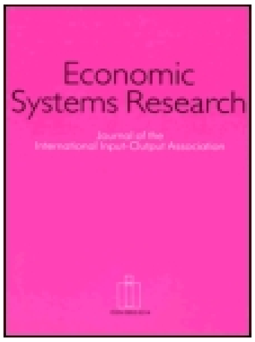

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Structural Analysis of International Trade: Environmental Impacts of Norway

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ABSTRACT *Final demand purchases initiate production processes that ultimately lead to environmental impacts. With the increase in international trade, many production processes occur outside of the country of final consumption. Whilst several studies have evaluated the pollution embodied in consumption and trade flows, few studies have investigated the structural linkages between domestic consumption and production in foreign regions. In this article we apply three complementary approaches to study the production network leading from the Norwegian economy to domestic and international environmental impacts: (1) the consumption perspective identifies final demand purchases that produce environmental impacts; (2) the production perspective identifies the production processes generating the pollution for a given demand; and (3) structural path analysis is used to provide the linkages between the global production networks linking consumption and production. We find that the three approaches provide different, but complementary information. For policy to focus on both sustainable consumption and production, all three approaches are required to fully identify environmentally important sectors in an economy.*

KEY WORDS: Input–output analysis, embodied pollution, international trade, structural path analysis, sustainable consumption and production

1. Introduction

Final demand purchases instigate production processes that ultimately generate pollution. With increasingly global production networks, many of the production processes occur outside of the country of final consumption. Several recent studies have shown that a

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significant amount of pollution is embodied in international trade (e.g. Ahmad and Wyckoff, 2003; Lenzen *et al.*, 2004; Nijdam *et al.*, 2005; Peters and Hertwich, 2006a). Ahmad and Wyckoff (2003) found that approximately 14% of OECD CO_2 emissions were embodied in imports and many countries had over 25% of their CO_2 emissions embodied in imports.[1] They assumed that developing countries had US technology. Peters and Hertwich (2006a) found that, for Norway, approximately 50% of the pollution embodied in imports came from developing countries, yet they represented only 10% of import value. Other studies have also found a large amount of pollution embodied in trade (Wyckoff and Roop, 1994; Battjes *et al.*, 1998; Lenzen, 1998; Machado *et al.*, 2001; Muradian *et al.*, 2002, among others).

Most studies determining the environmental impacts of economic activity have used input–output analysis (IOA; e.g. Herendeen and Tanaka, 1976; Gay and Proops, 1993; Lenzen, 1998; Ahmad and Wyckoff, 2003; Munksgaard *et al.*, 2005). IOA is a methodology used to describe and investigate the linkages between various actors in an economic system and more generally it can include environmental externalities (Leontief, 1970). A significant advantage of using IOA is the ability to trace the intricate chain of production processes instigated by a given final demand. This technique is often called structural path analysis (SPA; Defourny and Thorbecke, 1984). Despite the appeal of SPA, relatively few studies have applied SPA. Early work focused on linkages in the Social Accounting Matrix framework (Defourny and Thorbecke, 1984; Khan and Thorbecke, 1989). Several studies have had environmental motivations using hybrid Life Cycle Assessment (Treloar, 1997; Treloar *et al.*, 2001; Lenzen, 2002). Lenzen (2003) considered the environmentally important linkages in the Australian economy using several techniques including SPA. Peters and Hertwich (2006b) have applied SPA to household environmental impacts in Norway, but focused on the consumption patterns leading to environmental impacts.

Despite the interest in the impacts of trade on the environment (e.g. Jayadevappa and Chhatre, 2000; Copeland and Taylor, 2003), very few studies have considered the linkages between consumption and production in international production chains. Many studies have investigated the environmental impacts of household consumption (see the review by Hertwich, 2005), but these studies generally do not identify where in the production chain the environmental impacts occur. Lenzen (2003) applied SPA to identify the environmentally important paths linking consumption and production in the Australian economy including contributions of international trade using Australian technology. However, in practice, SPA generates innumerable paths and typically only a very small percentage of total paths are analyzed (see also Sonis *et al.*, 1997). While SPA identifies the most important paths it does not identify the aggregated environmental impacts of given production processes. We are not aware of any studies that have focused on the most significant production processes required to produce a given consumption bundle. The aim of this article is to analyse the aggregated environmental impacts of consumption and production separately, and then use SPA to analyse the linkages between consumption and production. We apply our methodology to Norwegian environmental impacts and show how the three approaches are relevant to different environmental policies.

Norway is an ideal country to study the environmental implications of international trade flows since it represents many extremes in its economic structure. Due to its climate, geography, and small size, Norway has become dependent on imports. Coupled with Norway's almost exclusive use of hydropower in electricity production, the environmental impacts embodied in Norway's imports are considerable when compared to the impacts within Norway (Peters and Hertwich, 2006a). Further, due to its natural resource base, Norway has a high dependence on energy and pollution intensive exports for its income; primarily oil and gas, international shipping, and metals manufacturing. Consequently, a structural study of Norway's export industries gives an interesting contrast to the household sector and the services based government sector. It is also likely that many of the results for Norway will generalize to other countries with a high level of pollution embodied in trade; such as Denmark, Finland, France, Korea, The Netherlands, New Zealand, and Sweden (Ahmad and Wyckoff, 2003).

In this article we consider the environmental impacts of Norway from a consumption perspective, a production perspective, and use SPA to identify the linkages between consumption and production. The SPA (discussed the next section) is applied using a multi-regional input–output model (presented in the third section) of the Norwegian economy. The structure of the Norwegian economy is described (in the fourth section), before we identify important linkages in the economy (in the fifth section) and consider the aggregated impacts of consumption and production separately (in the sixth section). We conclude by discussing the relevance of our results with respect to policy (in the seventh section).

2. Structural Path Analysis

Using input–output analysis (IOA), the total output of an economy is given by

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{1}$$

where $\mathbf{y}$ is the final demand and $\mathbf{A}$ is the interindustry requirements matrix (Leontief, 1941; Miller and Blair, 1985; United Nations, 1999). Solving equation (1) for the total output, $\mathbf{x}$, gives

$$\mathbf{x} = \mathbf{L}\mathbf{y} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{2}$$

where $\mathbf{L}$ is often called the Leontief inverse. Given the output of the economy it is possible to determine the environmental impacts and factor requirements using

$$\mathbf{f} = \mathbf{F}\mathbf{x} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{3}$$

where the element f_{pi} is the environmental impact (or factor usage) per unit output for pollutant (or factor) p in industry sector i (Leontief, 1970). The Leontief inverse can be expanded using a power series approximation giving (Waugh, 1950)

$$\mathbf{f} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{F}\mathbf{I}\mathbf{y} + \mathbf{F}\mathbf{A}\mathbf{y} + \mathbf{F}\mathbf{A}^2\mathbf{y} + \mathbf{F}\mathbf{A}^3\mathbf{y} + \mathbf{F}\mathbf{A}^4\mathbf{y} + \ldots \tag{4}$$

where $\mathbf{F}\mathbf{A}^t\mathbf{y}$ represents the impact from the t^{th} production layer (or tier). For instance, if $\mathbf{y}$ represents a demand on the production of one car, then $\mathbf{F}\mathbf{I}\mathbf{y}$ is the direct pollution emitted in the production of the car by the car manufacturer. To produce the car, inputs $\mathbf{A}\mathbf{y}$ from other industries are required; these industries emit $\mathbf{F}\mathbf{A}\mathbf{y}$ of pollution. In turn, these industries require inputs of $\mathbf{A}(\mathbf{A}\mathbf{y})$ and $\mathbf{F}\mathbf{A}^2\mathbf{y}$ of pollution is emitted. This process continues through the infinite expansion of the power series. There are also environmental impacts related to the direct consumption of fuel by households (see Gay and Proops, 1993).

