EET/2003/05

IEA/EET Working Paper

Challenges in energy and environment modelling: a materials perspective

Dolf Gielen and Sohbet Karbuz

November 2003

I N T E R N A T I O N A L   E N E R G Y   A G E N C Y

Report Number EET/2003/05
Paris, 3 November 2003

Challenges in energy and environment modelling: a materials perspective[1]

Dolf Gielen
Sohbet Karbuz

Abstract

This paper discusses the IEA ETP model and the challenges that are encountered in energy and materials modelling. A case study on carbon leakage is discussed in order to illustrate these challenges. The preliminary results suggest that industrial CO_2 emission mitigation policies are complicated by carbon leakage. However, this leakage effect can be balanced, to some extent, by policies that support the introduction of new energy technologies. In this study, leakage has been estimated based on a bottom-up systems engineering model. While it is technically possible to stabilise global industrial emissions at 2000 levels, the modelling results suggest 20 to 45 percent leakage, if only industrialized countries introduce CO_2 policies for their industries. 80 percent of this leakage can be attributed to changes in materials trade. This suggests that technological change alone is insufficient to prevent leakage, and trade and GHG policies should be co-ordinated. The paper also discusses a number of key modelling challenges and proposes some steps on how to establish research priorities.

9, rue de la Fédération, 75739 Paris Cedex 15
Dolf.Gielen@iea.org
Sohbet.Karbuz@iea.org

International Energy Agency
www.iea.org

[1] Paper presented at the OECD workshop on Environment and Economic Modelling. Ottawa, Canada, October 9-10, 2003.

Challenges in energy and environment modelling: A materials perspective

Table of Contents

Figures

Tables

1. Introduction

Policy makers need advice on which actions to be taken to reduce the environmental impacts of economic activities. In this process ex-ante modelling is widely applied as an analysis method. In recent years a lot of attention has been focused on climate change issues, and the relation between economic activities and greenhouse gas (GHG) emissions. Given the potential economic impact of climate change policies, modelling is a cost-effective way to avoid costly policy mistakes. This paper will focus on challenges in long-term GHG policy effect simulation.

The assessment of what we know and what we do not know about the relation between economic activities and climate change is well documented in the third assessment report of the Intergovernmental Panel on Climate Change (IPCC 2001). This paper will focus on the experience within the IEA (International Energy Agency) where the main modelling questions are. This could be areas for future co-operation. Also, a number of analogies may exist with other environmental policy areas, for example between energy related emissions and agricultural emissions, and between GHG emissions and other environmental problems such as waste. Therefore, the following discussion may be of a more general modelling interest.

First, the modelling challenges are determined by the problem that is studied. The environment is only one energy related concern. The IEA mission is to provide a secure and affordable energy supply with acceptable environmental impacts. While carbon dioxide (CO_2) emissions play an important role, they do not dominate the policy discussion. An analysis that does not take the other policy concerns into account is bound to be classified as less relevant.

Second, energy supply and demand is shifting from OECD Member countries[2] to developing countries. Economies of countries are increasingly linked by global trade, and the scale of environmental problems such as climate change is the world scale. Therefore, analysis needs increasingly a global perspective, incorporating sufficient detail for the non-OECD countries. Developing countries pose a special analytical challenge because of the scarcity of reliable statistical data.

Third, the IEA has created a strong position in energy modelling through its World Energy Outlook (WEO), an annual publication with a global perspective, based on a set of models. The annual character, the focus of the agency on one modelling system and a rigid review practice has created a credible modelling system. The modelling approach that is discussed in this paper will be integrated into the existing WEO framework.

Fourth, a model may allow the identification of key variables, where data quality management should focus. The close co-operation between the Secretariat, the Implementing Agreements and the Member country governments is a unique opportunity to collect a huge amount of high quality data. A model can help to make these data available to others. In essence, data quality is the basis for the quality of the modelling results. However, in a dynamic environment with rapidly changing staff there is a need for a data management system, and a model to be used as a data management system.

Fifth, a close relation exists between the physical flows of energy and materials in the economy and the environmental impacts of economic activities. Therefore, it makes sense to include physical flows explicitly in the assessment of environmental impacts, as an intermediate stage between monetary data and environmental impacts. Both energy and material flows are included in the IEA models, as discussed below.

---

[2] Iceland, Mexico Poland and the Slovak Republic are part of OECD but not yet IEA Member countries. All other OECD Member countries are also IEA Member countries.

Past experience and projections for the future suggest that technological change will play a key role in the decoupling of economic growth and physical flows, and in the decoupling of physical flows and environmental impacts. There are two ways to project technological change: either by looking at past trends, or by looking at engineering studies. Economic top-down models tend to take the former approach. Bottom-up models are based on technology data from engineering studies. Instead, extrapolations of historical responses to future years should be validated. Without validation it is not clear if extrapolation makes sense or not. On the other hand, engineering data often neglect technological problems that emerge during development or upscaling. Improved projections of technological change pose a major modelling challenge.

These issues will be illustrated in a discussion of the Energy Technology Perspectives (ETP) model, a new model that is being developed and used at the IEA. In this paper, a case study will be discussed where this model is applied to the problem of carbon leakage. The results illustrate the importance of physical flow modelling, trade, technological change and developing countries for the assessment of industrial CO_2 policies. A discussion of the main energy and materials modelling challenges will conclude this study.

2. The importance of physical material flows for carbon leakage analysis

A GHG policy can have economic consequences. Since economies of countries are linked via trade, the introduction of a CO_2 policy that affects production costs may change trade flows. Such relocation of flows and activities can occur via the fossil fuel markets (Burniaux and Martins, 1999), and via markets for products that are energy and GHG intensive, such as industrial commodities, notably materials. In the case of industrial commodities, changing activity in a region can have serious economic consequences. Therefore, governments are reluctant to burden industry with ambitious emission mitigation targets. This policy problem is known as carbon leakage.

In the following analysis, carbon leakage is defined in mathematical terms as the emission increase outside the policy region divided by the emission reduction inside the policy region. Zero percent carbon leakage means that emissions outside the policy region do not increase. One hundred and fifty percent carbon leakage means that emissions outside the policy region increase 1.5 times more than the emission decreases within the policy region. This situation may occur if policies result in a relocation of industry from energy efficient countries to developing countries with outdated technologies.

In the ETP model, leakage effects are modelled in a bottom-up framework. The model covers the whole energy and materials system, including energy and materials supply and demand. The value added of this approach, compared to econometric models, is that it takes the interaction of technological change and leakage effects into account. Moreover, upstream and downstream effects are considered explicitly, based on physical causal relations[3]. Previous analysis suggests that technological change will reduce leakage significantly (Gielen, 2000). It is difficult to forecast the leakage effects of CO_2 policies based on past experience, because the past is an unreliable measure for future technological change. This is a disadvantage of an econometric modelling approach where trade effects are assessed in terms of Armington elasticities (Armington, 1969). These elasticities are based on historical trade responses to price changes. Due to an inherent measurement problem for these elasticities, different studies use quite different figures (Kuik and Gerlagh, 2003). The changes due to climate policies may be much more substantial over a much longer period than any change over the last 50 years. Moreover, Armington elasticities are usually applied to very generic product baskets such as “energy intensive products”. In fact, different products in this basket may respond very differently to generic policy instruments (Gielen and Yagita 2002, Gielen and Moriguchi 2002). Finally, the trade policy environment may be radically different than in the past, as trade barriers may be reduced or completely removed.

The ETP model focuses on products with high upstream emission intensity per unit of product price, i.e. energy intensive materials. Not only energy carriers, but also materials flows are modelled in physical terms. The assessment of physical materials flows has certain advantages. For example, it allows a much more precise assessment of recycling potentials and materials efficiency potentials. Also, process energy efficiency (or energy productivity) data per tonne of material can be compared across regions with different currency units, contrary to energy efficiency figures per unit of value added. While materials prices and value added per ton differ widely due to local resource availability and trade limitations, a tonne of materials can provide more or less the same service worldwide[4]. A close relation exists between the physical materials production (in tons) and the energy use for production. In ethylene production for example, three quarters of the oil input is feedstock that is incorporated in the chemicals produced.

---

[3] Contrary to linkages based on financial transactions, an approach that is applied in Input/Output analysis.

[4] Given an identical materials quality, which can only be assessed by experts. For example thousands of steel qualities exist. Not all developing countries are able to produce the steel qualities that are needed for ultra-supercritical steam conditions. As a consequence, the electricity generation efficiency of coal fired power plants is about five percentage points lower, compared to new plants in industrialized countries (Viswanathan and Bakker, 2001).

Global bottom-up studies have addressed the leakage issue from a bottom-up perspective for specific materials such as iron and steel, petrochemicals and agriculture and forestry products (Gielen and Yagita 2002, Gielen et al. 2002, Gielen and Moriguchi 2003). Regional models have looked at multiple materials, but they have neglected leakage issues (OECD, 2001). This paper focuses on all key materials producing sectors together within the global energy supply and demand system.

