Rensselaer

Working Papers in Economics

Department of Economics, Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY, 12180-3590, USA. Tel: +1-518-276-6387; Fax: +1-518-276-2235; URL: http://www.rpi.edu/dept/economics/; E-Mail: sternd@rpi.edu

Shifting Trade Patterns as a Means to Reduce Global CO2 Emissions: Implications for the Aluminium Industry

Anders Hammer Strømman
Norwegian University of Science and Technology

Edgar G. Hertwich
Norwegian University of Science and Technology

Faye Duchin
Rensselaer Polytechnic Institute

Number 0508

June 2005

Shifting Trade Patterns as a Means to Reduce Global CO_2 Emissions: Implications for the Aluminium Industry

Anders Hammer Strømman [a] Edgar G. Hertwich [a] Faye Duchin [b]

[a] *Norwegian University of Science & Technology*
Department of Energy and Process Technology, Industrial Ecology Program
Høyskoleringen 5, 7491 Trondheim, Norway

[b] *Rensselear Polytechnic Institute*
Department of Economics
110 8th St. Troy, NY, 12180

Abstract

This paper investigates how changes in the international division of labor can contribute to reducing CO_2 emissions. The mitigation potential and costs implied by this mechanism are analyzed. Implications for the aluminium sector are assessed, including changes in the price of aluminium when global carbon emissions are constrained and the constraints are progressively tightened. The analysis makes use of the World Trade Model with Bilateral Trade (WTMBT), a linear program based on comparative advantage with any number of goods, factors, and regional trade partners. Minimizing factor use, WTMBT determines regional production, bilateral trade patterns, and region-specific prices. The model is extended for this study through the application of multi-objective optimization techniques and is used to explore efficient trade-offs between reducing CO_2 emissions and increasing global factor costs. This application demonstrates how the WTMBT, with its global scope and regional and sectoral production detail, can be used to build bridges between global objectives and concerns about a specific industry in specific regions. This capability can extend the reach of more traditional studies in industrial ecology.

Key words: input-output model, world trade model, bilateral trade, aluminium, CO_2

---

1 Introduction

Life Cycle Assessment (LCA) is prominent among the tools developed by quantitative industrial ecologists for analyzing environmental repercussions of pro-

7 June 2005

duction practices and identifying feasible options to reduce their impact. The application and adaptation of models and data originating in Input-Output Economics have gained momentum within the industrial ecology community in recent years, especially through the integration of monetary input-output data and physically-based process inventories.

An LCA assesses how environmental improvements in a specified technical system can be achieved through technological change and change in the division of labor, that is, the location of production of a specific product. Concern with geographic location is not always explicitly stated but enters the analysis emphatically albeit indirectly through codes of practice in accounting for transport, which is generally considered an important activity to include in an LCA.

Implications of alternative locations of production are normally assessed by constructing and comparing scenarios. The goal of a comparative LCA is to recommend one scenario over another based on an environmental rationale. Total enumeration of all scenarios is the common approach to this: so-called Leontief substitution models, like that proposed by Dantzig (1976), are rarely applied today.

LCA is concerned with factors of production like mineral ores. However, they are treated as environmental stressors only and not also as economic inputs. Their impact is assessed using pre-calculated indicators that reflect scarcity based on the assumption of constant levels, or constant rates of depletion, of available stocks of the resources in question. This treatment implicitly assumes that the amount of use by the system analyzed is negligible relative to the size of the stock. Since constraints on the availability of resources are ignored, LCA is applicable to problems involving modest and local changes but less suitable for scenarios about globally significant magnitudes of change.

The LCA framework does not formally concern itself with the problem that solutions may be environmentally benign but economically expensive. Analyzing how reductions in global CO_2 emissions are stimulated by technological changes or changes in the geographic location of production, and evaluating relative costs of different scenarios, can be achieved in a consistent and systematic manner only through a framework that is global in scope and makes use of the input-output representation to track not only material use but also costs.

The World Trade Model with Bilateral Trade (WTMBT) (Strømman and Duchin, 2005) provides a framework for such analysis. It is a linear program based on comparative advantage that minimizes factor use and determines regional production and prices of goods and bilateral patterns of trade. In this paper the model and its database are extended to analyze relations between global production and the environment, with focus on an application selected for its relevance for the industrial ecology community: the bauxite-alumina-aluminum industry. This study explores how changes in the global division of labor can contribute to reducing global carbon emissions, using multi-objective optimization techniques to develop a trade-off curve between CO_2 emissions and global factor costs. Implications for the global division of labor, prices, and emissions in different parts of the aluminium industry are examined under tightening global carbon constraints. Thus the study bridges the traditional gap between global objectives and their relevance for individual production sectors and specific geographic regions.

