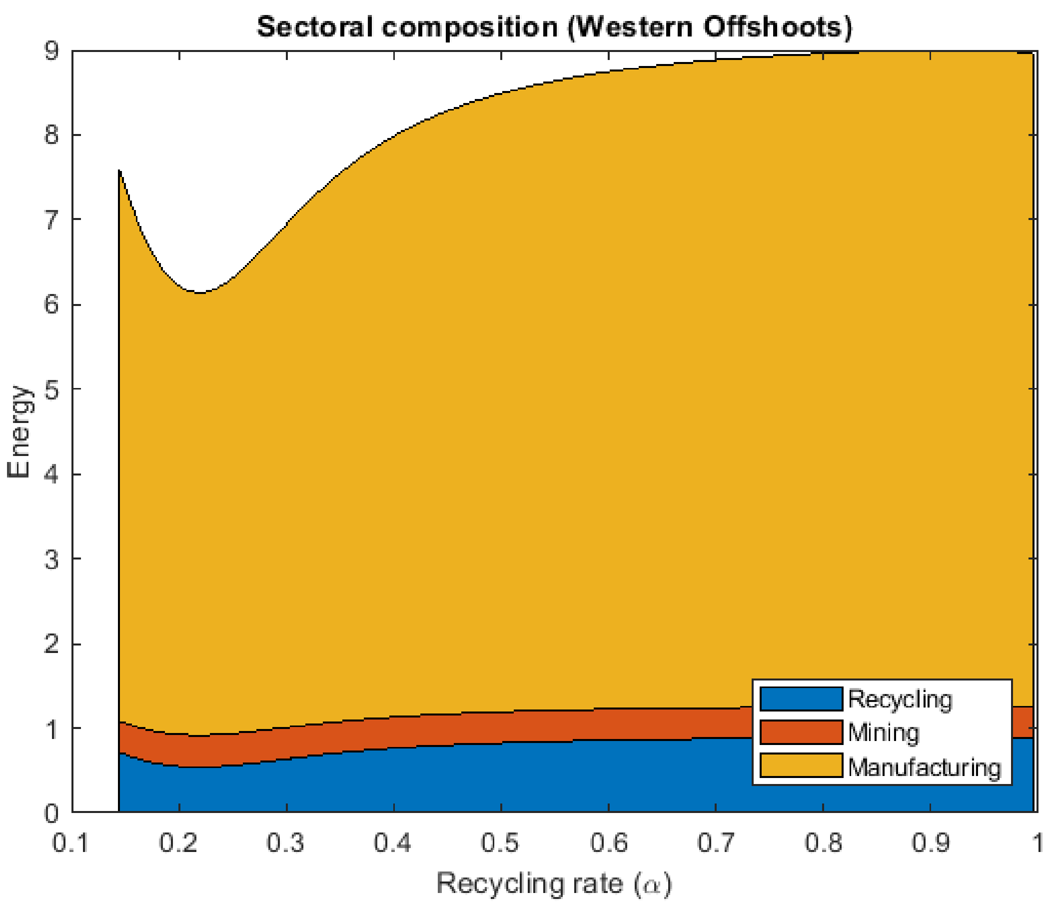


Figure B.22: Sectoral composition in the Western Offshoots

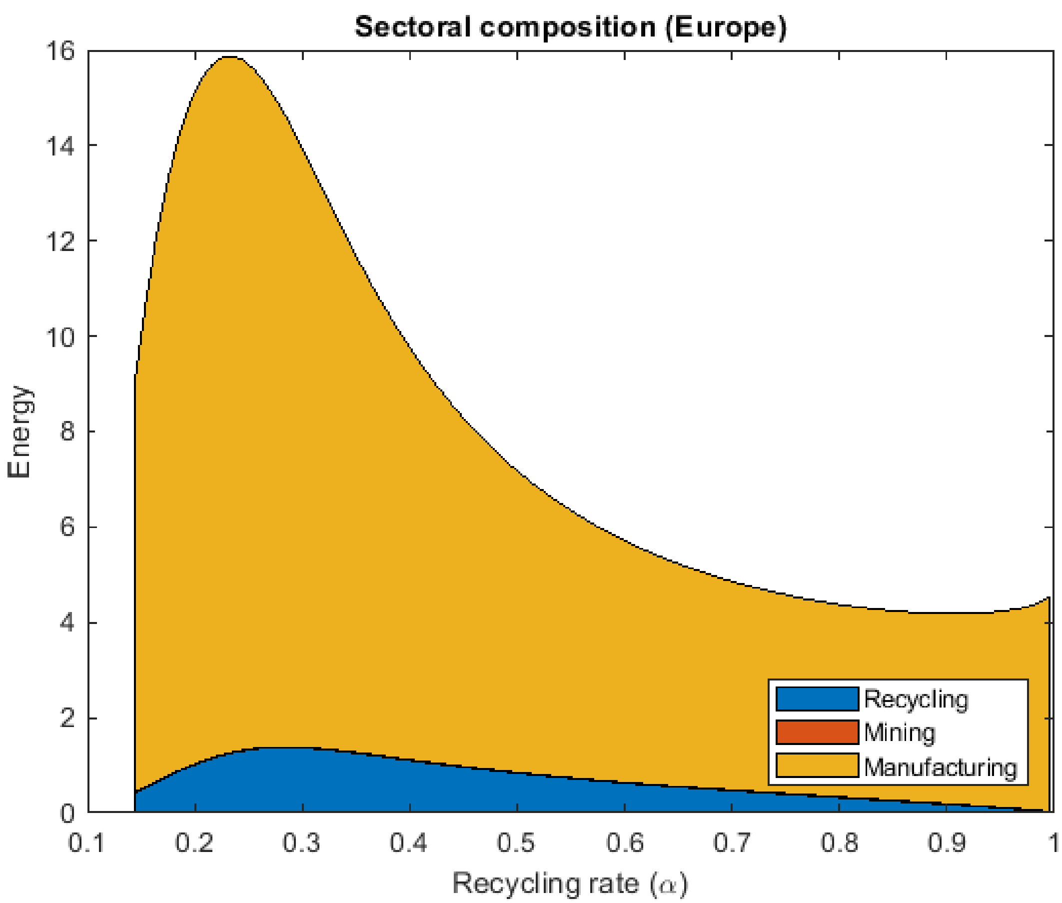