This approach can provide new insights. The regional supply of, for instance, certain renewable energy resources is limited. In a sector or product level analysis it is impossible to come up with a conclusive answer as to whether the use of such a renewable resource for materials production would constitute a reasonable strategy to reduce GHG emissions. For example, the question whether wood waste should be combusted in cement kilns or power plants requires a model that covers both sectors. Moreover, it is not possible to assess the impact of changes in materials production volumes (e.g. because of relocation) on the energy prices in case global energy markets are not included in the model. Therefore, important rebound effects may be neglected. A global regionalised model such as ETP does take such effects into account, but at the expense of regional detail.

In this study it is assumed that long-term supply (domestic vs. imports) is determined by minimum supply costs including transportation costs, and domestic and foreign products are assumed to be homogeneous. These assumptions correspond to a very high Armington elasticity in econometric terms. However, the high elasticity in this study is balanced by trade cost and a significant potential for regional emission mitigation based on technological change. Capital availability constraints are taken into account via region-specific discount rates. It is assumed that technology availability for commodity production will spread gradually. The next section discusses the characteristics of the ETP model in some more detail.

3. *The Energy Technology Perspectives (ETP) model*

3.1 General characteristics

The ETP model is a bottom-up systems engineering model that has been developed by the IEA. It is based on the MARKAL modelling paradigm (Rath-Nagel and Stocks, 1982). In a reference case, the least cost systems configuration is calculated by satisfying a certain demand. In subsequent policy analyses, the producer/consumer surplus is maximised by taking into account the shadow prices and demand elasticities for various demand categories[5]. The model covers the period 2000-2050 in 5-year intervals. The world is divided into 15 regions (see Figure 1).

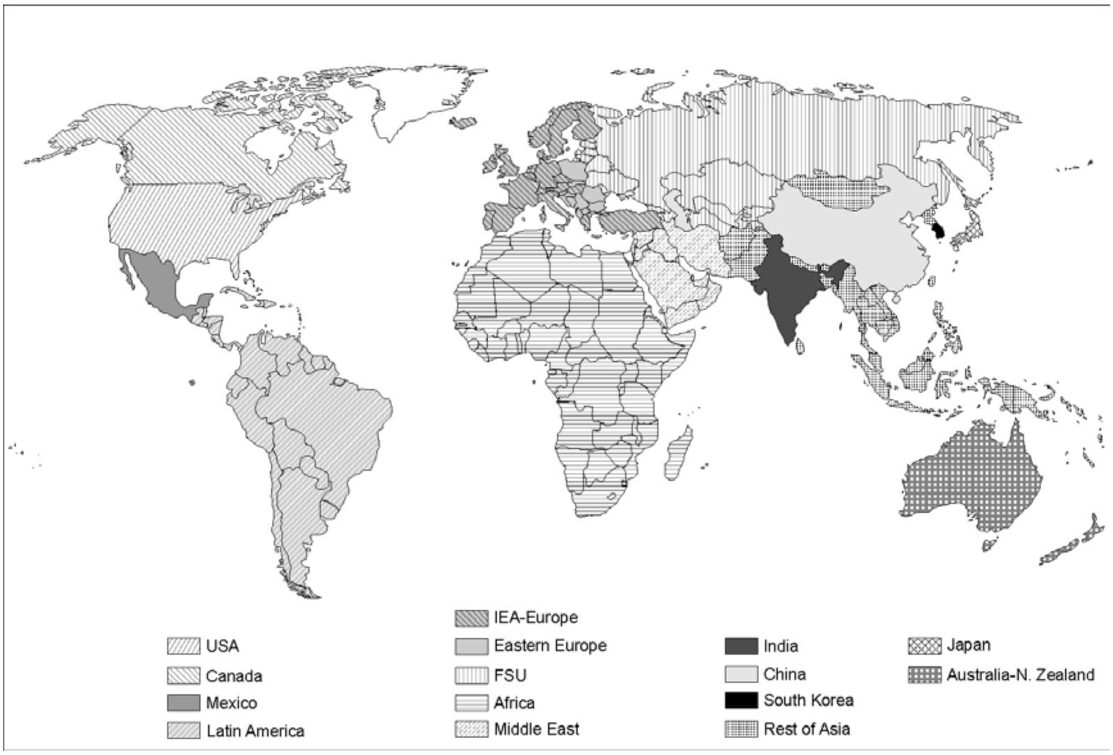

Figure 1: *Regional subdivision in the ETP model.*

The model is fairly large. It consists of a reduced matrix of 241 thousand rows and 343 thousand columns, and contains 1.6 million non-zero elements. However, it is fair to say that the size of a model is not a good indicator of quality. Especially for developing countries, much of the data needs further improvement. This is not a specific shortcoming of the ETP model. It is caused by a general lack of comprehensive and comparable statistical information sources on energy end-use and energy efficiency. Evidently, this is an area for future work.

The supply side is divided into a number of different types of fossil fuel resources. Apart from fossil fuels and nuclear energy, various types of renewables are discerned. For all these resources the potentials and the production costs have been assessed, based on engineering data. The production cost are combined with intra-regional and inter-regional transportation cost to the total sector-specific supply cost. These differ by energy carrier, by sector and by period.

[5] The model runs that are discussed in this study are still based on common MARKAL, without demand elasticities.

In order to capture load curve effects, electricity and heat production and demand are modelled in more detail. In MARKAL, the year is divided into six seasons: winter, summer and intermediate - divided into day and night. For each end-use category, a load curve is defined over these periods based on load patterns for individual demand categories. For each power supply option, a season-specific capacity factor can be defined.

Wherever possible, the demand is defined in useful energy terms. This means that the losses in the production of end-use services/useful energy from final energy are taken into account. This, in turn, increases the energy efficiency potentials, compared to a model that only covers the supply side. For example, an incandescent light bulb has an efficiency of about 10 percent, and a passenger car has an efficiency of about 20 percent. Many studies have shown that huge potentials exist to improve the end-use efficiency. Therefore, the model has been designed to take this potential into account. Also fuel substitution potentials on the end-use level are considered explicitly. Such assessment is only credible on the level of products and processes that are defined explicitly, because the technical feasibility of substitution depends on the characteristics of the application.

The common problem in modelling is the lack of good statistics on end-use. For IEA countries some data on end-use are available, e.g. from the IEA energy indicators study (IEA 2003b). For developing countries data availability is a problem. For the time being this part of the model contains a lot of additional engineering estimates that can be adjusted as new data become available. Another problem on the end-use side is that cost optimisation does not reflect real-world decision making adequately. For example, households choose their lighting based on the colour of the light or the lamp price, not on the basis of lowest life cycle cost. For the time being, such considerations are to some extent included in the model via sector-specific hurdle rates.

Table 1 provides an overview of global energy use in 2000. Total primary energy use amounted to 417 EJ[6]. Of this total, 128 EJ (31 percent) is used in upstream processes (transformation processes, the energy sector, and distribution losses). The remaining 289 EJ (69 percent) is used in end-use sectors. The model covers six end-use sectors: agriculture, residential, services, transport, industry and non-energy use. The relevance of various sectors is indicated in the energy balance in table 1. Industry related transformations, energy sector activities and non-energy use such as coke ovens, blast furnaces, naphtha steam-cracking and aromatics production from the IEA statistics have been allocated to industry, because these processes are closely related to this sector. Industry accounts for 91.46 EJ final energy use (32 percent). Industry related energy use in the other categories amounts to 16.22 EJ. In total, final industry energy use amounts to 107.68 EJ. Part of this is electricity, and part is heat. Part of the electricity and most of the heat purchased is generated in industrial combined heat and power (CHP) plants with a high efficiency[7], but the bulk (more than three quarters) of the electricity is purchased from the grid. Given current efficiencies in electricity production, industry demand represents 120-130 EJ primary energy, about 30 percent of total primary energy use. This brief analysis shows the importance of industry for total global energy use, and its related environmental impacts.

All energy related CO_2 emissions, including process CO_2 emissions in cement production and iron production, are covered in the model. Emissions from land-use change are for the time being omitted. Methane emissions are only considered to the extent they are energy related. Nitrous oxides (N_2O) emissions and PerFluoroCarbon (PFC) emissions are not included in this analysis. Some of these emissions are related to materials production, notably PFCs in primary aluminium production, and

[6] 1 EJ (ExaJoule) = 1000 PJ (PetaJoule) = 10^{18} Joule.

[7] The IEA fuel questionnaires ask only for an aggregate autoproducer CHP for all end-use sectors. This aggregate is reported under the heading "transformation sector" in the IEA energy statistics. The heat output from CHP plants for own use is translated into a fuel equivalent to produce the same amount of heat in a boiler. This fuel equivalent is excluded from CHP in the transformation sector, and included in the industrial final end-use. Therefore, a number of other sources must be used in order to analyse industrial CHP on the sub-sector level.

N_2O in the production of nitrogen fertilizers and nylon plastics. Finally the GHG impact of water emissions from airplanes at high altitudes has been considered. Compared to the CO_2 emissions, the non-CO_2 GHGs are of secondary importance in the industry sector. Moreover, industry has already made good progress in the reduction of these emissions (IAI, 2002).