The motivation for investigating options to reduce global CO_2 emissions is well described in Watson (2001). Many models and tools have been developed and numerous analyses performed to investigate options for CO_2 reductions. In this analysis we isolate a single mechanism to evaluate its potential contribution: economically efficient changes in the geographic location of production, especially of goods that are energy-intensive in their production or transport, to reduce global CO_2 emissions.

The rest of this paper is divided into 4 sections. Section 2 shows how the model was extended for this analysis and the following section describes the incorporation of data about the aluminium sector into the WTMBT. Section 4 reports results of the computations, and the final section provides a summary and conclusions.

2 Extending the World Trade Model with Bilateral Trade

2.1 World Trade Model With Bilateral Trade

The World Trade Model with Bilateral Trade (WTMBT) is the starting point for the analytic framework used in this study and is itself an extension of Duchin's World Trade Model (WTM) (2005). The features of WTMBT and its properties are described in Strømman and Duchin (2005). The family of models consists of linear programs that determine regional output and prices and trade flows, determined on the basis of comparative advantage. The variables and parameters are shown in Table 3.

A brief description of the primal program of the WTMBT is given below in terms of the objective function and 5 constraints. The fifth constraint is a new one that extends the existing model for the purposes of this study.

The objective of the WTMBT is to minimize global factor costs:

$$\min \quad z = \sum_i \pi_i' F_i x_i \tag{1}$$

The first constraints are the regional goods balances, where import flows generate the demand for transportation. This is achieved through the use of the T_{ji} matrices, one for each origin-destination pair of regions. The T_{ji} matrices are constructed by combining information on interregional distances and weights of goods and represents the weight-distance requirement of transport per unit of good imported, by the appropriate modes.

$$(I - A_i)x_i - \sum_{j \neq i} e_{ij} + \sum_{j \neq i} (I - T_{ji}) e_{ji} \geq y_i \quad \forall i \tag{2}$$

Factor input requirements are specified in the F_i matrix, and factor use in each region is constrained by the availability of factors, f_i. This is the second set of constraints:

$$F_i x_i \leq f_i \quad \forall i \tag{3}$$

The third set of constraints assures that each region actually benefits from trade. See Duchin (2005) for details. This is achieved by requiring that the value of exports not exceed the value of imports, both evaluated at no-trade prices; see equation 4.

$$p_i^{*'} (I - A_i) x_i \leq p_i^{*'} y_i \quad \forall i \tag{4}$$

In order to specify a global goal for CO_2 emissions within the WTMBT framework, a CO_2 constraint has been developed. Let ω be the n-vector that contains the CO_2 emissions per unit of fossil fuel combusted with positive entries for the fuels and zeros elsewhere[1] . $\omega' x_i$ quantifies the CO_2 emissions inherently associated with the fuels produced in region i. If q is the maximum allowed total global CO_2 emissions from fossil fuels, we have:

$$\omega' \sum_i x_i \leq q \tag{5}$$

---

[1] The emission coefficients are adjusted to account for the fact that not all fuels are combusted.

Table 1. Parameters and Variables for the WTMBT

	m		number of regions
	n		number of goods
	s		number of transport sectors
	k		number of factors of production
	i,j		indices for regions $i,j=1...m$
Parameters and Exogenous Variables	A_i	$(n+s)\times(n+s)$	matrix of interindustry production coefficients i region i
	F_i	$k\times(n+s)$	matrix of factor inputs per unit of output in region i
	D	$m\times m$	matrix of interregional distances
	W	$(n+s)\times(n+s)$	matrix of weight of goods
	T_{ij}	$(n+s)\times(n+s)$	matrix of requirements for transportation from i to j
	y_i	$(n+s)\times 1$	vector of final demand in region i
	π_i	$k\times 1$	vector of factor prices in region i
	f_i	$k\times 1$	vector of factor endowments in region i
	f_i^*	$k\times 1$	vector of factor use in absence of trade in region i
	p_i^*	$(n+s)\times 1$	vector of goods prices in absence of trade in region i
	ω	$(n+s)\times 1$	vector of carbon intensities of fuels
Objective Variables	z	scalar	global factor costs
	q	scalar	global CO_2 emissions
Primal Variables	x_i	$(n+s)\times 1$	vector of output in region i
	e_{ij}	$(n+s)\times 1$	vector of goods exported from region i to region j
Dual Variables min z	p_i	$(n+s)\times 1$	vector of goods prices in region i
	r_i	$k\times 1$	vector of factor scarcity rents in region i
	α_i	scalar	benefit-to-trade shadow price in region i
	υ_z	scalar	costs of global CO_2 level,q, constraint
Dual Variables min q	ν_i	$(n+s)\times 1$	vector of unit increase of CO_2 emissions for goods balance in region i
	ϱ_i	$k\times 1$	vector of unit increase of CO_2 emissions for factor constraints in region i
	β_i	scalar	unit increase of CO_2 emissions for b.o.t. constraint in region i
	υ_q	scalar	unit increase of CO_2 emissions for global factor costs level, z, constraint