Quite often, the largest contribution to the total embodied pollution does not occur in the zeroth ($t = 0$) tier (see Treloar, 1997; Lenzen, 2002; Norris, 2002). Further, only a small number of sectors may contribute to the environmental impacts in a given tier. For instance, in the production of aluminium, the first tier input of electricity produced by coal, might give the largest contribution to the overall environmental impacts, while the first tier input of insurance services may have a negligible impact. This suggests that an analysis of the linkages in the production chain that lead to large environmental impacts will identify areas for environmental improvements. This type of analysis is often referred to as Structural Path Analysis (SPA; Defourney and Thorbecke, 1984).

SPA leads to a study of a mathematical graph that can be produced from the coefficients in **F**, **A**, and **y**. Each of the n industry sectors in **A** represents a node in a connected graph, while **F** scales for the pollution intensity at each node and **y** gives the product mix. By following the series expansion in equation (4), the graph can also be expressed as a tree; each tier in the tree represents a different production layer and each node gives the contribution to total environmental impacts from the demand **y**. Figure 1 shows the representation of a two-sector economy in terms of a graph and a tree.

The number of nodes in the tree grows exponentially with each tier; each tier has n^{t+1} nodes. The zeroth tier gives the direct contribution – in terms of pollutant (or factor) p – from each production layer,

$$f_{pi}y_i \tag{5}$$

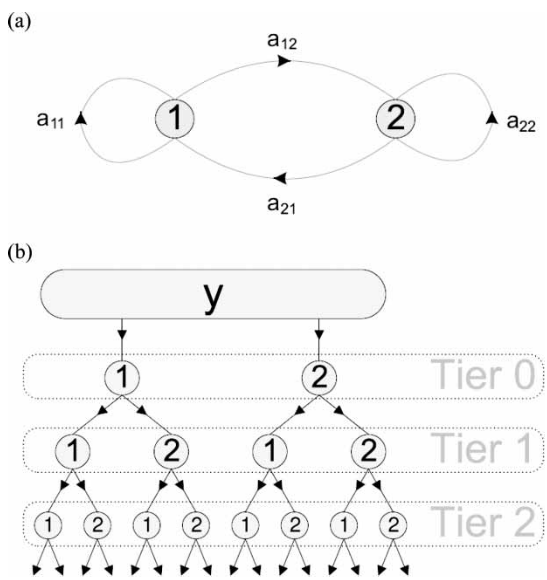

Figure 1. The representation of a two sector economy; (a) a graph, and (b) a tree

The n^2 first tier nodes are evaluated as

$$f_{pj} a_{ji} y_i \tag{6}$$

and represents the path $i \rightarrow j$. The n^3 second tier nodes are evaluated as

$$f_{pk} a_{kj} a_{ji} y_i \tag{7}$$

and represent the path $i \rightarrow j \rightarrow k$. The same pattern continues for all tiers. Using the second tier as an example, a final demand purchase (consumption) is represented by the start of the production chain, sector i. The end of a given production chain, sector k, represents the production sector that emits the pollutant p. The environmental impacts of any intermediate sector j, are considered in paths ending at j. Between two sectors there are, in general, an infinite number of pathways. By calculating all pathways, it is possible to determine the most important production paths from all tiers.

Extracting all paths for a given set $\mathbf{F}$, $\mathbf{A}$, and $\mathbf{y}$ can be a computational expensive task. Several authors have used methods of tree 'pruning' to reduce the number of paths calculated (Treloar, 1997; Treloar *et al*., 2001; Lenzen, 2002, 2003), although a detailed computational description of the methodology they applied has not been presented. We have used a dynamic tree data structure with tree pruning to extract the necessary paths. Our computational algorithms are described in Appendix A.

3. Multi-regional Input–Output Analysis

Our primary interest in this study is the analysis of environmental impacts of international production chains instigated from the Norwegian economy. We use a multiregional input–output model for our analysis (Lenzen *et al*., 2004; Peters and Hertwich, 2005, 2006a,b) and we only give a brief overview here. In this article, Norway (*NO*) is the domestic economy, denoted region 1, and Norway trades with $m - 1$ regions. The output in each region for total demand in Norway can be expressed as,

$$\begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \mathbf{x}_3 \\ \vdots \\ \mathbf{x}_m \end{pmatrix} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} & \mathbf{A}_{13} & \cdots & \mathbf{A}_{1m} \\ \mathbf{A}_{21} & \mathbf{A}_{22} & \mathbf{A}_{23} & \cdots & \mathbf{A}_{2m} \\ \mathbf{A}_{31} & \mathbf{A}_{32} & \mathbf{A}_{33} & \cdots & \mathbf{A}_{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{m1} & \mathbf{A}_{m2} & \mathbf{A}_{m3} & \cdots & \mathbf{A}_{mm} \end{bmatrix} \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \mathbf{x}_3 \\ \vdots \\ \mathbf{x}_m \end{pmatrix} + \begin{pmatrix} \mathbf{y}_{11} + \Sigma_{j \neq 1} \mathbf{y}_{1j} \\ \mathbf{y}_{21} \\ \mathbf{y}_{31} \\ \vdots \\ \mathbf{y}_{m1} \end{pmatrix} \tag{8}$$

where $\mathbf{x}_i$ indicates the output of region i; $\mathbf{A}_{ii}$ the interindustry requirements of domestic production in region i; $\mathbf{A}_{ij}$ the interindustry requirements by region j of imports from region i; $\mathbf{y}_{ii}$ the final demand purchases from domestic production; and $\mathbf{y}_{ij}$ the imports from region i to final demand in region j. Note that $\mathbf{y}_i^{im} = \Sigma_{j \neq i} \mathbf{y}_{ji}$ gives the total imports for final demand in region i; $\mathbf{A}_i^{im} = \Sigma_{j \neq i} \mathbf{A}_{ji}$ gives the total interindustry requirements of imports in region i; and $\mathbf{A}_i = \mathbf{A}_{ii} + \mathbf{A}_i^{im}$ gives the total interindustry requirements in region i. The columns in the matrix in equation (8) represent the inputs into production and the off-diagonal matrices are imports into production from foreign regions. When read across the rows, the off-diagonal terms are interpreted as interindustry exports,

$\mathbf{A}_{ij}$ is the export from region i to industry in region j. The first element in the final demand vector represents purchases from the domestic production system either for domestic or foreign (i.e. exports) final demand purposes. The other elements are imports into final demand.

To reduce the data requirements for equation (8) we only consider interindustry imports into Norway (*NO*); $\mathbf{A}_{i,NO} > 0$ for all $i \neq 1$ (=*NO*), and $\mathbf{A}_{ij} = 0$ for all $j \neq 1$ and all $i \neq j$. This implies that Norway imports into both final demand and industry, but the other regions do not trade with each other; for instance, there is no trade between the USA and Japan. We justified this assumption on the findings by Lenzen *et al.* (2004) for Denmark that these 'second-order' trade effects were of the order 1–4%. Similar results are also found in other regional input–output models (Round, 2001). If the 'second-order' trade effects are only a few percent, then the error introduced by this assumption is likely to be less than the uncertainties in the data used in the model. As a consequence of this assumption, we treat all exports from Norway together and do not separate between exports to final demand and exports to industry. Some of the exports from Norway to industries in other countries may have been used to produce an import into Norway. However, given Norway's small size, this effect is likely to be relatively small and would mean that a small share of Norway's exports should be allocated to Norwegian households or government. Further details on the rationale behind these assumptions can be found in Peters and Hertwich (2005, 2006a,b).