Table 1: *Aggregate world energy balance, 2000 (IEA 2003).*

	Coal [EJ/yr]	Biomass/ waste [EJ/yr]	Natural gas [EJ/yr]	Oil [EJ/yr]	Nuclear [EJ/yr]	Other renewables [EJ/yr]	Electricity [EJ/yr]	Heat [EJ/yr]	Total [EJ/yr]
Supply									
Total Primary Supply	**98.00**	**45.83**	**87.95**	**145.21**	**28.30**	**11.59**	**-0.01**	**0.02**	**416.90**
Transfers	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.45
Statistical Differences	-0.47	-0.01	-1.06	-0.08	0.00	0.00	0.00	0.00	-1.62
Consumption									
Transformation Sector	**-72.05**	**-5.81**	**-31.59**	**-13.34**	**-28.30**	**-11.34**	**55.35**	**11.79**	**-95.31**
Of which:									
Coke Ovens	-1.64	0.00	0.00	-0.05	0.00	0.00	0.00	0.00	-1.69
Blast Furnaces	-4.75	0.00	0.00	-0.07	0.00	0.00	0.00	0.00	-4.82
Petrochemical Industry	0.00	0.00	0.00	-0.02	0.00	0.00	0.00	0.00	-0.02
Charcoal Production Plants	0.00	-1.63	0.00	0.00	0.00	0.00	0.00	0.00	-1.63
Energy Sector	**-2.12**	**-0.01**	**-8.13**	**-8.76**	**0.00**	**0.00**	**-4.93**	**-0.99**	**-24.94**
Of which:									
Coke Ovens	-0.71	0.00	-0.02	0.00	0.00	0.00	-0.01	-0.01	-0.76
Blast Furnaces	-0.09	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	-0.10
Distribution Losses	**-0.13**	**0.00**	**-0.84**	**-0.21**	**0.00**	**-0.01**	**-4.82**	**-0.60**	**-6.62**
Total Final Consumption	**23.22**	**40.00**	**46.33**	**123.27**	**0.00**	**0.24**	**45.60**	**10.21**	**288.88**
Industry Sector	17.34	5.31	20.46	24.74	0.00	0.03	19.27	4.32	91.46
Iron and Steel	*5.79*	*0.20*	*2.05*	*0.70*	*0.00*	*0.00*	*2.43*	*0.39*	*11.56*
Chemical & Petrochemical	*2.00*	*0.10*	*7.92*	*13.59*	*0.00*	*0.00*	*3.13*	*1.16*	*27.89*
Non-Ferrous Metals	*0.47*	*0.01*	*0.80*	*0.44*	*0.00*	*0.00*	*2.07*	*0.26*	*4.04*
Non-Metallic Minerals	*3.69*	*0.13*	*1.60*	*1.52*	*0.00*	*0.00*	*1.07*	*0.12*	*8.12*
Machinery	*0.38*	*0.00*	*0.95*	*0.56*	*0.00*	*0.00*	*1.68*	*0.45*	*4.01*
Food and Tobacco	*0.65*	*0.80*	*1.25*	*0.88*	*0.00*	*0.00*	*1.15*	*0.34*	*5.07*
Paper, Pulp and Print	*0.54*	*1.10*	*1.15*	*0.64*	*0.00*	*0.00*	*1.64*	*0.12*	*5.18*
Others (Industry)	*3.84*	*2.97*	*4.73*	*6.41*	*0*	*0.02*	*6.11*	*1.51*	*25.58*
Transport Sector	0.25	0.36	2.25	71.07	0.00	0.00	0.81	0.00	74.73
Other End-use Sectors	5.23	34.33	23.63	20.16	0.00	0.21	25.52	5.89	114.97
Non-Energy Use	0.38	0.00	0.00	6.82	0.00	0.00	0.00	0.00	7.72
in: Ind/Transf/Energy [8]	0.38	0.00	0.00	6.82	0.00	0.00	0.00	0.00	7.19

3.2 Modelling of Industry and Materials

Within the industrial end-use sector, the following sub-sectors have been considered:

- Iron and steel;
- Non-ferrous metals;
- Non-metallic minerals;
- Machinery;
- Food and tobacco;
- Paper, pulp and print;

[8] Non-energy use refers to the production of asphalt, lubricants, refinery aromatics and propylene, and some refinery products such as white spirit and waxes.

- Textile and leather;
- Other industries.

However, more detail is needed to identify technological energy policy options such as fuel substitution and energy efficiency improvements. Therefore, a detailed hybrid approach has been developed. Part of the sub-sector final energy demand is allocated to specific materials producing processes. This is done on the basis of statistical information regarding materials production, and engineering data regarding the energy consumption per ton of material. These materials production processes are modelled explicitly. The remaining final energy demand is allocated to energy services: process heat, feedstock, electrolysis, steam, machine drives, and others. This subdivision is based on knowledge about activities in specific sub-sectors, end-use analysis data for specific fuels, and additional engineering estimates. The boundary between process heat and steam has been set at a temperature level of 200 ºC. It is possible to use steam at higher temperatures, but this requires a careful site-by-site analysis. This approach results in an underestimation of CHP potentials, especially in the chemical industry.

Most process heat, feedstock and electrolysis energy and a significant share of the power from motors is required for materials production. Therefore, most of the remaining final energy demand ends up in the categories of steam and others. The quantity of residual process energy and electrolysis energy could be decreased by explicit modelling of additional materials such as copper, fertilizers and methanol. Since some energy use is not clearly linked to a specific commodity, there will always be a need for a residual energy service approach.

Final energy demand is converted into a demand for energy services, based on efficiency assumptions. The energy services are defined in terms of useful energy from the energy conversion equipment. For example, in the case of electric motors, the energy efficiency figure refers to the useful energy from the motor. In case most of the useful energy from the motor is lost in an oversized pump, such losses are not taken into account in the definition of useful energy. This results in, especially for electricity, a low estimate of energy efficiency potentials.

The modelled materials have been selected on the basis of physical production data, and energy intensities per unit of product (Table 2). The physical production data were taken from United Nations statistics (UN 2003) and from industrial production statistics (IISI 2002, IAI 2002). Energy intensity data were obtained from analyses for industrialised countries or global averages. The energy intensity is expressed as Gross Energy Requirement (GER) - the primary energy needed for all processes to generate a tonne of materials. The energy efficiency figures may be 50 percent higher or lower in case of high or low energy intensities in a country[9]. The analysis has concentrated on the main energy consuming regions (Japan, USA, and Western Europe). These data have been supplemented with country-specific data for major developing countries such as China and India. For regions where no detailed data were available, key industry structure data such as recycling rates have been combined with process energy efficiency data for other regions of a similar development level.

The database contains current materials production processes and alternative production processes based on new technologies or other fuels that could become attractive from an energy policy perspective. The data for these processes are taken from technology assessment studies.

[9] Note that studies have shown that some high energy-intensities in developing countries can be explained by system boundary differences. For example, some countries include residential energy use by the factory employees in industrial energy demand. On the other hand, some of the energy efficiency analyses neglect a different product slate, such as cast iron in the iron and steel industry, which is important in some developing countries. Also statistical double counting can explain some of the seemingly high energy intensities. Of course outdated production processes and scale effects are a cause of lower energy efficiency in developing countries. However, a closer look at the process level often reveals that differences between new installations in developing countries and developed countries are in fact limited.

Engineering studies suggest that different regional materials energy intensities can be explained by a number of specific factors. The most important ones are:

- different resource use (e.g. primary materials production vs. recycling);
- different fuel and feedstock use (e.g. ethylene production from ethane and from naphtha steam-cracking);
- use of older production processes in some regions (e.g. the wet production process for Portland cement production, the open hearth furnace for steel production);
- process scale differences (e.g. small-scale blast furnaces and coking plants in China and India).

Such regional differences have been analysed and taken into account explicitly. The sources for region-specific data are listed in tables 2 and 3.

Table 2: The relevance of industrial materials production for the world energy system.

	Prod/cons [Mt/yr]	Prim/rec [percent]	GER prim	GER rec	Prim energy demand [EJ/yr]	Region-specific data sources
Steel	1000	65/35	20-30	5-15	20.0	(Worrell et al. 1999, Gielen and Moriguchi 2003)
Aluminium	23.4	90/10	150-200	5-15	4.5	(USGS 1998, IAI 2002)
Ethylene	100	100/0	60	-	6.0	(Matthews 2001, Park 2002)
Propylene	50	100/0	60	-	3.0	
Benzene	30	100/0	50	-	1.5	
Toluene	15	100/0	50	-	0.8	
Xylenes	25	100/0	50	-	1.3	
Ammonia	100	100/0	30	-	3.0	(Beer 1998)
Chlorine (with NaOH co-production)	35	100/0	30	-	1.1	(Gielen 1997)
Paper (from pulp)	320	-	8	-	2.6	(Hekkert and Worrell, 1998)
Chemical pulp	119	-	15	-	1.7	(Hekkert and Worrell, 1998)
Mechanical pulp	36	-	10	-	0.4	(Hekkert and Worrell, 1998)
Cement	1643	100/-	3-5	-	6.0	(Gielen 1997, Martin et al. 1999, JCA 2001)
Total					51.9	

Thirteen categories of materials have been considered explicitly in the ETP model (table 2). Together they account for almost half of global industrial energy use, expressed in primary energy equivalents. Benzene, Toluene and Xylenes have been aggregated into one category BTX. For some of these materials, a chain of processes has been modelled. For example in case of steel production coke ovens, sintering plants, blast furnaces, basic oxygen furnaces, casting, hot rolling and cold rolling have been modelled separately. This detailed process approach is important because the improvement options must be assessed on the process level, since an accurate assessment on the aggregate sector or materials level is not possible. The chain approach ensures that interactions are taken into account. For example, a more efficient rolling process may increase the steel yield, which reduces the need for iron production and for coke production.