In the dual program shown below, the price variable corresponding to this constraint, υ_z, represents the unit cost associated with the limitation on CO_2 emissions, q.

$$
\begin{aligned}
\text{max.} \quad & z = \sum_i y_i' p_i - \sum_i f_i' r_i - \sum_i p_i^{*'} y_i \alpha_i - q \upsilon_z && (6)\\
\text{s.t.} \quad & (I - A_i')p_i - F_i' r_i - (I - A_i')p_i^* \alpha_i - \omega \upsilon_z \quad \leq \pi_i F_i' \quad \forall i && (7)\\
& (I - T_{ji}')p_i - p_j \quad \leq 0 \quad \forall i, j \in i \neq j. && (8)
\end{aligned}
$$

The dual maximizes the total value of final demand net of rents, subject to two price constraints. The first determines prices in regions that produce and export a given good while the second describes price formation in importing regions.

2.2 The Trade-off Curve between CO_2 Emissions and Global Factor Costs

The relationship between global CO_2 emissions and global factor costs can be explored through the construction of an efficiency frontier, a collection of efficient points such that no other feasible solution can have lower CO_2 emissions without increasing global factor costs, and vice versa. This frontier is a trade-off curve, describing options to efficient tradeoffs between the two objectives. The trade-off curve will be constructed using the constraint method of Cohon and Marks (1975), which involves first solving the WTMBT to identify the end points that minimize factor costs and CO_2 emissions, respectively.

To identify the solution with the lowest CO_2 emissions, the objective function is altered by removing the CO_2 constraint and re-introducing it into the model as the objective function:

$$\min \quad q = \omega' \sum_i x_i. \tag{9}$$

The program is solved subject to the constraints (2), (3), and (4) above. An additional constraint representing the original objective function is introduced to limit global factor costs (Eq. 7); this must not be binding when determining the lowest achievable CO_2 emissions:

$$\sum_i \pi_i' F_i x_i \leq z \tag{10}$$

In the program defined by (9), (2), (3), (4), and (10), the dual variables represent the costs in carbon (rather than in dollars). The dual program maximizing CO_2 emissions is presented below:

$$\begin{aligned}
\text{max.} \quad & q = \sum_i y_i' \nu_i - \sum_i f_i' \varrho_i - \sum_i p_i^{*'} y_i \beta_i - z \upsilon_q && (11) \\
\text{s.t.} \quad & (I - A_i')\nu_i - F_i' \varrho_i - (I - A_i') p_i^* \beta_i - \sum_i \pi_i F_i' \upsilon_q \quad \leq \omega \quad \forall i && (12) \\
& (I - T_{ji}')\nu_i - \nu_j \quad \leq 0 \quad \forall i, j \in i \neq j. && (13)
\end{aligned}$$

In particular, the dual variables corresponding to Eq. 2, which in the WTMBT represent the regional prices of goods, now represent the increase in CO_2 emissions per unit increase in demand for each good in each region, ν_i.

It should be noted that $\upsilon_q = 1/\upsilon_z$ for a given pair of objective functions q and z on the efficiency frontier with unique solution to the primal and dual variables. Practically this means that when applying the constraint method, the indifference curve will be the same either whichever one of the two options – total factor costs or total carbon emissions – is chosen as the objective function while the other is introduced as a constraint (Cohon and Marks, 1975).

Once the end points are identified, the construction of the tradeoff curve proceeds by solving the WTMBT multiple times to minimize global factor costs under a tightening CO_2 constraint until the lowest possible global CO_2 level is reached. For each of the increments, 500 in this implementation, the z corresponding to a given q is identified. Then the WTMBT is solved to minimize CO_2 emissions under a tightening global factor cost constraint at the values of z for each increment found in the previous problem. This is done to identify the increase in CO_2 emissions per unit increase in demand for a given good ν_i. At each increment the solutions of the two models are compared to ensure that both are identical in the primal, indicating uniqueness.