Figure B.23: Sectoral composition in Europe

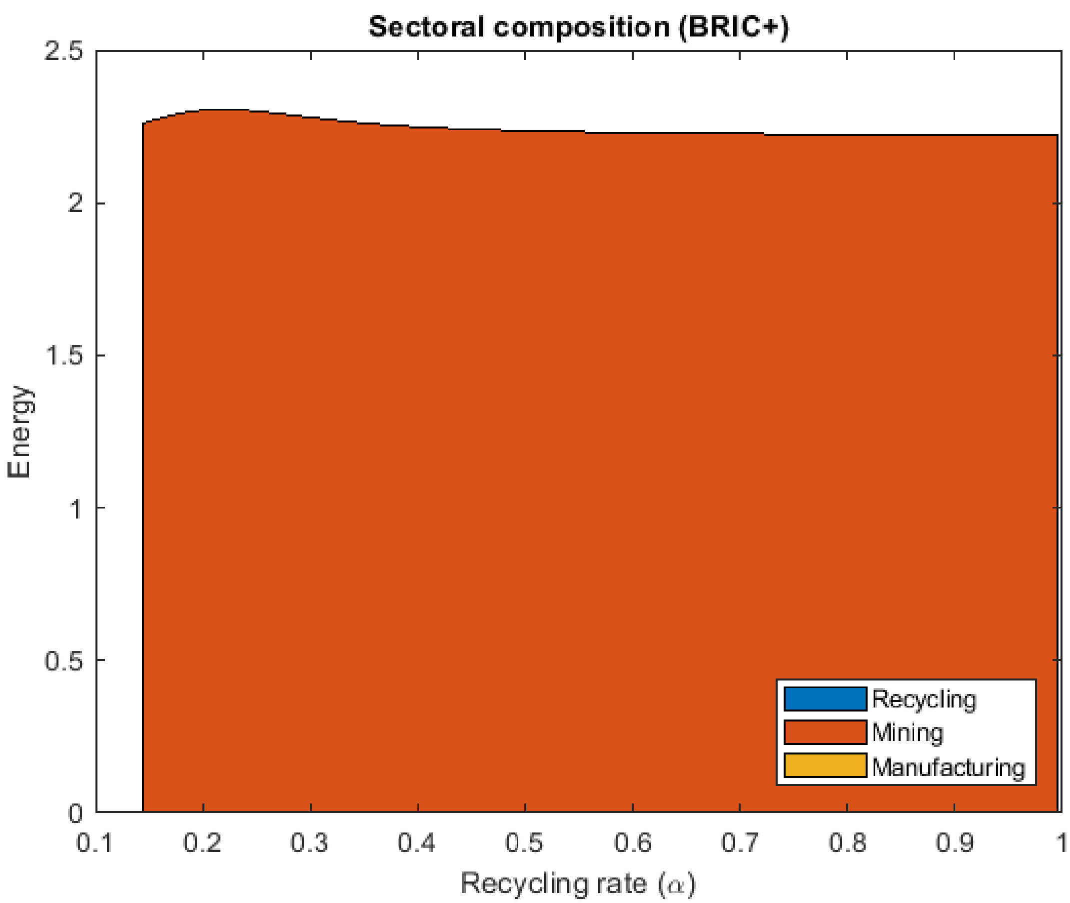


Figure B.24: Sectoral composition in BRIC+