3.3 New Technologies

A number of GHG emission mitigation options have been considered:

- Energy efficiency options, based on emerging technologies;
- Fuel substitution;

- Increased use of CHP plants;
- Increased recycling of waste materials;
- CO2 capture and sequestration.

The model considers only improvements in production processes. Increased efficiency of materials use and materials substitution have not been considered in this study. Earlier analyses suggest that the potential of these options could be substantial, in the order of 30 percent of industrial energy consumption for materials production (OECD, 2001). This reduces energy efficiency potential estimates. Table 3 describes the options by sector. The potentials for emission reduction are expressed in comparison to current production levels, current reference technologies, and current recycling rates. The figures are indicative, and do not account for the cost-effectiveness of various measures. It should be noted that figures cannot be added because of interactions that will reduce potentials. This is another important reason to use a model based on a life cycle approach.

Table 3: Energy saving and CO_2 emission mitigation options in the model, and their potential for emission reduction, based on current production levels and current production technology. Figures cannot be added up.

		Global potential [Mt CO2/yr]	Global primary energy saving potential [PJ]	Source
Iron & steel	Substitute Open-Hearth Furnace by Basic Oxygen Furnace	<5		(Gielen & Moriguchi, 2003)
	Increased recovery of steel scrap	200-350		(Jiang et al. 1998)
	Direct reduced iron (gas based)			(Worrell et al. 1999)
	Increased coal injection in blast furnaces	350		(Chiang et al. 1998)
	Charcoal injection blast furnaces	225		(Chatterjee 1998)
	Increased energy recovery from blast furnace gas	10		
	Substitution of beehive coke ovens and wet quenching coke ovens with dry quenching	65		
	Replace mini blast furnaces	50-100		
	CO2 capture and sequestration	750		
Aluminium	Substitution of Söderberg cells with Hall-Héroult cells		100 PJ	(Zhang et al. 1994)
	Substitution of Hal-Héroult cells with bipolar anode cells		100 PJ	(Schwarz et al. 2001)
	Increased aluminium recycling		1000 PJ	
Ethylene	Increased plastic waste recycling		1-2 EJ naphtha	(Gielen and Yagita 2002)
propylene	Biomass feedstocks		1-2 EJ naphtha	(Gielen et al. 2002)
	Energy efficient crackers		0.5 EJ residual gas	
BTX	Biomass feedstocks		1 EJ naphtha	(Gielen et al. 2002)
Ammonia	CO2 capture and sequestration, feedstock substitution	150		(Worrell 1994, Beer 1998, Gerlagh and Dril 2000)
Chlorine	Mercury/diaphragm/membrane cells		100 PJ	(Gielen 1997, World Chlrorine Council 2002)
Pulp&paper	Increased waste paper recycling			(Hekkert and Worrell, 1998)
	Black liquor gasification		1.500	(Beer 1998, p. 96) (Martin et
	Condensing belt drying		500	al. 2000)
	Impulse drying		600	(Nordqvist et al. 2001)
	Cogeneration		600	(Schumacher and Sathaye,
	Chemical pulping, continuous digesters		300	1999)
	Integrated paper&pulp mills		500	
Cement	Switch from wet process to dry process		500	(Gielen 1997, Martin et al.
	Waste wood incineration	100-200		1999,Nordqvist and Nilsson
	Multi-step pre-drying kilns		500-1500	2001)
	Blast furnace slag/Fly-ash cement	100-200		
	CO2 capture and sequestration	500-750		
Other process heat	Fuel substitution		-	
Other steam	Fuel substitution			Fang (1999), IEA Clean Coal
	Cogeneration		10,000	Centre (2002)
	Coal washing		5,000	Lemar (2001)

3.4 Trade

For all the materials a global commodity market has been modelled. Trade flows in 2000 have been calibrated with trade statistics, whereas, for later years they are determined by cost considerations only. This is a simplification of the real-world situation, for example, where non-tariff barriers exist.

Due to the regions geography and economic reasons, the bulk of the interregional materials trade is based on seaborne shipping. Total world seaborne trade amounted to 5.1 billion tons in 1999 (Table 4). Oil tankers (crude oil and oil products) represent 42 percent of all world trade in 1999. The remainder (41 percent) is dry bulk. With regard to materials, iron ore, bauxite/alumina, phosphate rock and (part of) oil products must also be accounted for. Together, they account for about 15 percent of global seaborne shipping. Global materials flows have been increasing rapidly over the last decades (Moriguchi, 1999). There is no reason to assume that this trend will abate.

Table 4: World seaborne trade of main bulk commodities, 1999 *(Fearnleys, 1999)*

	Tonnage [Mt]	Tonne-km [10^9 t.km]	Fraction [percent]	CO_2 [Mt/yr]
Iron ore	410	2220	10.3	44
Coal	480	2430	11.3	49
Grain	210	1170	5.4	23
Bauxite/alumina	53	295	1.4	6
Phosphate rock	31	135	0.6	3
Crude oil	1480	7500	34.9	150
Oil products	410	2010	9.4	40
Others (mainly containers)	2140	6150	28.6	123
Total	5100	21480	100.0	430

The ocean shipping market can be split into two categories: tramp shipping and liner shipping. The tramp shipping market is close to perfect competition. The liner shipping market has different characteristics, where maritime conferences have been exerting some mild oligopoly power, adding an estimated 6.7 percent to transport costs in 1998 (Micco and Perez, 2001).

Trade cost can be split into transportation cost and other cost such as transaction cost, taxes and levies and insurance. Transportation costs depend on several factors such as ship specification, trade and route and general market conditions. There is a large share of fixed cost, e.g. for loading and harbour cost. A 10 percent increase in distance generates roughly a 2 percent increase of transportation cost (Micco and Perez, 2001). The value per weight unit is also important (a doubling of value per unit of weight increases transport costs by 55 percent). The more expensive the product, the higher is the insurance and hence the overall transport cost. Doubling the volume of trade between particular ports reduces transport costs by 3-4 percent (Micco and Perez, 2001).

Freight rates for containers are still four to eight times higher than for bulk commodities, and transportation of chemicals is more expensive than dry bulk. However, containers allow shipment of smaller volumes and may reduce transfer costs and inland shipping costs. Transportation costs on land to and from the harbours can be very important. An extra 1,000 km by sea raises costs by only 10 $/t, while the same distance by land raises costs by 70 $ per ton. Being landlocked increases a countries transport costs on average by 110 $ per ton, equivalent to increasing the distance by sea by about

10,000 km (Limao and Venables, 1999). The issue has not been considered in this study, but this brief discussion provides some insights regarding key uncertainties and areas for future analysis. As a consequence, the study may overestimate trade in case production is located inland (which is an important issue, for example, for forestry products, such as paper and pulp). Trade cost data are based on international public spot prices for transportation, augmented for harbour costs, levies and other transaction cost.

Non-tariff measures (NTMs) are also called barriers or distortions. There is a large variety of non-tariff measures. They may broadly be classified into five categories:

- Measures to control the volume of imports;
- Measures to control the price of imported goods;
- Monitoring measures including price and volume investigations and surveillance;
- Production and export measures;
- Technical barriers.

Price or volume control measures have been used extensively in the past for industrial development reasons by developed and developing countries. The Global Agreement on Trade and Tariffs (GATT) does not ban the use of all NTMs. As a consequence, such measures may become dominant elements of trade policies in future years. However, such a development would be contrary to the spirit of the ongoing trade liberalization and the efforts of the World Trade Organization (WTO). The assumption of reduced NTMs results in a high estimate of trade and trade effects of climate change.

In the model all commodities are traded in a global market, and costs are shared between importers and exporters. Trade costs range from 25US$ per ton between neighbouring regions for bulk commodities such as cement, scrap and direct reduced iron (DRI), up to 200 US$ per ton for aluminium ingots for long-range transport. These values are based on recent market prices. For the time being the trade costs are not differentiated between the regions. Obviously, this is a crude estimate. However, as the trade costs depend only to a limited extent on the actual distance, this simplification is not a major distortion of the real-world situation. It is assumed that trade costs are halved in real monetary units over the next 20 years due to reduced NTMs, new harbour facilities and economies of scale.