The model is programmed in GAMS and solved with Cplex. Pre- and post-processing of data is performed in Matlab.

3 The Aluminium Sector

Global primary aluminium production has expanded by an order of magnitude since 1975, and this growth is expected to continue, stimulated in particular by growing demand in India and China (Bergsdal et al., 2004), which starts from a low base, an order of magnitude lower than in Europe and North America. However, even in the latter regions the use of aluminium is still expanding; in 2002 the transportation sector absorbed as much as 30% of aluminium use (Bergsdal et al., 2004), and this percentage may increase further along with demand for lighter and more fuel-efficient cars.

The principal data source for the WTMBT database is Duchin (2005)[2] and, in order to focus on the aluminium industry, three goods were added to the database: bauxite extraction, alumina and aluminium. Appendix A lists the goods, factors and regions comprising the database. Electricity and services are not tradable. The region-specific availability of bauxite is constrained to reflect both domestic deposits and the capacity to extract them, estimated on the basis of annual production statistics. Sector-specific capital constraints for the aluminum and aluminium sectors are introduced: see Table 2; and for data on production in the base year, see Table 3. Data on intermediate aluminium consumption were incorporated into the manufacturing sector by disaggregating purchases from the mining and minerals sector using regional aluminium consumption data and prices from UNCTAD (2004).

Table 2
Intermediate and Factor Inputs per Unit of Output for Bauxite, Alumina and Aluminium Sectors

Units: All goods and factors in $ US 2004 per ton. Except fuels, in 10^6 tce and electricity in kWh. Bauxite and alumina in tons. Labor, in workers and bauxite ore in tons

Goods	Bauxite	Alumina	Aluminium
Coal	0	0.0960	0.6915
Oil	0.0028	0.1376	0.0211
Gas	0	0.1016	0.0897
Electricity	0.4	106	17167
Min	*	8.5	180
Agriculture	*	-	-
Manufcturing	*	83	112
Services	*	9.5	129
Bauxite	0	2.685	0
Alumina	0	0	2.132
Land	*	0	0
Labour	*	$0.66 \cdot 10^{-3}$	$3.36 \cdot 10^{-3}$
Capital	*	30.4	70.4
Bauxite Ore	1.0	-	-

Sources Atkins (2003); Bureau of Economic Analysis (2002); U.S Census Bureau (1999b,a)

(*) Indicates that regional coefficients for the mining industry are based on Duchin (2005)

---

[2] Monetary units are measured in US prices of 1970; prices were inflated to 2004 US dollars using the US GDP deflator, BEA (2005)

Table 3. Aluminium, Alumina and Bauxite Production Statistics 1990

Units 10^3 ton	World	NA	WE	FSU	Asia	China	Japan	ME	EE	LA	Africa	ANZ
Bauxite	115096	495	3000	9246	6418	3655	0	93	6554	26261	17984	41391
Alumina	44233	6157	4880	5327	1260	1134	841	167	3492	9758	607	10610
Aluminium	19526	5616	3544	3523	638	854	34	295	1078	1853	598	1492

Source: United Nations Conference on Trade and Development (2004)

4 Results

4.1 *Reducing CO_2 emissions through changing the international division of labor.*

The trade-off curve between global factor costs and CO_2 emissions is shown in Figure 1; it represents the most efficient combinations of the two objective functions. For a given value of global factor costs, the lowest feasible CO_2 emissions can be found on this curve. Solutions that are feasible but less efficient, i.e., those with higher CO_2 emissions, can be found in the area above the curve. The area below the curve contains infeasible combinations; this means that for given total factor costs, no CO_2 value to the left of the curve can be obtained.

The optimal solution of the WTMBT when minimizing factor costs is found at the right end point of the tradeoff curve. The factor costs can be read from the y axis. To the left of this point the CO_2 constraint becomes binding. As the CO_2 constraint gradually is tightened, global factor costs increase until the point where the lowest possible level of CO_2 emissions is reached at the left end point of the curve.