3.1. Capital and Margins

It can be argued that the industry use of capital should be included into intermediate inputs as it ultimately occurs to facilitate production (Lenzen, 2001). Statistics Norway provided data on the intermediate use of capital by industry, $\mathbf{K}_{\mathrm{d}}$. This allowed us to 'internalize' capital into the interindustry coefficients using

$$\mathbf{A}^d_{NO} = (\mathbf{Z}^d + \mathbf{K}^d)\hat{\mathbf{x}}^{-1}_{NO} \tag{9}$$

where $\mathbf{x}_{NO}$ is the total output of the economy and the 'hat' represents diagonalization (see Lenzen, 1998, 2001). However, we did not have capital distributed by industry for imports. Imported capital represented 25% of capital expenditure.

The Norwegian input–output tables have an additional row and column representing 'trade and transport margins'. The column shows the production of margins by industry and the row shows the use of margins by both industry and final demand. These data need to be internalized into the interindustry requirements to make the data consistent with other data sets and since the production of margins belongs to the basic value of production.[2] The vector $\mathbf{q}$ describes the required inputs to produce the margins, while the row vector $\mathbf{v}'$ describes the purchases of margins from each sector. Both industry and final demand purchase margins and so $\mathbf{v}'$ can be broken into two parts, $\mathbf{v}' = (\mathbf{v}'_{ind}, v_{\mathrm{y}})$. The margins can be normalized and the input–output system written as

$$\begin{pmatrix} \mathbf{x} \\ x_t \end{pmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{a}_{\mathrm{q}} \\ \mathbf{a}'_{\mathrm{v}} & 0 \end{bmatrix} \begin{pmatrix} \mathbf{x} \\ x_t \end{pmatrix} + \begin{pmatrix} \mathbf{y} \\ v_{\mathrm{y}} \end{pmatrix} \tag{10}$$

where $\mathbf{a_q} = \mathbf{q}/x_t$ with $x_t = \Sigma_i\{\mathbf{v}_{ind}\}_i + v_\mathbf{y}$, and $\mathbf{a}'_\mathbf{v} = \mathbf{v}'_{ind}\hat{\mathbf{x}}^{-1}$. This implies $x_t = \mathbf{a}'_\mathbf{v}\mathbf{x} + v_\mathbf{y}$ and substituting this expression into $\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{a_q}x_t + \mathbf{y}$ gives

$$\mathbf{x} = (\mathbf{A} + \mathbf{T})\mathbf{x} + (\mathbf{y} + \mathbf{a_q}v_\mathbf{y}) \tag{11}$$

where $\mathbf{T} = \mathbf{a_q}\mathbf{a}'_\mathbf{v}$ is the matrix with internalized margins and $\mathbf{a_q}v_\mathbf{y}$ is the vector that gives the distribution of margins to final demand. In effect, this process distributes the margins proportionally to each sector and final demand; this assumes that margins are supplied with the same technology to each industry and final demand.

3.2. Data Sources and Data Preparation

To reduce the data requirements, input–output data were only collected for Norway's seven major importing partners, which represent 61% of imports into Norway. The remaining imports into Norway originate in nearly 200 different countries. It was assumed that these imports were produced using the technology of one of Norway's major trading partners and the allocation was based on comparisons of energy use per capita, CO_2 emissions per capita, and gross domestic product per capita (World Bank, 2005); see Table 1. In our data set, 74% of the countries were classed as developing countries and given Chinese technology. Given the large impacts originating in developing countries (see later), it would be better to have input–output data for different classes of developing countries. However, we have found that China, on average, gives a reasonable representation of other developing countries (see Peters and Hertwich, 2006b, for more details).

The input–output and emissions data were constructed in a previous study (Peters and Hertwich, 2006b) and the data came from a variety of sources (Hubacek, 2002; Suh and Huppes, 2002; Nansai *et al.*, 2003; Statistics Norway, 2003; Bureau of Economic Analysis, 2005; Eurostat, 2005a). As a result, the data required several manipulations to make the complete data set consistent (Lenzen *et al.*, 2004; Peters and Hertwich, 2006b). First, to allow for a comparison of the data between regions, the data were mapped into a NACE industry classification (Eurostat, 2005b) with 49 sectors that gave the best overlap of the data sets; see Appendix B. Second, the Consumer Price Index (CPI) in

Table 1. The aggregation of Norway's import trade

Aggregated Region	Regional Code	Technology	Import Share by technology (%)	Import Share by aggregation (%)
Sweden	SE	Swedish	14	19
United Kingdom	UK	British	13	14
North America	NA	USA	10	12
Germany	DE	German	10	25
Denmark	DK	Danish	7	14
Japan	JP	Japanese	4	7
Developing Countries	DC	Chinese	4	10
Total			61	~100

Note: the 'Import Share by technology' represents the imports from Norway's seven largest importing partners and the 'Import Share by aggregation' represents the new import shares after aggregation of like regions.

each country was used to convert the monetary data from the base year into 2000 values (SourceOECD, 2005). Finally, the currencies were converted into Norwegian Kroner (NOK) using Market Exchange Rates for the base year of 2000 (OANDA, 2005). Peters and Hertwich (2006a) discuss issues related to the use of Market Exchange Rates or Purchasing Power Parity for the currency conversions. Our data set only had overlap for the pollutants CO_2, SO_2, and NOx.

Generally, data are not available to separate the imports to industry or final demand by country of origin. However, data usually are available for total imports into Norway. We use trade shares to estimate the imports to industry by country $\mathbf{A}_{i,NO}$ from the total imports to industry $\mathbf{A}_i^{im}$. A similar calculation is performed for final demand. More details on this assumption can be found in Lenzen *et al*. (2004) and Peters and Hertwich (2006b). We did not convert trade data to free on board (fob) prices from the cost, insurance, freight (cif) prices. Since we only consider trade shares, this essentially assumes that all imports have the same insurance and freight margins.

The manipulations of the data into a consistent data set represent the biggest source of uncertainty in the following calculations. The underlying input–output and emissions data are known to have inaccuracies due to statistical sources and method of compilation (Rypdal and Zhang, 2000; Statistics Norway, 2003); however, error distributions for input–output and emissions data are rarely published. Many of the uncertainties are difficult to quantify; for instance, the errors introduced by mapping to a new classification system, aggregation of input–output data, allocation of trade data, choice of exchange rates, inflation measures, and so on. Given the large uncertainties in the data, care needs to be taken with the results. The various sources of uncertainty are discussed in more detail in Peters and Hertwich (2006b).

4. Economic Structure and Environmental Impacts of Norway

Before proceeding it is beneficial to investigate the economic and environmental structure of Norway. The Norwegian economy has some unique characteristics, particularly related to the export industries, the electricity mix, and a high dependence on imports. Figure 2 shows the share of expenditure, domestic emissions, and the embodied global emissions for the total final demand of households, governments, and exports. As described earlier capital expenditure is internalized into the results and we have ignored changes in stocks due to the small contribution. The expenditure includes the expenditure on both domestic and imported products. The domestic emissions are the direct and indirect emissions occurring in Norway due to Norwegian economic activity. The global emissions include the emissions embodied in both final demand and industry imports into Norway.

Figure 2 shows that the bulk of Norway's economic activity results from exports (45%),[3] but exports account for about 75% of Norway's domestic emissions. A further breakdown shows that the exports are dominated by the pollution intensive oil and gas sector, international shipping, metal manufacturing, and chemical production. Household expenditure contributes about 35% to final demand expenditure, but produces approximately 20% of Norway's domestic emissions. When the emissions embodied in imports to households are considered, the relative share of CO_2 emissions for households increases to nearly 30%. Since only 19% of household expenditure is on imports, this illustrates that Norway has significantly cleaner production technology than the imports into Norway.