Trade is also a source of GHG emissions. According to IEA energy statistics, bunker fuel use (for ocean-going vessels) amounted to 133 Mtoe in 2000. This equals an emission of 430 Mt CO_2, about 2 percent of global CO_2 emissions. However, the impact of increased trade on CO_2 emissions has been neglected in this analysis.

3.5 Model calibration and validation

Regional production growth is a function of regional materials demand and trade. Materials demand has been forecast as a function of population, per capita GDP and an income elasticity. For low-income countries, materials demand is closely linked to GDP. However as GDP increases, demand is increasingly decoupled from economic growth (see e.g. Jänicke et al., 1992). This decoupling has been taken into account in the materials demand projections. The global materials production projection in the reference case is shown in figure 2. The growth between 2000 until 2050 ranges from 30 percent to 120 percent, and suggests a continuation of the trends in the past decade. The growth rate is lower than in the 1990-2000 periods, especially for chemicals, due to a saturation of demand. This is a working assumption that needs further analysis. For the time being, no demand elasticities have been taken into account. This results in an underestimation of the impact of pricing policies.

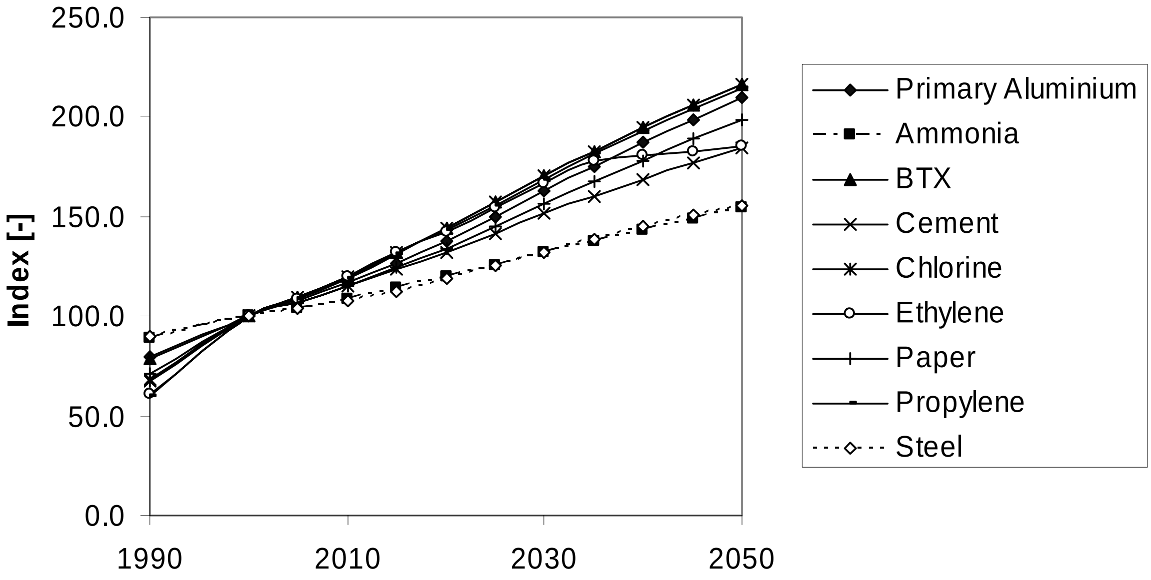

Figure 2: *Global materials demand projections index (2000=100)*

First, the model was run only with industrial materials demand. This way the final energy demand for materials production is calculated for the base year 2000. Next, the total final energy demand was analysed for the base year 2000, split into end-use categories and calibrated with the IEA statistics. For this purpose, a set of spreadsheets has been developed, called the ETP Model Builder (EMB). These spreadsheets allow for ready updating of the model base year data when new data become available; new materials are added; or if greater regional detail is aimed for. The advantage of the spreadsheet approach is that it allows for easy and consistent calculation of residual capacities and average efficiencies for the base year, something which would be very laborious without the spreadsheets.

Transformation sector processes such as CHP, coke ovens, blast furnaces and chemical processes that are in fact industrial activities have been allocated to industrial energy use. Final energy use for materials production is subtracted from the final energy demand. The remaining final energy use has been allocated to energy services that have been discussed above, see also table 5. The bulk of the remaining energy use is allocated to steam production and most residual electricity is allocated to motors. For each energy carrier, an end-use process has been modelled for the base year, characterised by an efficiency of existing equipment and new equipment, cost, life span and capacity factor. The investment needs and the average efficiency of this equipment over time is calculated by the model. The total useful energy demand in this category amounts to 64.6 EJ. One third of this end use is in the chemicals sector, and one third in the category ‘other’ (which includes other sectors that are not analysed in more detail and industrial energy use that is not allocated in the statistics). From an end-use category perspective, steam represents almost a quarter of the residual end-use.

Table 5: Residual world industrial useful energy demand, 2000 [EJ useful/yr]

	Process heat	Feedstock	Electrolysis	Steam	Motors	Other	Total
Iron & Steel	1.41	0.00	0.00	2.72	0.43	0.21	4.78
Non-ferrous	0.61	0.00	0.27	0.49	0.28	0.12	1.76
Chemicals	5.60	7.56	0.51	5.35	1.83	1.02	21.87
Paper & Pulp	0.00	0.00	0.00	1.06	0.03	0.82	1.91
Non-metal minerals	1.71	0.00	0.00	0.00	0.37	0.38	2.47
Food, Beverage & Tobacco	0.00	0.00	0.00	2.94	0.78	0.57	4.29
Textile & Leather	0.00	0.00	0.00	1.28	0.56	0.05	1.90
Machinery	0.33	0.00	0.00	1.75	1.01	0.08	3.16
Other	0.00	0.00	0.00	0.00	0.00	22.49	22.49
Total	9.67	7.56	0.78	15.58	5.31	25.73	64.62

The IEA World Energy Outlook (WEO) is based on explicit sector demand projections of final energy over the period 2000-2030 for OECD countries (WEO 2002). The ETP model, on the other hand, covers the period 2000-2050, and ETP industry data include part of the transformation and energy sectors. Therefore, matching the WEO figures for future years is not straightforward. As a working assumption the residual demand is set proportional to the WEO GDP growth (WEO 2002).

3.5 Policy simulation

Five policy cases have been analysed:

- Reference scenario, no CO_2 policy (REF);
- CO_2 tax global 25$/t CO_2 (GLO25);
- CO_2 tax IEA Member countries 25$/t CO_2 (IEA25);
- CO_2 tax global 50$/t CO_2 (GLO50);
- CO_2 tax IEA Member countries 50$/t CO_2 (IEA50).

International trade agreements limit the room for government action to prevent leakage (Charnovitz, 2003). However, at this moment it is not yet clear if import taxes would violate WTO rules. The EU has recently agreed to an EU-wide CO_2 emission permit trading scheme involving several industrial sectors, but the actual implementation is left to the member state governments (the so-called subsidiary principle). Currently, it is also not yet clear which action governments aim for in order to prevent leakage. The emission permit trade analysis will be a next step in the model development.

4. Modelling results

The model results suggest that global GHG emissions can be reduced significantly. In the GLO50 scenario, emissions are reduced by 25 Gt in 2030 and by 35 Gt in 2050, compared to the reference scenario. This represents an emission reduction of 60 percent, and it stabilises global emissions around 2000 levels. This would mean that there is a significant potential for emission mitigation at cost levels well below what previous studies have concluded. However, this effect depends critically on global co-operation. In the IEA50 scenario, the emission reduction amounts to 8 Gt in 2030 and 10 Gt in 2050. This scenario would imply an ongoing increase of global emissions by more than 30 percent compared to 2000 levels, despite the significant efforts in IEA Member countries.

The leakage is shown in figure 3 on the aggregate economy level. The leakage effects tend to increase in time, to a level of 3-5 percent in the IEA25 scenario and 7-11 percent in the IEA50 scenario. These effects are relatively modest.

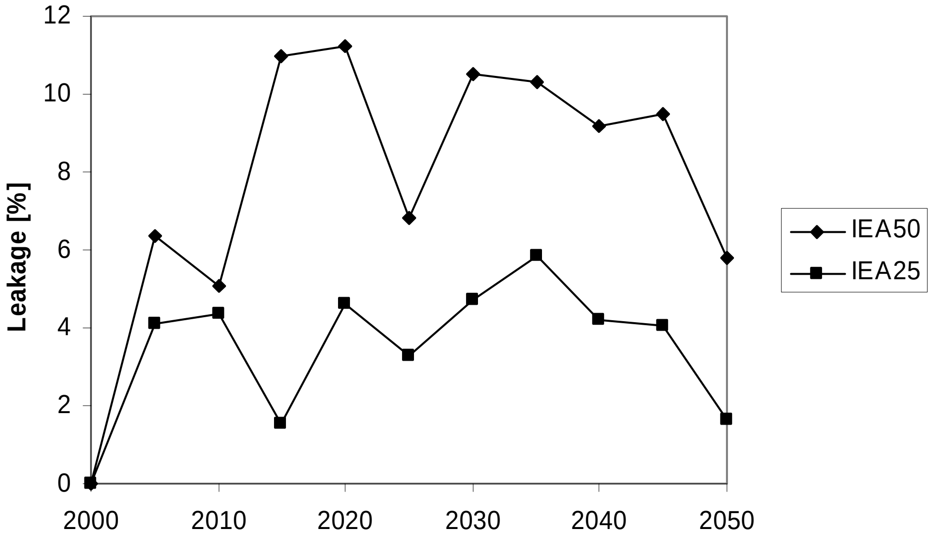

Figure 3: *Leakage in scenarios where only IEA Member countries take action*

A closer look at industrial emissions is provided in figure 4. Base year (2000) emissions amount to 8.7 Gt CO_2. This includes the industrial transformation sector emissions, the emissions from industrial CHP and CO_2 from inorganic sources (cement production and iron production). In the reference scenario, these emissions increase by 78 percent over the period 2000- 2030, and by 80 percent over the period 2030-2050. This increase is completely accounted for by the growth of emissions in non-IEA Member countries.