To achieve this, the global division of labor changes: this is the mechanism by which a reduction can be achieved in this model. The CO_2 emissions in the model are associated with the combustion of fossil fuels and can be reduced

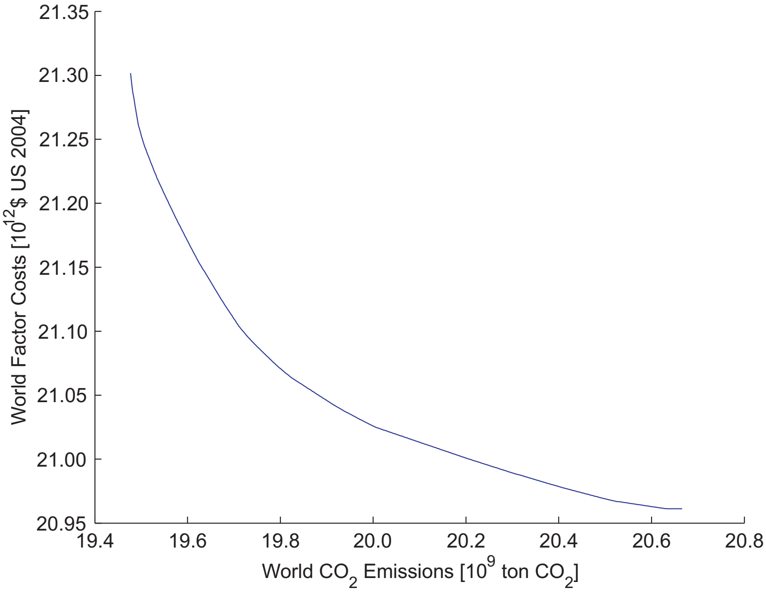

Fig. 1. Efficiency frontier between global factor costs and CO_2 emissions

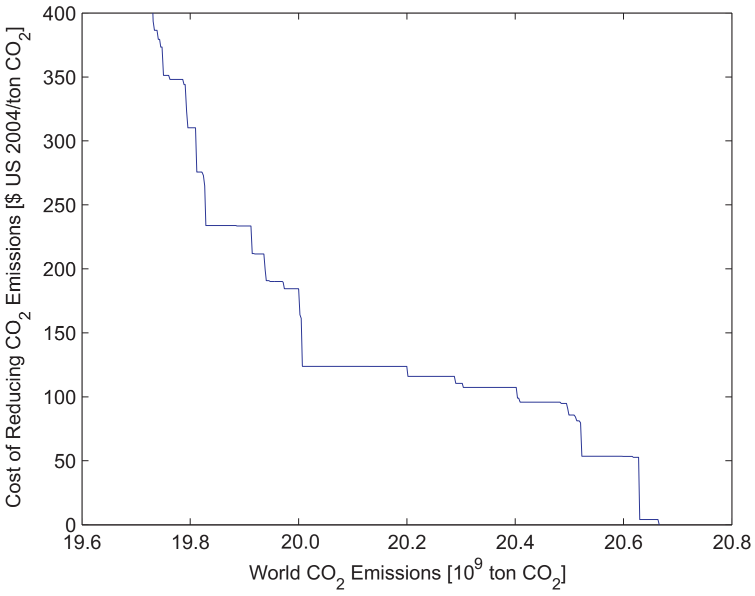

Fig. 2. Unit cost of reducing CO_2 emissions

only by lowering fuel use. The results show that moving from the solution minimizing global factor costs to the solution minimizing CO_2 emissions involves a reduction of coal, oil and gas output by 9%, 4% and 4%, respectively. There are only minor variations of around ±1% in the output of most other goods and service sectors, with the notable exception of the transport sector, which is significantly affected. Globally the amount of ton-kilometers transported is reduced by 40%. The results show that the number of producing regions increases for five out of the ten tradable goods and remains unchanged for three others. This result corresponds to increased self-sufficiency and less trade.

The induced change in the global division of labor shows a clear trend of moving production out of regions where coal is the prevailing energy carrier. China and Australia in particular experience a significant reduction in output of several goods. North America and Latin America increase production of several goods, but no region experiences as great a change in production patterns as China or Australia. By shifting production away from China and Australia, it is possible to lower global CO_2 emissions by $1150 \cdot 10^6$ tons CO_2[3]; however, this comes at an overall increase in factor costs of $350 \cdot 10^9$ \$ US 2004.

As we move from high emissions and low cost leftward towards low emissions and high cost, the slope of the curve changes. In Figure 2 the absolute value of the dual variable to the carbon constraint, υ_z, is displayed. This figure shows the first derivative of the trade-off curve (which is discontinuous since the trade-off curve is piecewise linear). This curve shows how the cost per reduced

---

[3] Conversion to tons of carbon emitted is obtained by multiplying carbon dioxide emissions by 12/44.

ton of CO_2 varies as global CO_2 emissions are gradually diminished through changes in the global division of labor. From this curve we can see that a sharp increase in the gradient occurs at a global reduction of $650 \cdot 10^6$ and $850 \cdot 10^6$ tons CO_2 (equivalent to global CO_2 emissions of about 20.0 and $19.8 \cdot 10^9$ tons CO_2, respectively).