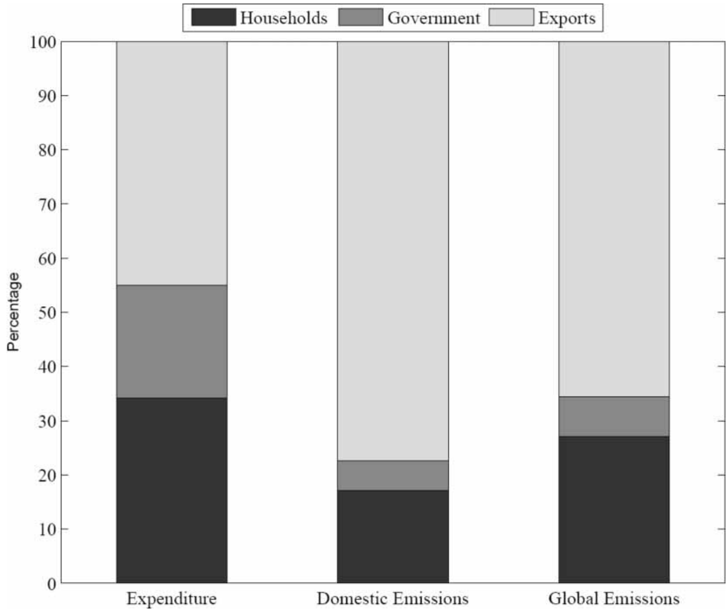

Figure 2. The share of households, government, and exports in final demand expenditure, domestic emissions, and global emissions

Government expenditure represents about 20% of Norway's income, and the share of emissions is low both domestically and globally. This reflects the service orientated nature of government expenditure and also a small share of expenditure on imports (1%).

Table 2 gives a breakdown of the global CO_2 emissions from households, governments, and exports. 'Norway: Direct fuel use' shows the domestic emissions from direct fuel use by Norwegian households; for instance, the use of petrol in private transportation or wood in heating a private house. 'Norway: Production for final demand' represents domestic emissions occurring in the production of products within Norway for final demand. To produce these items domestically requires imports into industry and these emissions are shown as a separate row, 'Imports: To industry'. There are also imports directly to final demand and these emissions are shown separately as 'Imports: To final demand'. The 'Intensity' is the total emissions divided either by the final demand expenditure or the generated output corresponding to this expenditure. Although not shown in the tables, about half of the CO_2 emissions embodied in imports originate from developing countries despite representing only 10% of the import value (Peters and Hertwich, 2006a).

Several conclusions can be drawn from Figure 2 and Table 2. The emissions embodied in imports are considerable and disproportional to the expenditures on imports. This is because the Norwegian economy has a low-emission intensity due primarily to the use of hydropower in electricity generation. The pollution embodied in imports is particularly evident in the household sector. Exports are more pollution intensive compared to households and governments. This reflects the pollution intensive nature of Norway's primary export industries; oil and gas, shipping, and metals. The pollution intensity of government expenditure is relatively low, reflecting a high expenditure on services.

Table 2. The CO_2 emissions resulting from the different final demands

	Household	Government	Export	Total
Norway				
Direct fuel use	4.9	-	-	4.9
Production for final demand	8.3	2.6	37.5	49.8
Imports				
To final demand	7.1	0.3	0.9	13.3
To industry	6.1	3.0	13.7	23.6
Total	26.4	5.9	52.1	91.6
Intensity (final demand)	0.0526	0.0192	0.0787	0.0582
Intensity (generated output)	0.0330	0.0119	0.0489	0.0379

Note: the 'Total' does not correspond to the sum of the rows since we have not included changes in stocks. The emissions are in millions of tonnes of CO_2 and the intensities are in kg CO_2 per NOK.

The remainder of this article considers the environmental impacts of households, governments, and exports in more detail. In particular, different methods are used to illustrate why households, government, and exports have different emission structures.

5. Structural Path Analysis

Norway's dependence on trade and its clean energy supply make it an interesting case study for the environmental impacts of international production networks. In this section we use structural path analysis (SPA) to study the international linkages originating from Norway's households, government, and exports. We only present the results for CO_2, but later discuss some aspects of the results for SO_2 and NOx.

Before proceeding it is worth considering the total contribution from each tier in the power series expansion in equation (4). Table 3 shows the percentage contribution from the first eight tiers. The export and household sectors are dominated by the zeroth tier emissions. For the export sectors this relates primarily to direct emissions from international shipping and direct processing in the oil and gas sector, while for the household sector this relates primarily to the direct use of fuel for private transportation and space

Table 3. The percentage contribution from each tier in the power series expansion

Tier	Household	Government	Export	Total
0	37.1	13.1	58.8	43.8
1	18.2	19.8	15.1	18.1
2	14.8	20.3	10.0	13.5
3	10.7	16.6	6.2	9.1
4	7.2	11.4	3.9	5.9
5	4.6	7.3	2.4	3.7
6	2.9	4.5	1.5	2.3
7	1.8	2.7	0.9	1.4

Note: direct household emissions are included in the household sector.

heating. The government sector has larger impacts occurring in higher tiers. Below, we use SPA to show that this is due primarily to low direct emissions in the service sectors and purchases of pollution intensive products via the construction sector.

The production paths in the SPA are described using the abbreviations in Table 1 and Appendix B. As an example, 'NO,Land T' are the emissions in Norway from the direct purchase of land transport in Norway (this excludes personal car use); 'NO,Metals → DE,Metals' is the path from the purchase of metals in Norway to the emissions in the metal sector in aggregated Germany; 'DC,Clothing → DC,Chemical' is the path from the purchase of clothing from developing countries to the emissions in the chemical sector in developing countries. In the calculations the cut-off threshold for sub-trees was taken as 0.001% of total emissions and a maximum of eight tiers were searched. This could be set higher, but it is unlikely that there would be significant contributions after eight tiers. We only consider the top 25 paths below. In a total enumeration of the tree structure there would be an infinite number of paths, most of which make very small contribution to the overall impacts (see Treloar, 1997; Norris, 2002).

5.1. Household Consumption

Table 4 shows the top ranking paths for CO_2 emissions resulting from household consumption.[4] The most important contribution to household environmental impacts is the direct emissions from personal fuel use; 80% is from transportation and 20% is from space heating (other than electricity). Of more relevance for this study are the emissions resulting from consumer purchases. The first, second, and fifth top-ranking paths are the direct purchase of transportation services by households, this coupled with direct emissions from personal car usage reinforces the importance of mobility in causing environmental impacts. Food appears in many high ranking paths, reflecting the high expenditure on food in households. Surprisingly, the purchase of clothing from developing countries occurs in many high ranking paths, despite a relatively low expenditure in that sector (more details in Peters and Hertwich, 2006b). Direct imports from foreign regions comprise 50 of the top 100 paths (results not shown). This reflects the relatively pollution intensive nature of imports to households given the low household expenditure on imports (19%). Overall, the results show that policies should be directed at mobility, food, clothing, and chemicals (see Hertwich, 2005).[5] The policy implications are discussed further below.