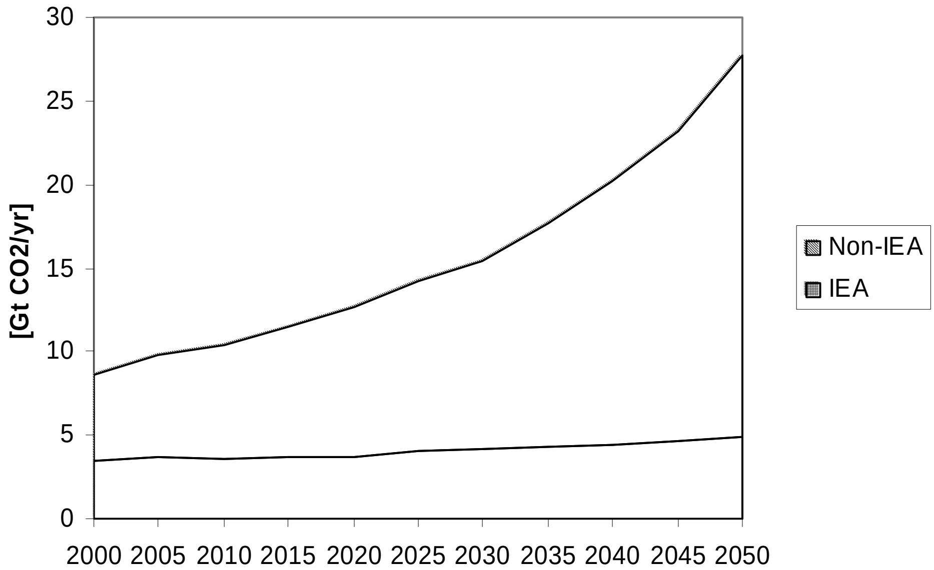

Figure 4: *Industrial CO_2 emissions in the reference scenario. (Includes industrial transformation sector processes, industrial CHP and inorganic CO_2 emissions. Excludes carbon storage and upstream emissions in electricity and fossil fuels production).*

Figure 5 shows the industrial emissions in 2030 for various scenarios. In the GLOB50 scenario, the emissions are stabilised at the 2000 levels. However, if only the IEA Member countries introduce a policy, total global emissions keep rising by 65 to 68 percent, even though emissions in IEA Member countries are reduced by 21 to 39 percent, compared to 2000 levels.

Within industry, recycling rates are up in case a GHG policy is introduced. Energy efficient production processes are introduced for paper, chlorine and other materials. The use of raw coal for industrial boilers in developing countries is abandoned, which results in an efficiency increase of 10-20 percent. The reason why energy efficiencies do not increase substantially compared to the reference scenario, is that all cost-effective energy efficiency measures are already included in the reference scenario. CO_2 capture and sequestration is introduced in ammonia, cement and iron production.

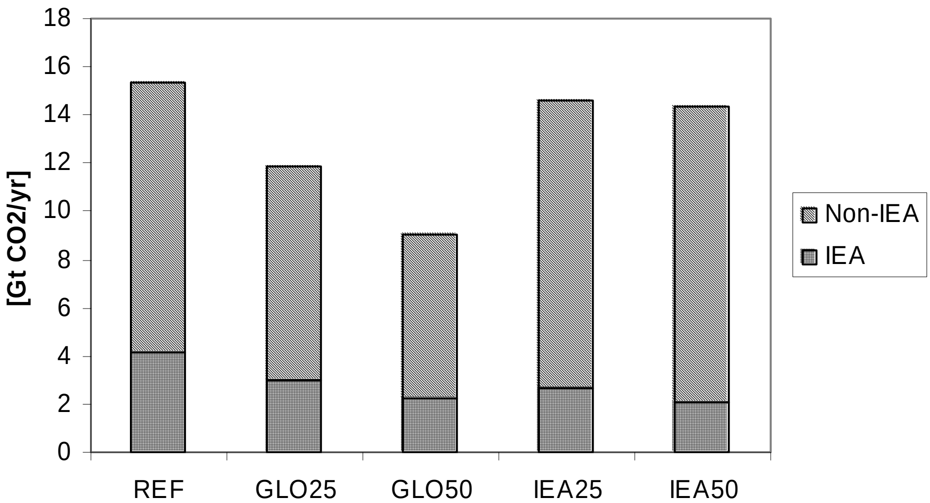

Figure 5: *Industrial CO_2 emissions in various policy scenarios, 2030. (Includes industrial transformation sector processes, industrial CHP and inorganic CO_2 emissions. Excludes carbon storage and upstream emissions in electricity and fossil fuels production.)*

The leakage for industry is shown in figure 6. It increases gradually until 2035, and declines somewhat in later periods. At its peak, it amounts to 30 percent in the IEA25 scenario and 45 percent in the IEA50 scenario. The industrial leakage effect is much more substantial than the leakage for the economy as a whole (figure 3). It suggests that industry is especially vulnerable to leakage, and that the commodity trade effects are more important than the fossil fuel trade effects. Note that leakage rates are already comparatively high in the IEA25 scenario, which represents a relatively modest policy effort.

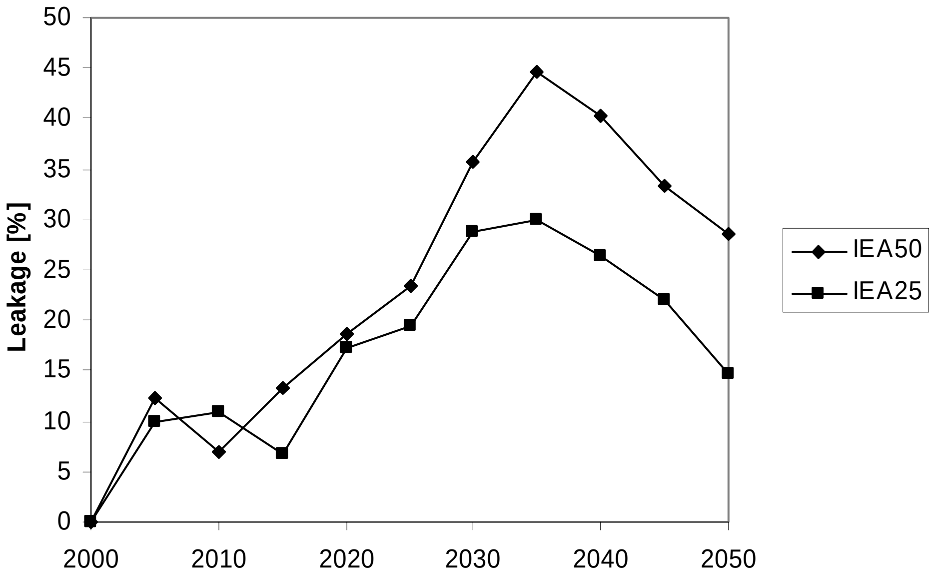

Figure 6: *Industrial leakage effects*

Figure 7 shows the share of industrial leakage in total leakage. It is measured as the share of industrial emissions increase in total emissions increase, compared to the reference scenario, in non-IEA countries. This share increases gradually in time. In 2030, industrial leakage represents 100 percent of total leakage in the IEA25 scenario, and 50 percent of total leakage in the IEA50 scenario. In later years in the IEA25 scenario, the share exceeds even 100 percent. This means that the fuel channel for other sectors *reduces* the leakage in the industry sector. Especially in later periods, industrial leakage represents the bulk of total leakage. This result brings about important policy consequences. It suggests that in a situation with limited policy efforts, a leakage discussion should focus on in the industrial sector. The fuel leakage channel for other sectors is of secondary importance, unless one moves to higher tax levels, which are unlikely in a policy environment without global GHG emission reduction commitments.