The costs of obtaining these reductions can be determined from Figure 1. A reduction in global CO_2 emissions by $650 \cdot 10^6$ tons CO_2 implies an average cost of 90 $ US 2004 /ton CO_2, while a reduction of $850 \cdot 10^6$ tons CO_2 involves an average cost of 115 $ US 2004/ton CO_2. The IPCC, in their Working Group III: Mitigation Report (Pachauri, 2001), presents costs and reduction potential achievable through various options of technological change. Compared to their results we find that obtaining a reduction in global CO_2 emissions through a change in the international division of labor has a comparable potential and costs equivalent to their high-cost estimates for more efficient personal transport or for global energy and material efficiency improvements in the manufacturing sector.

4.2 Implications for the aluminium sector

Aluminium production and transport are energy-intensive and in this section we investigate how the distribution of production, price, and associated CO_2 emissions in the global aluminium sector are affected as increasingly tighter constraints are placed on global CO_2 emissions.

As stated in the previous section the general trends observed are reduced trade with production shifts out of those economies that are the most coal-intensive. The same trends can also be observed in the bauxite - alumina - aluminium value chain. The production of bauxite in Australia is almost halved, reducing the region from being the largest producer to the second largest following Latin America. The production is shifted to several regions including Africa, Western Europe, the former Soviet Union and Asia. The production of alumina in Australia is also almost halved, causing the region to relinquish its status as the prominent producer. Production is to a large extent shifted to the former Soviet Union. The major producers of aluminium in the base case, i.e., with a non-binding CO_2 constraint, are North America, Western Europe and the former Soviet Union. The production of aluminium in China and Australia is phased out and shifted completely to North America making it the primary producer of this good as well as the largest consumer. In the aluminium-related sectors a shift is observed from the low-cost, coal-intensive economies to the higher-cost, less coal-intensive economies. The increase in costs is naturally reflected in an aluminium price that rises as the CO_2 constraint is progressively tightened.

Figure 3 shows that an aluminium price index (i.e., the computed price relative to the price in the absence of carbon constraints) which starts at unity, increases up to, and flattens out at, 1.3 until the point where global CO_2 emissions are reduced below $650 \cdot 10^6$tons CO_2. The relative price then increases gradually up towards 2.7 times that of the unconstrained case at $850 \cdot 10^6$ tons CO_2 reduction and subsequently increases sharply.

We next investigate the increase in global CO_2 emissions that would be incurred for a unit increase in aluminium demand and inquire how this figure changes as global emissions are reduced by the reallocation of production to different regions.

The answer is provided by the dual variable, $\{\nu_i\}_{al}$, corresponding to Eq. 2 when minimizing CO_2 emissions in the WTMBT under a global factor-cost constraint. Figure 4 shows that the unit increase of CO_2 emissions for a unit increase in aluminium demand declines steeply before flattening out at 35 tons CO_2/ton Al at a $650 \cdot 10^6$ ton CO_2 global decrease. After this point it drops rapidly below 30 tons CO_2/ton Al and gradually decreases down to 13 tons CO_2/ton Al at the end point of $1150 \cdot 10^6$ tons CO_2 reduction. However, this reduction in CO_2 emissions comes at the cost of a very high aluminium price.

At a global reduction of $650 \cdot 10^6$ ton CO_2 emissions, the price of aluminium is about 1.3 times the base price and marginal CO_2 emissions are close to 35 ton CO_2/ton Al.