5.2. Government Consumption

Table 5 shows the top ranking paths for CO_2 emissions resulting from government consumption. The impacts from government expenditure are dominated by expenditure on health, education, and public administration. The government provides large amounts of funding for construction in the public sectors and this is reflected in the environmental impacts. For construction, the expenditure on non-metallic products leads to large impacts. The purchase of transport from the public sectors also causes large impacts; in particular, business trips by air appear in many early paths. Direct purchase of chemicals by the government occurs in many top ranking paths and a large fraction of these impacts are embodied in imports. Only 33 of the top 100 paths end in foreign regions, which

Table 4. The 25 top-ranking paths for CO_2 emissions starting from a household purchase (left) and ending with the polluting sector (right)

Rank	Tier	Contribution (%)	Path
0	-	18.56	Household
1	0	4.22	NO,Land T
2	0	2.67	NO,Water T
3	0	1.07	NO,Ref. Pet.
4	1	0.89	NO,Food → NO,Fish
5	0	0.83	NO,Air T
6	0	0.77	NO,Food
7	0	0.62	NO,Trade
8	0	0.59	NO,Other
9	1	0.49	NO,Ref. Pet. → NO,Oil/gas
10	0	0.42	NO,Chemical
11	1	0.39	NO,Food → NO,Agric
12	1	0.32	DC,Clothing → DC,Chemical
13	0	0.32	DC,Food
14	1	0.32	NO,Aux T → NO,Land T
15	1	0.32	DC,Clothing → DC,Textiles
16	0	0.32	NO,Electricity
17	0	0.30	NO,Agric
18	1	0.29	NO,Trade → NO,Water T
19	0	0.26	DC,Chemical
20	1	0.26	NO,Business → NO,Construction
21	0	0.25	NO,Non-met
22	2	0.25	NO,Business → NO,Construction → NO,Non-met
23	0	0.23	NO,Post
24	1	0.23	NO,Water T → NO,Water T
25	1	0.22	NO,Land T → NO,Land T

Note: the country abbreviations are given in Table 1 and the NACE abbreviations in Appendix B. There were 15,980 paths to the eighth tier above the threshold value, representing 66% of total emissions.

reflects the relatively low expenditure on imports by the government sector (about 1%). Overall, the impacts from government consumption are low when compared to household consumption and exports, see Table 2. Reductions in impacts can be made by addressing expenditure and efficiencies in mobility, construction, and chemicals in public institutions.

5.3. Exports

Table 6 shows the top ranking paths for CO_2 emissions resulting from export demand. The impacts in the export sector are dominated by direct emissions from international shipping and production in the oil and gas sector. Following this, there are significant direct impacts in the metals and chemicals sectors. A large fraction of the impacts in higher order paths are embodied in imports from foreign regions. Indirect imports of electricity occur in many paths, particular in the production of metals in foreign regions. Almost half of the top 100 ranking paths end in foreign regions. The policy implications for exports are discussed in more detail below together with the consumption and production perspectives.

Table 5. The 25 top-ranking paths for CO_2 emissions starting from a government purchase (left) and ending with the polluting sector (right)

Rank	Tier	Contribution (%)	Path
1	0	3.96	NO,Health
2	0	3.07	NO,Public
3	0	1.45	NO,Land T
4	1	1.43	NO,Public → NO,Construction
5	2	1.39	NO,Public → NO,Construction → NO,Non-met
6	0	1.30	NO,Education
7	1	1.00	NO,Public → NO,Air T
8	1	0.88	NO,Health → NO,Chemical
9	1	0.82	NO,Education → NO,Land T
10	1	0.72	NO,Public → NO,Water T
11	1	0.66	NO,Public → NO,Land T
12	0	0.55	NO,Chemical
13	1	0.54	NO,Health → NO,Land T
14	1	0.49	NO,Health → NO,Construction
15	0	0.48	DC,Chemical
16	2	0.47	NO,Health → O,Construction → O,Non-met
17	1	0.42	NO,Education → O,Construction
18	2	0.41	NO,Education → O,Construction → O,Non-met
19	2	0.38	NO,Public → A,Business → A,Coal
20	0	0.38	DE,Chemical
21	1	0.37	NO,Aux T → O,Land T
22	0	0.33	NO,Members
23	1	0.29	NO,Education → O,Air T
24	2	0.28	NO,Public → A,Business → A,Electricity
25	1	0.27	NO,Health → C,Chemical

Note: there were 16,468 paths to the eighth tier representing 64% of total emissions.

5.4. Results for SO_2 and NOx

We have only displayed the results for CO_2 in the above sections. Generally, the results for SO_2 and NOx follow similar trends; however, there are consistent differences compared to the CO_2 results. Compared to the emissions intensity of CO_2, Norway generally has a better performance compared to other regions for SO_2 and a generally worse performance for NOx (Peters and Hertwich, 2006b). These conclusions are consistent with SO_2 being prevalent in the burning of fossil fuels in electricity production and NOx resulting from the combustion of fossil fuels in the oil and gas and the international shipping sectors. Consequently, the trade flows appear earlier in the top ranking paths for SO_2 compared to CO_2. The results are particularly prominent for developing countries based on a high use of coal. The results of the SPA for NOx offers an interesting contrast since there is a relatively small variation in the emissions intensities for NOx across regions. Consequently, most of the top ranking paths for NOx originate from domestic production.

The emissions embodied in the international trade flows have more policy relevance for global pollutants such as CO_2, compared to local pollutants such as SO_2 and NOx. The CO_2 emissions have an impact at a global level and consequently CO_2 emissions have an effect on all citizens regardless of the origin of the emissions. In this case, the emissions

Table 6. The 25 top-ranking paths for CO_2 emissions starting from an export purchase (left) and ending with the polluting sector (right)

Rank	Tier	Contribution (%)	Path
1	0	21.78	NO,Water T
2	0	19.48	NO,Oil/gas
3	0	8.14	NO,Metals
4	0	3.40	NO,Chemical
5	1	1.86	NO,Water T → NO,Water T
6	0	1.56	NO,Ref. Pet.
7	1	1.45	NO,Metals → DE,Metals
8	0	1.09	NO,Land T
9	0	0.95	NO,Fish
10	1	0.87	NO,Oil/gas → NO,Oil/gas
11	1	0.77	NO,Oil/gas → NO,Water T
12	1	0.72	NO,Ref. Pet. → NO,Oil/gas
13	2	0.47	NO,Water T → DC,Aux T → DC,Electricity
14	0	0.42	NO,Air T
15	1	0.41	NO,Metals → SE,Metals
16	0	0.39	NO,Paper
17	1	0.39	NO,Water T → UK,Ref. Pet.
18	2	0.36	NO,Metals → DE,Metals → DE,Electricity
19	1	0.36	NO,Chemical → NO,Chemical
20	1	0.32	NO,Metals → NO,Metals
21	0	0.29	NO,Non-met
22	2	0.26	NO,Metals → DC,Mining → DC,Electricity
23	1	0.24	NO,Water T → DE,Ref. Pet.
24	1	0.24	NO,Food → NO,Fish
25	1	0.23	NO,Oil/gas → NO,Air T

Note: there were 7,185 paths to the eighth tier representing 85% of total emissions.

embodied in trade have significant policy implications. On the other hand, SO_2 and NOx emissions have an effect at a more local level. Consequently, the global policy implications are arguably less significant. However, there is still an issue of burden shifting; for instance, relocation of pollution-intensive industry to developing countries.

6. The Consumption and Production Perspectives

The SPA describes which production paths lead to the greatest impacts in the international production chain. All the paths start with a final demand purchase, however, it is sector at the end of the production chain that causes the environmental impacts. So an analysis of the starting point of the paths will identify which consumption activity causes impacts (consumption perspective) and an analysis of the end-points of the paths will identify which production activities cause environmental impacts (production perspective).