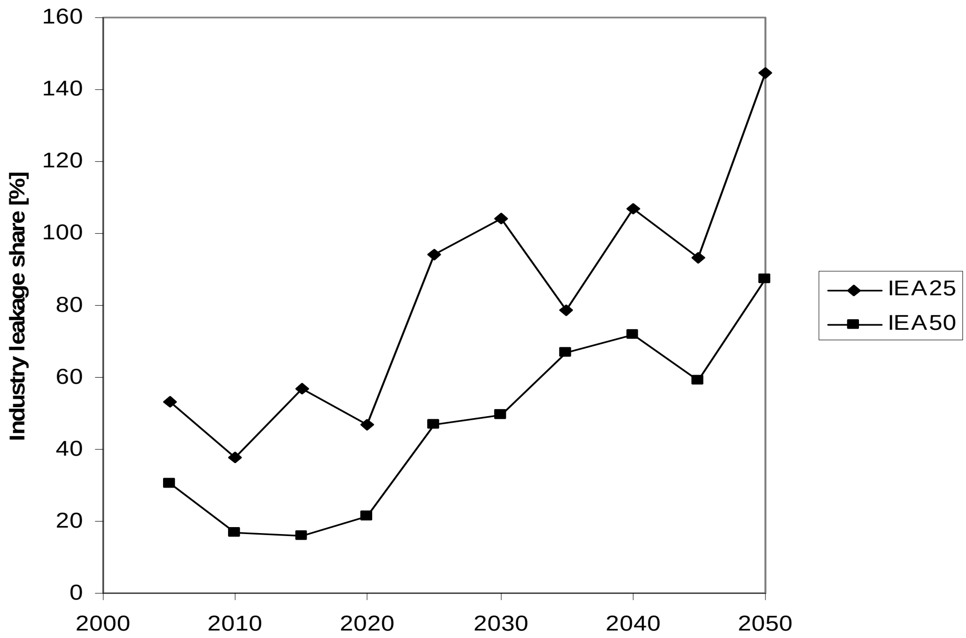

Figure 7: *Industrial leakage as a share of total leakage*

The next step is to split the industrial leakage into a fuel channel and a materials trade channel. The materials trade flows are elaborated in table 5. The results suggest significant changes for certain materials. Even in the GLO50 scenario with global policies, location choice is affected. This result is of policy relevance: industrial CO_2 policies will affect the location choice, even in a global policy regime. From an IEA Member perspective the effects, however, are mostly beneficial: industry activity increases for cement and chemical pulp, and more waste paper and steel scrap is collected. Production of energy intensive commodities such as ammonia, propylene, mechanical pulp and aluminium declines. The relocation effect is much stronger in the IEA50 scenario. Based on the flow data in table 6 and CO_2 intensities of materials, the leakage through changing trade flows amounts approximately to 300-500 Mt CO_2. This equals 60-80 percent of the total leakage.

The result for steel is in stark contrast with previous analysis that suggested significant leakage effects (Gielen and Moriguchi, 2003). That study concluded 40 Mt relocation of primary steel production from Japan and Europe in 2030, in case these two regions would introduce a tax of 80 $/t CO_2. To some extent the different result can be explained by different policy regimes analysed.

Table 6: Decrease of world materials production in IEA Member countries compared to reference scenario in case of global and/or IEA policy, 2030. Negative figures indicate an increase.

	GLO50		IEA50	
	Share [percent]	Level [Mt/yr]	Share [percent]	Level [Mt/yr]
Aluminium	3.4	1.4	40.9	16.0
Ammonia	20.6	38.7	8.9	13.1
Aluminium scrap	0.0	0.0	0.0	0.0
BTX	0.0	0.0	0.1	0.0
Cement	-6.5	-156.3	6.4	164.0
Chlorine	0.0	0.0	0.0	0.0
DRI	-3.3	-4.3	5.5	9.8
Ethylene[10]	2.8	3.8	9.7	12.9
Paper	-0.2	-0.9	4.8	25.5
Chemical pulp	-10.4	-34.2	-18.5	-48.0
Mechanical pulp	5.0	2.7	5.1	2.7
Ppu	-0.2	-0.8	4.8	24.3
Propylene	6.0	4.8	11.3	8.6
Waste paper	-99.8	-46.6	0.9	3.1
Steel scrap	-2.2	-15.0	-0.1	-0.4
Steel	0.0	-0.4	1.0	11.1

In order to better explain these results the materials shadow prices for Western Europe are analysed in table 7. The results indicate an impact ranging from a slight price reduction (for waste paper) to more than 200 $ per tonne price increase for aluminium. As expected, the most important price effects are for aluminium - the material with the highest GHG intensity per tonne. Note also the price effects for aluminium scrap and steel scrap. As the price of primary materials increases, there is more incentive to recycle, resulting in higher scrap prices. This poses an incentive for increased scrap recovery.

Table 7: Materials shadow price, Western Europe, 2030

	BASE [$/t]	GLO25 [$/t]	GLO50 [$/t]	IEA25 [$/t]	IEA50 [$/t]
Aluminium	1487	1621	1668	1578	1607
Ammonia	129	149	144	149	33
Aluminium scrap	1264	1332	1428	1347	1376
BTX	365	382	390	356	367
Cement	67	87	90	67	67
Chlorine	384	395	395	389	383
DRI	89	107	129	80	80
Ethylene	606	655	737	615	618
Paper	461	468	478	464	456
Chemical pulp	253	262	263	249	250
Mechanical pulp	253	253	253	263	250
Propylene	345	355	333	341	330
Waste paper	15	15	15	15	15
Steel scrap	83	114	138	89	87
Crude steel	159	193	218	165	162

In conclusion, leakage seems a serious issue for industry, and governments should be cautious in the design of GHG policies for this sector. Technological change is a key factor for limiting carbon

[10] It is problematic to ship gaseous components such as ethylene and propylene. However it is straightforward to ship plastics such as polyethylene and polypropylene. The trade flows refer to such plastics.

leakage. The analysis suggests that the most effective emission mitigation can be achieved via measures such as CO_2 capture and sequestration, a technology that needs further development. Policies should encompass as many countries as possible, because this tends to reduce leakage effects. However, even a global policy would affect industry location choice, a result that should be considered in the international GHG policy negotiations. The results also suggest that a significant reduction in trade cost (e.g. because of successful trade negotiations) can result in an increased carbon leakage. Therefore, it is recommended to co-ordinate trade policies and climate policies.

Model analysis with trade cost stabilised at the 2000 level showed no significant trade flows. This suggests that the results are sensitive with regard to the trade cost assumptions. This result can also be interpreted as a policy opportunity to mitigate any leakage effects, based on a restricted liberalisation of trade regimes.

5. Discussion

The ETP model results suggest that it is possible to achieve a global stabilisation of emissions. In the long run, it is even possible to reduce emissions. However, this outcome depends critically on international co-operation, and new technology development and deployment.

In the reference case, industrial CO_2 emissions double by 2030, and triple by 2050. In case of a global policy regime it is possible to stabilise emissions at 2000 levels. This stabilisation is largely based on the introduction of new technologies. Even in the case of global policies, some industry relocation would occur. According to the model, this relocation would be beneficial for the IEA Member countries. However, the results are less encouraging if only IEA Member countries introduce a policy. First, because these countries represent only 27 percent of total global industrial emissions by 2030. Second, leakage poses a major problem. The results also suggest 3-10 percent leakage for the energy system as a whole, in case IEA countries introduce policies for GHG emission reduction while other countries do not introduce similar policies. Therefore, for the economy as a whole, leakage seems an issue of secondary importance. However, the bulk of this leakage can be attributed to the industry sector, where leakage is significant. Between 20 and 45 percent of the emission reduction in IEA Member countries would be balanced by emission increases in non-IEA countries. 60-80 percent of this leakage can be attributed to changes in materials trade. This shows that technological change alone is insufficient to limit leakage effects. Leakage results depends on trade cost assumptions and assumptions regarding technological change and trade regimes. The results mentioned refer to a liberalized global market which is only limited by transportation cost.

Leakage effects differ significantly by material. Therefore, an analysis that aggregates all materials will not generate useful insights. That is why detailed assessment is required which would take materials specific potentials for technological change into account.

Governments should consider that industry could be affected significantly in any policy regime, whether global or restricted to certain regions. A combination of trade liberalization and tightened CO_2 policies could increase the problem. However, even moderate import levies could alleviate the problem. The feasibility of such an approach should be considered in more detail.

The industry module of the ETP model is a first step to a global integrated energy and materials systems model that can help to understand the interaction of climate policies and industrial production activities. This analysis shows that the production of the 13 materials that are considered in the model represent about half of global industrial energy demand. In the future, this approach can be expanded by adding more materials. A number of petrochemical products, inorganic materials such as bricks and glass, wood products such as sawn wood and panels, and copper are prime candidates, given the global production energy use. Furthermore, agriculture and food products constitute an important category as well because of the land use link with afforestation and bioenergy production, and the non-CO_2 GHG emissions. Analysis of materials use in products and subsequent waste handling will improve the assessment of materials efficiency use.

The conclusions in this paper are based on a model that, like any other model, is a stylised representation of reality. Therefore, the absolute figures should be treated with care, and more uncertainty analyses should be done to assess the sensitivities of the results for input data and model structure. Trade cost and new emission mitigation technologies are prime candidates for such sensitivity analysis.