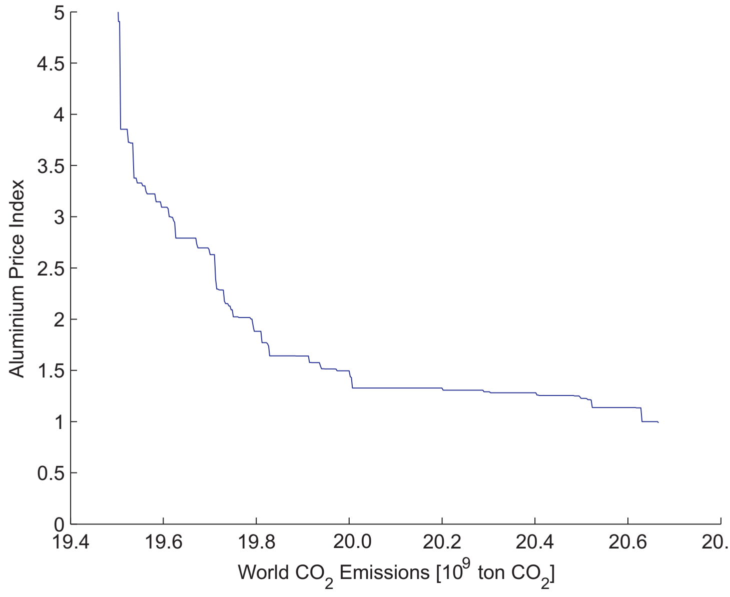

Fig. 3. Aluminium prices under global CO_2 constraints

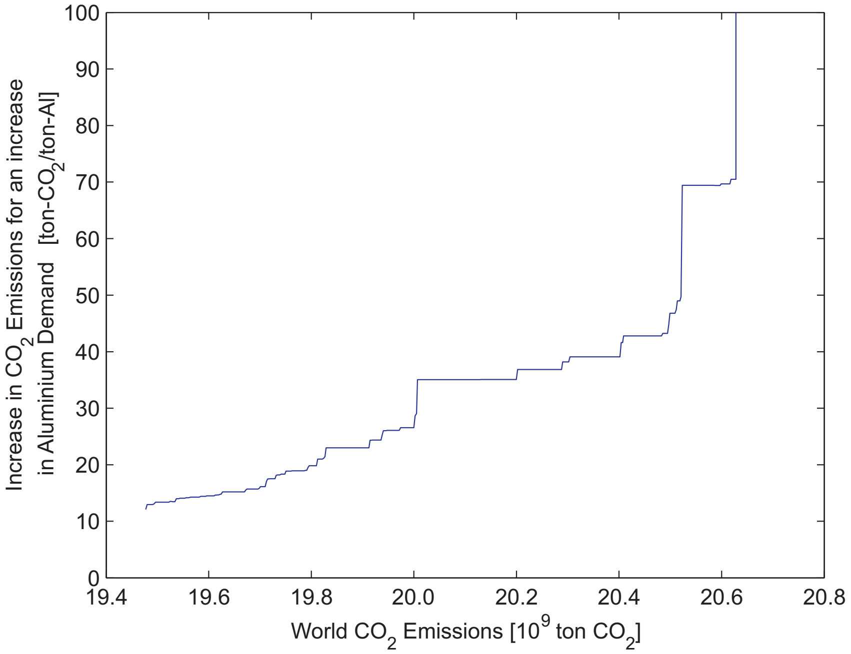

Fig. 4. Increase in CO_2 emissions pr unit increase in aluminium demand

5 Discussion and Conclusion

The World Trade Model with Bilateral Trade (WTMBT) has been applied with multiple objective functions to analyze how the reallocation of production can reduce global CO_2 emissions. An efficiency frontier between global factor costs and global CO_2 emissions is constructed and shows that a change in the division of labor can lower global CO_2 emissions by $1150 \cdot 10^6$ tons. However, this entails an overall increase in factor costs of about $350 \cdot 10^9$ \$ US 2004. This example shows how the model can be used to explore the envelope of cost trade-offs for reducing global CO_2 emissions.

The reduction in global CO_2 emissions is obtained by a change in the global division of labor causing a reduction in intermediate consumption of coal by 9% and of oil and gas by 4% each. In the present formulation, there is no technological change although that can be readily incorporated into the input-output framework. It is found that the global division of labor changes by shifting production out of coal-intensive economies when carbon emissions are constrained. The output of Australia and China is significantly reduced for several goods, and the compensating increases elsewhere are dispersed over several regions. The amount of interregional transport measured in ton-kilometers is reduced by 40% due to increased self-sufficiency and less trade.

As we move leftwards from high emissions and low cost towards low emissions and high cost, the cost per reduced ton of CO_2 increases. The results obtained here indicate that a change in the global division of labor can reduce global

CO_2 emissions by $650 \cdot 10^6$ tons CO_2 at an average cost of 90 $ US 2004 /ton CO_2. A reduction of $850 \cdot 10^6$ tons CO_2 would, however, imply an average cost of 115 $ US 2004/ton CO_2. Compared to the findings reported by the IPCC, a reduction in global CO_2 emissions through a change in the international division of labor has comparable potential and costs to those of their high-cost estimates for more efficient personal transport or for global energy and material efficiency improvements in the manufacturing sectors.