It is straightforward to determine the contribution to total impacts from the consumption and production perspectives using equation (3). From the consumption perspective, element (p, i) of the matrix

$$\mathbf{F}_{consumption} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{y}} \tag{12}$$

gives the total environmental impacts in terms of pollutant p for each element y_i of demand in the consumption bundle $\mathbf{y}$ (recall that $\hat{\mathbf{y}}$ represents the diagonal matrix obtained from $\mathbf{y}$). From the production perspective, element (p, k) of the matrix

$$\mathbf{F}_{production} = \mathbf{F}\hat{\mathbf{x}} \tag{13}$$

where $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, gives the total environmental impacts in terms of pollutant p from each production process k resulting from the entire consumption bundle $\mathbf{y}$.[6]

The consumption and production perspectives can be explained in the context of the SPA. For the path $i \rightarrow \cdots \rightarrow$ k, element (p, i) of the matrix $\mathbf{F}_{consumption}$ gives the total impact from all paths starting at i irrespective of the length or end-point of the path. While element (p, k) of the matrix $\mathbf{F}_{production}$ gives the total impacts from all paths ending in sector k irrespective of the instigating sector i. The differences between the two approaches leads to different policy interpretations and these are elaborated on in the following sections.

6.1. Household

Table 7 shows the top 10 sectors from the consumption and production perspective for household demand. Using the production perspective, 9% of Norwegian CO_2 emissions occur in electricity production in developing countries, even though Norwegian consumers do not directly purchase electricity from developing countries. Electricity generation in aggregated Germany and chemical production are also very important. Non-metals are important from the production perspective since they are used as an input, in for example, the construction sector. The transportation sectors rank high from both perspectives since transportation is used both directly and to facilitate production. From the consumption

Table 7. The top 10 sectors producing CO_2 emissions instigated from household demand from the production and consumption perspective

	Production		Consumption	
	Percent	Rank	Percent	Rank
DC,Electricity	9.3	1	0.0	–
NO,Land T	6.4	2	6.2	4
NO,Water T	5.1	3	3.8	6
DC,Chemical	3.7	4	0.9	21
DE,Electricity	3.0	5	0.1	100
NO,Air T	2.2	6	1.4	13
NO,Non-met	2.0	7	0.4	35
DC,Ref. Pet.	2.0	8	0.1	95
NO,Ref. Pet.	1.9	9	2.1	10
NO,Fish	1.8	10	0.3	37
NO,Food	1.2	17	8.1	2
NO,Trade	0.9	23	6.9	3
DC,Food	0.6	29	2.3	9
NO,Aux T	0.3	47	2.7	8
NO,Business	0.3	51	8.1	1
DC,Clothing	0.2	60	5.5	5
NO,Hotels	0.2	78	2.9	7

Table 8. The top 10 sectors producing CO_2 emissions instigated from government demand from the production and consumption perspective

	Production		Consumption	
	Percent	Rank	Percent	Rank
DC,Electricity	8.0	1	0.0	–
NO,Land T	6.4	2	2.1	7
NO,Non-met	4.9	3	0.0	40
NO,Water T	4.0	4	0.3	16
NO,Health	4.0	5	25.6	2
NO,Construction	3.9	6	0.0	54
NO,Air T	3.4	7	0.1	20
NO,Chemical	3.2	8	0.9	12
DC,Chemical	3.2	9	1.7	8
DE,Electricity	3.1	10	0.0	–
NO,Public	3.1	11	38.7	1
NO,Education	1.3	19	13.0	3
NO,Trade	0.7	29	1.1	10
NO,Aux T	0.4	49	3.2	6
NO,Members	0.3	51	4.1	4
NO,Business	0.3	57	1.6	9
NO,Recreation	0.1	89	3.6	5

perspective trade and business sectors are important due to a large sales volume. Food and clothing do not rank high from the production perspective since these products are rarely the end-point of production processes.

Overall, the results show that mobility again dominates. The consumption perspective shows that consumption of food, clothing, and business activities must be reduced or different consumption patterns recommended. Due to consumer needs, this may be a difficult option. From the production perspective, it is seen that the emissions are occurring in electricity production, chemicals, and manufacturing sectors, predominately in foreign regions. In the 100 top ranking sectors from the production perspective, 78 occur in foreign regions. This suggests that an alternative way to reduce household environmental impacts is to focus on the production processes in both Norway and abroad. Further, the marginal abatement costs are also likely to be lower in developing countries, for instance, compared to Norway. The results suggest that a holistic environmental policy should focus not only on domestic consumption and production, but also foreign production.

6.2. *Government*

Table 8 shows the top 10 sectors from the consumption and production perspective for the government sector. Again, electricity and chemical production in developing countries and aggregated Germany dominate the impacts from the production perspective. These sectors have small or no impacts from the consumption perspective as they are rarely purchased directly. Owing to the high level of construction activity in the government sectors, the construction and non-metals sectors are considerably higher in the production perspective compared to the consumption perspective. The importance of construction would not be recognized if the results are only considered from the consumption perspective.

Table 9. The top 10 sectors producing CO_2 emissions instigated from the export sectors from the production and consumption perspective

	Production		Consumption	
	Percent	Rank	Percent	Rank
NO,Water T	25.6	1	31.3	1
NO,Oil/gas	21.6	2	26.7	2
NO,Metals	9.2	3	15.5	3
DC,Electricity	4.6	4	0.0	–
NO,Chemical	4.5	5	5.7	4
DE,Metals	3.0	6	0.1	28
NO,Land T	2.1	7	1.6	7
NO,Ref. Pet.	2.0	8	3.0	5
DE,Electricity	1.7	9	0.0	–
NO,Fish	1.4	10	1.5	8
NO,Food	0.4	29	2.2	6
NO,Trade	0.3	33	1.4	10

Mobility is important from both perspectives. From the production perspective, 70 of the top 100 ranking paths occur in foreign regions.

As for households, the results for government expenditure also suggest that the global dimensions of Norwegian consumption need to be considered in environmental policy. Despite only 1% of government expenditure being on imports, over one half of total CO_2 emissions from government expenditure are embodied in imports due to interindustry imports instigated from government expenditure (Table 3).

6.3. Export

Table 9 shows the top 10 sectors from the consumption and production perspective for the export sectors. Water transport, oil and gas, metals, and chemicals are the most important sectors from both perspectives due to high direct emissions in those sectors. Again, electricity production in foreign regions is important even though there are no direct purchases of electricity from foreign regions; the impacts occur due to imports to industry required to produce Norwegian exports. From the production perspective, 75 of the top 100 ranking paths occur in foreign regions.

The importance of imports in the environmental impacts of pollution intensive Norwegian exports is perhaps surprising. The direct emissions from international transportation, oil and gas, and metals manufacturing account for about 50% of the CO_2 emissions. If these emissions are deducted, then the emissions embodied in imports to industry required to produce exports becomes significant. Again, these results suggest that Norwegian environmental policy needs to consider the environmental impacts occurring outside of Norway.

Since Norwegian exports are to meet the demands of foreign consumers, then the policy implications for exports may be different to domestic final demand. Strict environmental policies that lead to reductions in exports will have a strong effect on domestic income (Figure 2), and further, it is likely that the environmental impacts will be lower if production occurs in Norway compared to another region. This raises the question of who should be allocated the emissions from Norwegian exports (for further discussions see Kondo *et al.*, 1998; Munksgaard and Pedersen, 2001; Peters and Hertwich, 2006a).

7. Discussion and Policy Relevance

We applied structural path analysis to the international production chains instigated by the Norwegian economy. By considering household, government, and export final demands separately we were able to highlight the different economic and environmental structures in the Norwegian economy. The Norwegian export industries are pollution intensive, based largely on oil and gas, international shipping, metals, and chemicals. The government sector has a low emission intensity since it is based heavily on providing health, education, and administrative services to households. The household sector has a pollution intensity lying between the government sector and the export industries.