6. Modelling recommendations

Throughout the paper a number of areas for future long-term research have been identified:

- The potentials for increased materials efficiency and dematerialisation;
- The link between GDP growth and demand for energy and materials services;
- The interaction of carbon leakage and trade liberalization;
- The interaction of permit trade regimes and technological change;
- The interaction of biomaterials, bioenergy, food production and trade liberalization;
- Improved forecasting of technological change;
- Improved representation of consumer decision making processes in bottom-up models;
- Future technology availability barriers across world regions;
- Deployment barriers for new technologies, including public acceptance issues for technological solutions such as nuclear energy, certain types of renewable energy and CO_2 capture;
- The interaction of environmental problems such as climate change, waste and land use biodiversity.

During the next months at the IEA attention will be focused on improvement of the end-use side in the ETP model. This includes data collection on disaggregated end-use sectors, especially on developing countries, demand responses to price change and model validation based on comparison with results from other analyses.

7. References

Armington, P.S. (1969) A theory for demand of products distinguished by place of production. IMF staff papers vol. 16, no. 1, pp. 159-176.

Beer, J. de (1998) Potential for industrial energy-efficiency improvement in the long term. PhD thesis, Utrecht University, the Netherlands.

Burniaux, J.-M., Oliveira Martins, J. (1999) Carbon emission leakage: A general equilibrium view. ECO/WKP(2000)15. Economics Department Working Papers no. 242. OECD, Paris.

Charnovitz, S. (2003) Trade and climate: potential conflicts and synergies. PEW center on Global Climate Change.

Chatterjee (1998) Steel industry in South East Asia with particular reference to India. Proceedings 2nd international congress on the science and technology of ironmaking and 57th ironmaking conference proceedings. Iron& Steel Society, Warrendale (PA) USA, pp. 93-105.

Chiang, L.K., Zhi Ming, M.A., Kong, L. (1998) Mini blast furnaces in China: Current status and future developments. Proceedings 2nd international congress on the science and technology of ironmaking and 57th ironmaking conference proceedings. Iron& Steel Society, Warrendale (PA) USA, pp. 1567-1580.

Couch, G.R. (2001) Metallurgical coal production. IEA Coal Research – The Clean Coal Centre, London. ISBN 92-9029-370-5.

Fang, J., Zeng, T., Shen Yang, L., Oye, K., Sarofim, A. and Beer, J. (1999) Coal utilization in industrial boilers in China – a prospect for mitigating CO_2 emissions.

Fearnleys (2000) World bulk trades 1999. Oslo, Norway.

Gerlagh, T. Dril, A.W.N. van (2000) The Fertiliser industry and its energy use. Prospects for the Dutch energy intensive industry. ECN-C-99-045. Petten, the Netherlands.

Gielen, D.J. (1997) Technology characterisation for ceramic and inorganic materials. Input data for Western European MARKAL. ECN-C-97-064.

Gielen, D.J. (2000) On Carbon Leakage and Technological Change. Energy and Environment 11(1): 49-63.

Gielen, D.J., Yagita, H. (2002) The long term impact of GHG reduction policies on global trade. A case study for the petrochemical industry. European Journal of Operational Research 139: 665-681.

Gielen, D.J., Moriguchi, Y., Yagita, H. (2002) CO_2 emission reduction for Japanese petrochemicals. Journal of Cleaner Production 10: 589-604.

Gielen, D.J., Moriguchi, Y. (2003) Technological potentials for CO_2 emission reduction in the iron and steel industry. International Journal of Environmental Technology and Policy 1, no. 3: 229-249.

Gielen, D.J., Fujino, J., Hashimoto, S., Moriguchi, Y. (2002) Biomass strategies for climate policies? Climate Policy 87: 1-15.

Hekkert, M.P., Worrell, E. (1998) Technology characterisation for natural organic materials. Input data for Western European MARKAL. Utrecht University, STS, rep. No. 98002.

International Iron and Steel institute (2003) Steel Statistical Yearbook 2002. Brussels.

IAI (2002a) Perfluorocarbon emissions reduction program 1990-2000. International Aluminium Institute.

IAI (2002) Current IAI statistics: energy used in alumina production and energy used in aluminium smelting. International Aluminium Institute. Via Internet: http://www.world-aluminium.org/iai/stats/

IEA (2003) Beyond 2020. Energy statistics database. International Energy Agency, Paris.

IEA (2003b) Energy efficiency indicators. In preparation.

IEA CCC (2002) Coal upgrading to reduce CO_2 emissions. IEA Clean Coal Centre. CCC/67. ISBN 92-9029-382-9.

IISI (2002) Steel statistical yearbook 2002. Brussels.

IPCC (2001) IPCC Third Assessment Report – Climate Change 2001. http://www.ipcc.ch/

Jänicke, M., Mönch, H., Binder, M. (1992) Umweltentlastung duch industriellen Strukturwandel? Eine explorative Studie űber 32 Industrieländer (1970 bis 1990). Edition Sigma, Berlin.

JCA (2001): Energy consumption. Japan Cement Association, Via Internet: http://www.jcassoc.or.jp/Jca/English/Ue.html

Jiang, K., Hu, X., Matsuoka, Y. and Morita, T. (1998) Energy technology changes and CO_2 emission scenarios in China.

Kuik, O., Gerlagh, R. (2003) Trade liberalization and carbon leakage. The Energy Journal, vol. 24, no. 3, pp. 97-120.

Lemar, P.L. (2001) The potential impact of policies to promote combined heat and power in US industry. Energy Policy 29, p. 1243-1254.

Limao, N. and Venables, A.J. (1999). Infrastructure, geographical disadvantage and transport costs. The World Bank, Washington DC. Via Internet: http://econ.worldbank.org/

Martin, N., Worrell, E., Price, L. (1999) Energy efficiency and carbon dioxide emissions reduction opportunities in the US cement industry. LBNL-44182.

Martin, N., Anglani, N., Einstein, D., Khrushch, M., Worrell, E. and Price, L. (2000) Opportunities to improve energy efficiency and reduce greenhouse gas emissions in the US paper and pulp industry. LBNL-46141.

Matthews, R. (2001) Olefins production. Presentation at the NEU-CO_2 workshop, November 7th-9th, IEA, Paris.

Micco, A., Perez, N. (2001). Maritime transport costs and port efficiency. Inter-American Development Bank, Santiago, Chile. Via Internet: http://www.iadb.org/oce/pdf/Ports1.pdf

Moriguchi, Y. (1999) Material flow data book. – World resource flows around Japan (in Japanese). ISSN 1341-4356. CGER-D022-'99. National Institute for Environmental Studies, Tsukuba, Japan.

Nordqvist, J. and Nilsson, L.J. (2001) Prospects for industrial technology transfer in Chinese cement industry. In ACEEE summer study proceedings, volume 2, pp. 223-236.

OECD (2001) Instruments and Technologies for Climate Change Policy. An Integrated Energy and Materials Systems Modelling Approach. ENV/EPOC/GEEI(99)15/final. Paris, 2001.

Park, H.-C. (2002) Fossil fuel use and CO_2 emissions in Korea: New NEAT results. Paper presented at the NEU-CO_2 workshop, September 2003, Amsterdam.

Rath-Nagel, S., Stocks, K. (1982) Energy modelling for technology assessment: the MARKAL approach, Omega, Volume 10, Issue 5, Pages 493-505 Schumacher, K., Sathaye, J. (1999) India's pulp and paper industry: productivity and energy efficiency. LBNL-41843.

Schwarz, H.-G., Briem, S., Zapp, P. (2001) Future carbon dioxide emissions in the global material flow of primary aluminium. Energy 26, pp. 775-795.

UN (2003) Industrial commodity production statistics. Dataset 1950-2000. Disk EIS 02, 20 February 2003. Umited Nations Statistics Division, New York.

USGS (1998) Primary aluminium plants worlwide – 1998. Part 1 –detail. US Geological Survey, Reston, VA.

Viswanathan, R., Bakker, W. (2001) Materials for ultrasupercritical coalpower plants – boiler materials: Part 1. Journal of Materials Engineering and Performance, vol. 10, no. 1, February 2001, pp. 81-95.

WEO (2002) World Energy Outlook 2002. International Energy Agency, Paris.

Worell, E., Martin, N., Price, L. (1999) Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector. LBNL-41724.

World Chlorine Council (2002) Chlorine and Caustic Soda. Chlor-Alkali Manufacturing Processes. Via Internet: www.worldchlorine.com

Zhang, H., Nora, V. de, Sekhar, J.A. (1994) Materials used in the Hall-Heroult cell for aluminium production. The Minerals, Metals and Materials Society TMS, Washington DC.

Existing IEA/EET Working Papers

EET/2003/01 - Uncertainties in relation to CO_2 capture and sequestration. Preliminary results. Dolf Gielen.

EET/2003/02 – The Future of Energy Star and Other Voluntary Energy Efficiency Programmes – Alan Meier.

EET/2003/03 - Applying Portfolio Theory to EU Electricity Planning and Policy-Making – Shimon Awerbuch with Martin Berger.

EET/2003/04 - The Future Role of CO_2 Capture and Storage: Results of the IEA-ETP Model Dolf Gielen.