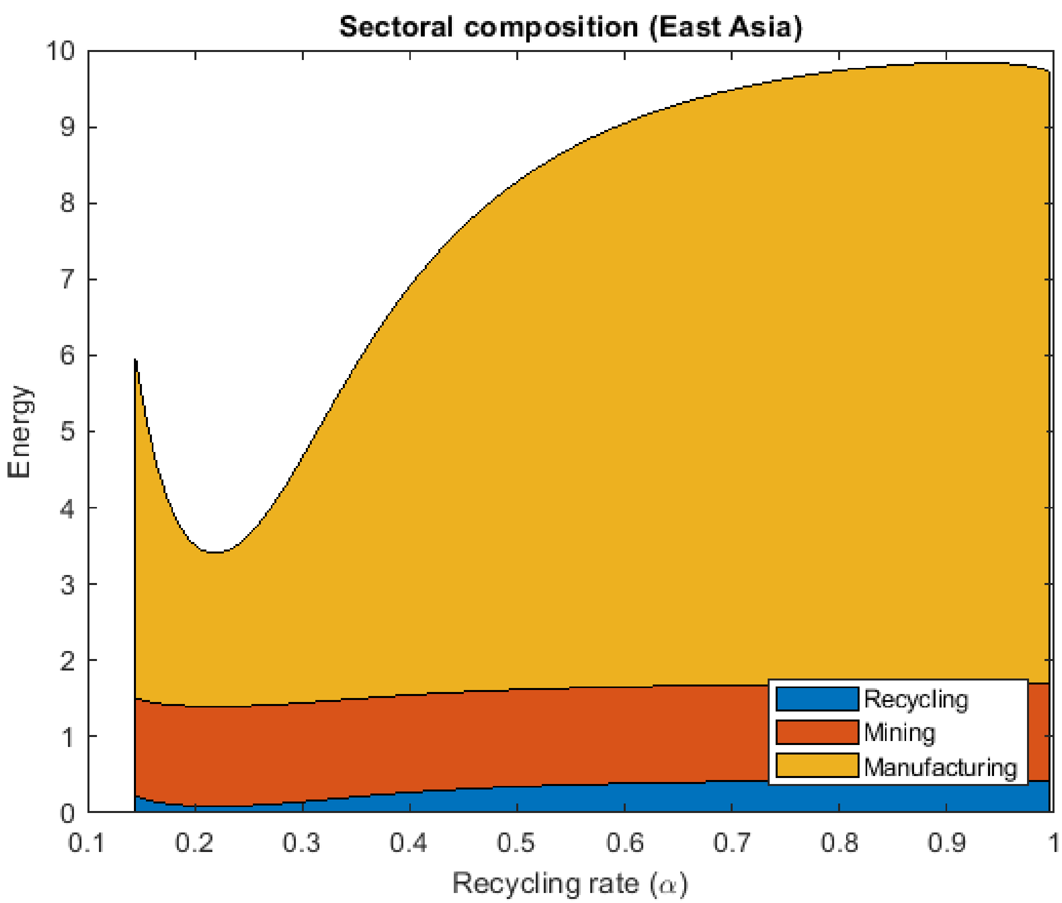


Figure B.25: Sectoral composition in East Asia

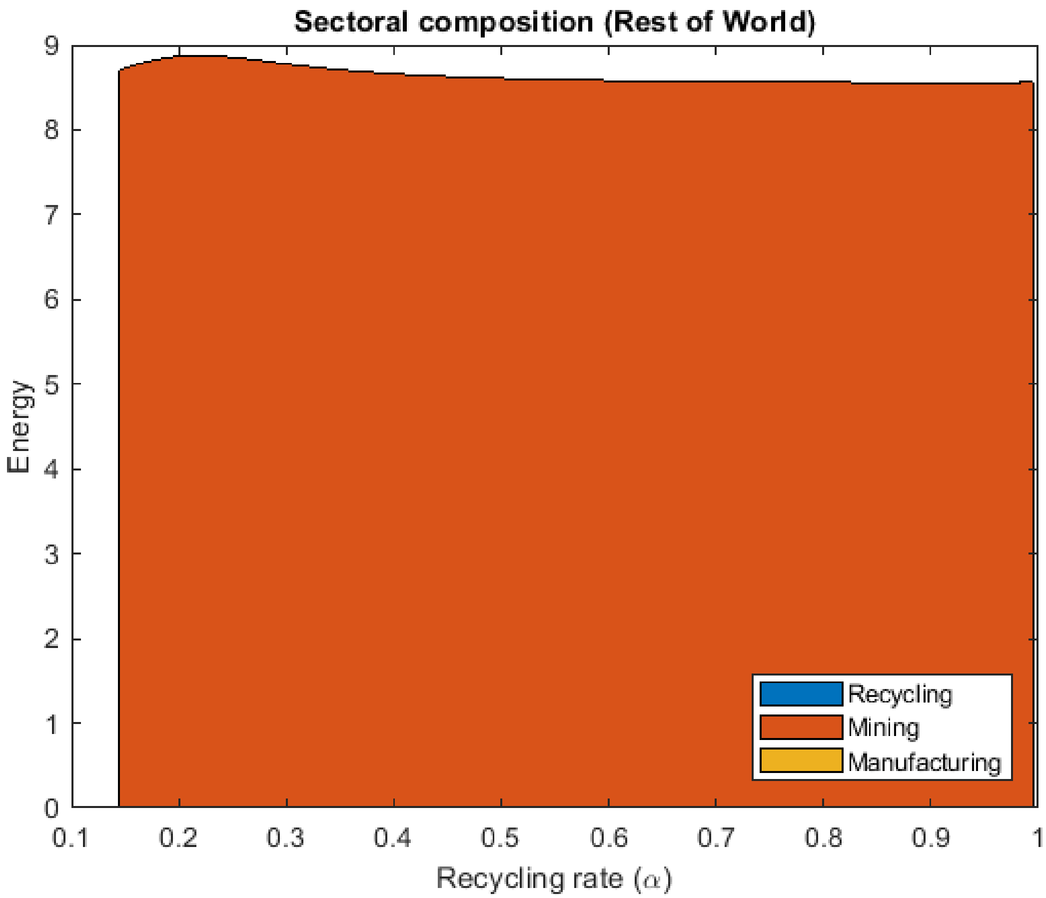