Implications for the bauxite, alumina, and aluminium sectors are investigated more closely. The production of bauxite and alumina in Australian is almost halved and is shifted to several regions including Africa, Western Europe, the former Soviet Union and Asia. Production of aluminium in China and Australia is phased out and shifted completely to North America, making the latter the primary producer as well as consumer of this good. Overall, a shift is observed from low-cost, coal-intensive economies to higher-cost, less carbon-intensive economies. The increases in costs reflected in the aluminium price, which starts at unity relative to the base price, increases up to 1.3 and then flattens out until the point where global CO_2 emissions are reduced by $650 \cdot 10^6 \text{tons} CO_2$. The relative price then increases gradually up to 2.7 times that of the unconstrained case for a reduction of $850 \cdot 10^6$ tons CO_2 and subsequently increases sharply.

This study illustrates the potential of the World Trade Model framework to enable interdisciplinary collaboration on crucially important questions involving both physical and economic analysis. The case of aluminium was selected because of the importance of resources to the industrial ecology community. While the numerical values in the database and consequently in the results are crude, they are of plausible magnitudes and hopefully are adequate to demonstrate the power of the approach. Improving the database will need to be the work of a larger community of analysts.

References

Atkins, P. (Ed.), 2003. Life Cycle Assessment of Aluminium: Inventory Data of the Worldwide Primary Aluminium Industry. International ALuminium Institute.

Bergsdal, H., Strømman, A. H., Hertwich, E. G., 2004. The Aluminium Industry - Environment, Technology and Production. No. 8 in IndEcol Report Series. NTNU IndEcol, Trondheim.

Bureau of Economic Analysis, 2002. 1997 Benchmark Input-Output Accounts. U.S. Department of Commerce.

Bureau of Economic Analysis, 2005. Gross Domestic Product: Implicit Price Deflator. U.S. Department of Commerce.

Cohon, J. L., Marks, D. H., 1975. A review and evaluation of multiobjective programing techniques. Water Resources Research 11 (2), 208–220.

Dantzig, G. B., 1976. On the reduction of an integrated energy and interindustry model to a smaller linear program. The Review of Economics and Statistics 58 (2), 248–250.

Duchin, F., 2005. A world trade model based on comparative advantage. Economic Systems Research 17 (2), 1–22.

Pachauri, R. (Ed.), 2001. Climate Change 2001: Mitigation. Intergovernmental Panel on Climate Change - United Nations.

Strømman, A. H., Duchin, F., 2005. A world trade model with bilateral trade based on comparative advantage. RPI Working Paper - Submitted .

United Nations Conference on Trade and Development, 2004. UNCTAD Handbook of Statistics 2004 Database. Vol. TD/STAT.29. United Nations, Geneva.

U.S Census Bureau, October 1999a. Alumina Refining, 1997th Edition. No. EC97M-3313A in Manufacturing - Industry. U.S Department of Commerce.

U.S Census Bureau, September 1999b. Primary Aluminum Production, 1997th Edition. No. EC97M-3313B in Manufacturing - Industry. U.S Department of Commerce.

Watson, R. T. (Ed.), 2001. Climate Change 2001: Synthesis Report. Intergovernmental Panel on Climate Change - United Nations.

A Goods, Regions and Factors

Table A.1
Goods and Sectors

Code	Full Name	Units
Coal	Coal	tce - tons of coal equivalent
Oil	Oil and oil distillates	tce - tons of coal equivalent
Gas	Natural gas	tce - tons of coal equivalent
Elec.	Electricity	1970 US dollars
Mining	Mineral products	1970 US dollars
Agric.	Agricultural products	1970 US dollars
Manuf.	Manufactured sectors	1970 US dollars
Serv.	Services	1970 US dollars
Baux.	Bauxite	ton
Amina.	Alumina	ton
Alu.	Aluminium	ton
Crude.	Crude oil tanker transport	ton-kilometers (tkm)
Bulk.	Bulk carrier transport	ton-kilometers (tkm)
Cont.	Container ship transport	ton-kilometers (tkm)
LNG.	Liquefied natural gas carrier transport	ton-kilometers (tkm)

Table A.2
Regions

Code	Full Name
NA	High Income North America
WE	Western Europe
FSU	Former Soviet Union
Asia	Asia
China	China
Japan	Japan
ME	Middle East
EE	Eastern Europe
LA	Latin America
Africa	Africa
ANZ	Australia, New Zealand

Table A.3
Factors of Production

Code	Full Name
Land	Land
Labor	Labor
Capital	Capital
Coal	Raw coal
Oil	Oil in reservoir
Gas	Gas in reservoir
Bauxite	Bauxite in ore