Through the SPA we identified the production paths starting from the Norwegian economy and leading to environmental impacts. We found that a large portion of the environmentally important paths lead into international trade flows. Due to the relatively low pollution intensity of the Norwegian economy the environmental impacts arising in foreign regions, particularly developing countries, was significant. We then used the consumption and production perspectives to determine the accumulated environmental impacts. The consumption perspective identifies the consumer purchases that lead to environmental impacts, while the production perspective identifies which sectors produce the pollution. We considered the production perspective for a given final demand, thereby providing an important link between consumption and production. In terms of SPA, the consumption perspective sums the impacts from the consumer purchases instigating production, while the production perspective sums the impacts from the sectors emitting the pollution irrespective of the instigating sector.

Some previous studies have found SPA too specific to be useful in practice (e.g. Sonis *et al.*, 1997). Our results also suggest that SPA should be used in conjunction with other approaches. For instance, from the production perspective, electricity production in developing countries is clearly dominant; in contrast, the SPA only identities electricity production in very few top-ranking paths. The apparent contradiction appears since the environmental impacts of electricity production in developing countries arise from numerous small contributions and not a few single, but large, contributions. These small paths are often neglected in SPA studies (Treloar *et al.*, 2001; Lenzen, 2002; Norris, 2002) and further it is often infeasible to investigate all possible paths (Sonis *et al.*, 1997). However, by collecting the information on all paths above a given tolerance and sorting appropriately, SPA becomes an invaluable tool to identify the linkages between certain consumption activities and production processes.

A comparison between the consumption and production perspectives highlights the differences between the two approaches (see Tables 7–9). For example, Norway does not import electricity from developing countries; however, final demand purchases initiate production processes and international trade flows which lead to a large use of electricity in developing countries. The pollution from this indirect use of electricity is dominant in the environmental impacts of Norway. Another interesting example is air travel. Only one-third of air transport in Norway is purchased directly in final demand; the remaining two-thirds of air travel is purchased through production processes instigated by final demand purchases. The SPA identifies 'business trips' as a significant user of air travel. In this way, the different approaches provide complementary information.

In terms of sustainable consumption and production policy, the three different approaches identify different sectors as environmentally important. The consumption perspective determines the aggregated impacts of consumption activities, such as the aggregated impact of the oil and gas industry in Norway or the aggregated impacts of households (see also Hertwich, 2005). This approach is useful for some types of analysis, but may shift the emphasis to the wrong areas. For instance, the consumption perspective may identify essential products and services, such as food, shelter, education, and health, as environmentally damaging. Substitution away from these items may not be possible, but substitution in the production network away from polluting production methods may be possible. In this situation, the production perspective may be more appropriate.

The production perspective is better suited to identifying the aggregated environmental impacts of different production processes. In this study we have regularly identified electricity production with coal as environmentally significant. Further, it is the aggregated impacts of numerous small inputs of electricity in the entire production chain that lead to the large environmental impacts. Thus, if policy focuses on the polluting sectors that are significant in most production networks, then this will have an affect on most consumption activities and any costs will be propagated through the production network. Ultimately, it is the consumer that will pay, but the costs occur further upstream in the production network.[7]

Perhaps the biggest challenge with the production perspective is that a significant share of the environmental impacts occurs externally to the country of consumption. Our results continually highlighted the importance of international trade linkages instigated by Norwegian consumption. In terms of policy, these results suggest that domestic environmental policy needs to consider the global dimensions of consumption and production. Further, abatement costs are generally lower in developing countries compared to developed countries. However, due to limited political jurisdiction it is likely to be difficult for domestic policy to act across political boundaries without a more global policy framework. Some authors have attempted to address this issue by using different methods of allocating emissions to countries (see articles by Kondo *et al*., 1998; Munksgaard and Pedersen, 2001; Peters and Hertwich, 2006a).

8. Conclusion

In summary, our results show that the three different approaches are complementary, both in terms of analysis and policy. The consumption perspective identifies consumption patterns that lead to high environmental impacts. The production perspective identifies the production processes that lead to the greatest environmental impacts for a given consumption bundle. The SPA is a useful tool to show the linkages between consumption and production. Through the use of a multiregional input–output model we were also able to highlight the importance of trade linkages using these methods. The calculations show that the trade flows instigated by the Norwegian economy lead to considerable environmental impacts. The global nature of the environmental impacts offers additional challenges to policy.

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Notes

[1]Authors own calculations based on Table 3 in Ahmad and Wyckoff (2003).

[2]This approach is unique to Norway, but as of 2001 Statistics Norway distributes the margins in the **A** matrix as for most other countries.

[3]These numbers differ slightly from the official publications since we have internalized capital.

[4]The results for households have been analyzed to some extent in Peters and Hertwich (2006b) and so only a brief review of the main conclusions are given here.

[5]Note that the chemicals sector includes chemicals used in the household; paint, detergent, fertilizers, pesticides, personal care products, and so on.

[6]Suh (2004) used similar techniques, although a different terminology. Our production perspective is the same as 'output contribution analysis'. The consumption perspective is similar to 'input contribution analysis', but operating at a different tier. We use a different terminology to reflect the policy relevance of consumption and production.

[7]Gallego and Lenzen (2005) discuss a method of combining consumer and producer responsibility.

[8]It is possible to code the algorithm without recording the path. This will save storage space but will increase complexity as a series of pointers are required to scan backwards through the tree structure to obtain the path.

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Appendix A. The SPA Algorithm

The general concept of the algorithm we use is to construct a tree data structure as in Figure 1(b). Our method is to first recursively construct the tree structure and then later read the tree by 'de-constructing' it. This type of data structure and method is regularly used in computer science and is well described in most textbooks on data structures and algorithms.

Each node in the tree contains both the path and the path's contribution to environmental impacts given by equations (5)–(7), and so on for higher tiers. In practice it is not possible to evaluate the infinite number of nodes in the tree (see Treloar, 1997; Treloar *et al.*, 2001). To avoid total enumeration of the tree we calculate the contribution of each sub-tree below a given node. If the contribution is greater than a given tolerance, then we construct a new layer below that node. As a result the tree has varying depths depending on the contribution from each node, see Figure 3.

We use pseudocode to describe each of the functions in our SPA algorithms. The pseudocode gives enough detail to allow implementation in a wide range of programming languages. Most of the functions require inputs of $\mathbf{F}$, $\mathbf{A}$, and $\mathbf{y}$ from the input–output data. Many of the algorithms also require the total impacts for an arbitrary demand,

$$\mathbf{F}_{total} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1} \tag{A1}$$

For large systems it can be time-consuming to calculate $\mathbf{F}_{total}$ (Peters, 2005) so it is best to calculate it once, store it, and then use it as an input into the various functions. We use Z to represent the paths leading to an impact. For example, the path $i \rightarrow j \rightarrow k$ is represented by $Z = [i,j,k]$ and the environmental impacts are given by – see equation (7) – $f_{pk}a_{kj}\, a_{ji}\, y_i$. The consumer purchases from sector i, which instigates a flow through sector j, to production and ultimately pollution (of type p) in sector k. In the following sections we describe each of the elements required to perform the SPA.

Contribution of the Node

Each node in the data structure stores the contribution from that node as given by equations (5)–(7), and so on for higher tiers. The value of the node can be constructed recursively as in Algorithm 1. In Algorithm 1, $Z[t]$ refers to element t in the array Z and LENGTH(Z) gives the number of elements in Z.