Figure B.26: Sectoral composition in the Rest of the World

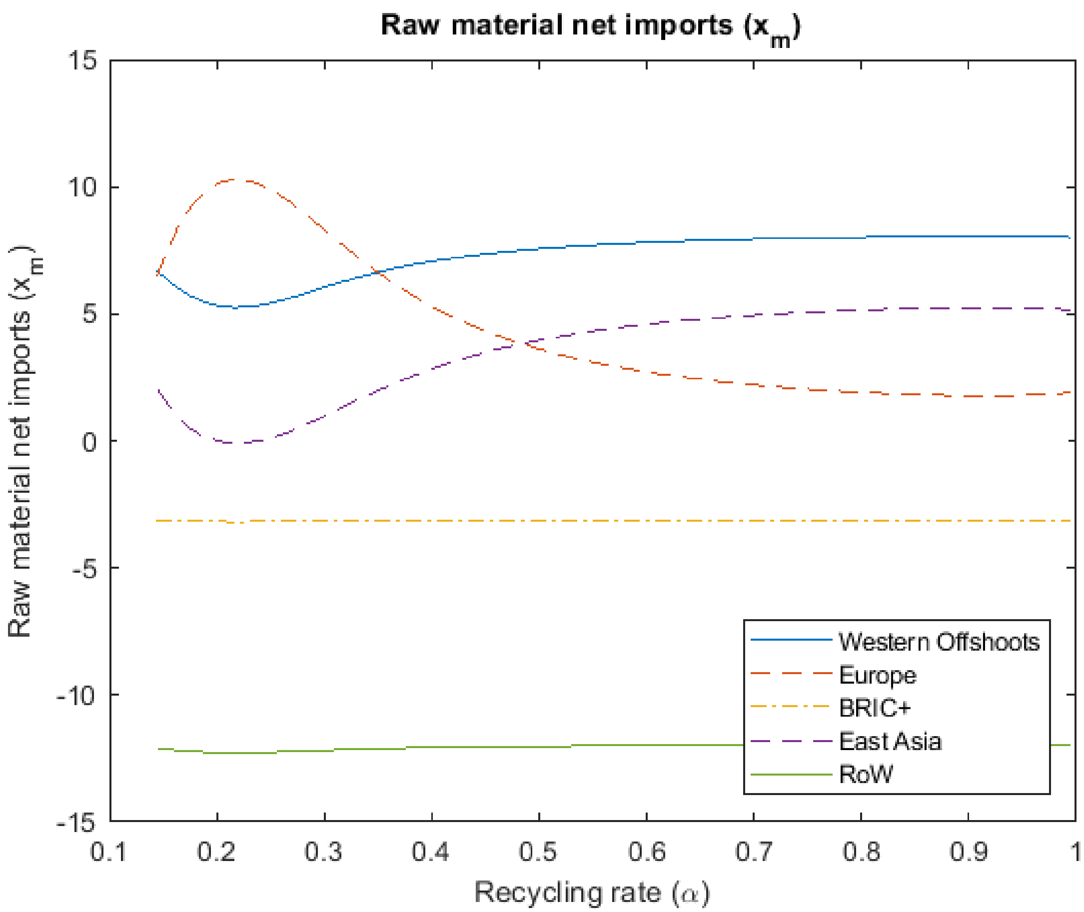


Figure B.27: Raw material net imports in the five-region world

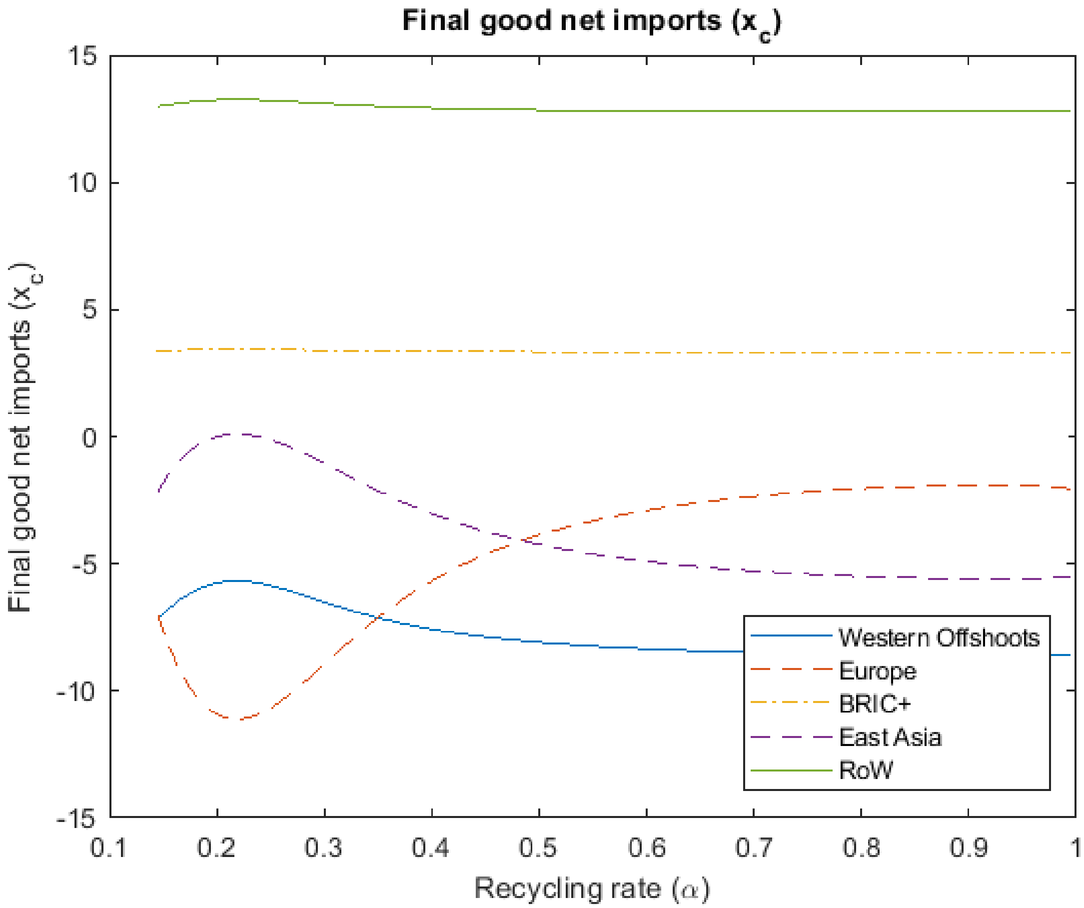


Figure B.28: Final good net imports in the five-region world