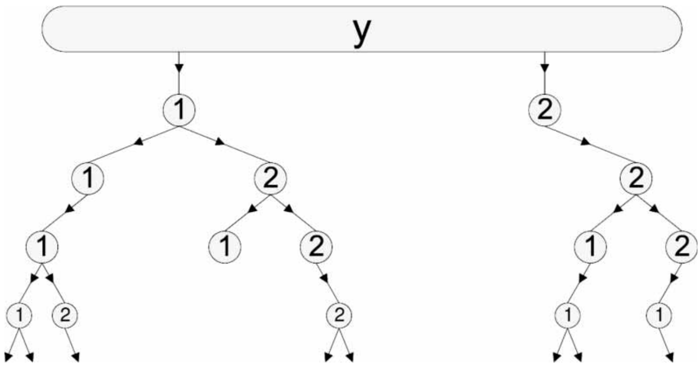

Figure 3. The irregular structure of the tree due to the varying depths that the algorithm penetrates searching for the most significant paths

Algorithm 1: CONTRIBUTION_NODE(**F**, **A**, **y**, Z)
$\tau = \text{LENGTH}(Z)$

$node_Z \leftarrow \mathbf{y}(Z[1])$
for $t \leftarrow 2$ **to** τ
    $node_Z \leftarrow node_Z * \mathbf{A}(Z[t], Z[t-1])$
end
return $\mathbf{F}(Z[\tau]) * node_Z$

Contribution of the Sub-tree

To 'prune' the tree at different levels requires calculation of the impacts in each sub-tree. This is conceptually similar to Algorithm 1, but calculates the contribution from the total sub-tree originating at the node, rather than the contribution of the node alone. This is presented in Algorithm 2. Algorithm 2 first constructs the demand vector at the node, $\mathbf{y}_Z$, and then uses $\mathbf{F}_{total}$ to calculate the direct and indirect impacts in the sub-tree below the node. There is some redundancy between Algorithms 1 and 2, which can be exploited when constructing the tree in Algorithm 3. This redundancy has not been exploited here to enhance clarity.

Algorithm 2: CONTRIBUTION_SUBTREE(**F**, **A**, **y**, $\mathbf{F}_{total}$, Z)
$\tau = \text{LENGTH}(Z)$

$node_Z \leftarrow \mathbf{y}(Z[1])$
for $t \leftarrow 2$ **to** τ
    $node_Z \leftarrow node_Z * \mathbf{A}(Z[t], Z[t-1])$
end
$\mathbf{y}_Z(Z[\tau]) \leftarrow node_Z$ All other elements of $\mathbf{y}_Z$ are zero
return $\mathbf{F}_{total} * \mathbf{y}_Z$

Constructing the Tree

There are many possible algorithms for constructing the tree structure (see Lenzen, 2003). In this article we have chosen a recursive algorithm that searches depth-wise until a maximum depth is reached, T_{max}, or until the contribution from the remaining sub-tree is below a given tolerance, *tol*; see Algorithm 3. Depending on the application, other strategies might be applied; for instance, Strømman (2005) choose a method based on searching the sub-tree with the largest contribution.

The different tree pruning methodologies may give different solutions and lead to different computational times. We have chosen a conservative approach that calculates the environmental impact in the entire sub-tree below a given node. This is the most correct approach, but it will follow many paths with small overall impacts. The algorithm can be sped up by increasing the tolerance, *tol*. Alternatively, less conservative approaches can be used that do not calculate the environmental impacts from the entire sub-tree, but rather from the first one or two tiers below a given node. These approaches may reduce computational times, but may also miss some important contributions that occur in lower tiers.

In Algorithm 3, the data structure *tree* contains the contribution of the node *tree.node*, the path leading to that node[8] *tree.Z*, and an array of pointers to the next *n* sub-trees *tree.next*. We denote a null pointer by *0* in the algorithm. In the algorithm we have assumed that pointers can be implemented in the computer language chosen.

Algorithm 3: CONSTRUCT_TREE ($\mathbf{F}$, $\mathbf{A}$, $\mathbf{y}$, $\mathbf{F}_{total}$, T, T_{max}, *tol*, Z)

```
if T = T_max
    Construct the final node
    tree.Z ← Z
    tree.node ← CONTRIBUTION_NODE(F, A, y, Z)
    for i ← 1 to LENGTH(y)
      tree.next ← 0
    end
else
    Add a new sub-tree
    tree.Z ← Z
    tree.node ← CONTRIBUTION_NODE(F, A, y, Z)
    for i ← 1 to LENGTH(y)
      Z ← [Z,i]
      if CONTRIBUTION_SUBTREE(F, A, y, F_total, Z) < tol
        Sub-tree is negligible
        tree.next ← 0
      else
        Recursively build a new sub-tree
        tree.next ← COSTRUCT_TREE (F, A, y, F_total, T + 1, T_max, tol, Z)
      end
    end
end
return (tree)
```

Reading the Tree

Once the tree has been constructed it is simply a case of reading the data from the tree into a useable format. This is easily performed by recursively scanning all the nodes in the tree and retrieving the path and contribution from each node, see Algorithm 4. This algorithm stores the path and contribution from each path in a global array, *paths*.

Algorithm 4: READ_TREE (*tree*, $\mathbf{y}$)
  for $i \leftarrow 1$ **to** LENGTH($\mathbf{y}$)
    if $tree \neq 0$
      $next.node \leftarrow tree.node$
      $next.Z \leftarrow tree.Z$
      $paths \leftarrow [paths, next]$
      READ_TREE (*tree*, $\mathbf{y}$)
    end
end
return *(paths)*

Putting it Together

Once the tree has been constructed and the information read into the array *paths*, then the data are ready for analysis. In our analysis we sorted the paths in terms of their contribution. This sorting algorithm is not shown here as it is well covered in any textbook on computer algorithms. The final data can then be formatted and displayed as required. The SPA can then be performed as in Algorithm 5.

Algorithm 5: SPA ($\mathbf{F}$, $\mathbf{A}$, $\mathbf{y}$, T_{max}, *tol*)
$\mathbf{F}_{total} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}$
tree = CONSTRUCT_TREE ($\mathbf{F}$, $\mathbf{A}$, $\mathbf{y}$, $\mathbf{F}_{total}$, T, T_{max}, *tol*, Z)
paths = READ_TREE (*tree*, $\mathbf{y}$)
paths = SORT_PATHS (*paths*)
PRINT_PATHS (*paths*)

An important part of any algorithm is computation times. Computation times are reduced significantly by calculating $\mathbf{F}_{total}$ in advance and then storing it for later use (Peters, 2005). In many cases we exploit sparse matrix algebra to save computation times and memory usage. The most computationally demanding part of the algorithm is CONTRIBUTION_SUBTREE since it is called up to n^{t+1} times, depending on the number of cut-off sub-trees. There is a possibility to combine CONTRIBUTION_SUBTREE and CONTRIBUTION_NODE due to similar structures but this has not been pursued here to enhance clarity.

We programmed the algorithms using Matlab version 7. The Matlab programming language is not designed for using dynamic data structures and we had to employ inefficient code to represent null pointers. For our sparse system with 392 sectors computation times took from minutes to tens of minutes depending on the number of paths. For a 3200 sector LCA system (data from Strømman *et al*., 2006) computation times were around two hours for nine tiers. These times could be reduced somewhat by using a programming language designed for dynamic data structures such as C.

Appendix B. Classification Schemes

Statistical Classification of Economic Activities in the European Community (modified NACE REV.1)

01	Agric	Agriculture, hunting and related service activities
02	Forestry	Forestry, logging and related service activities
05	Fish	Fishing, operation of fish hatcheries and fish farms; service activities incidental to fishing
10	Coal	Mining of coal and lignite; extraction of peat
11	Oil/gas	Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction excluding surveying
13	Mining	Mining of metal ores
14	Quarry	Other mining and quarrying
15	Food	Manufacture of food products and beverages
16	Tobacco	Manufacture of tobacco products
17	Textiles	Manufacture of textiles
18	Clothing	Manufacture of wearing apparel; dressing and dyeing of fur
19	Leather	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear
20	Wood	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
21	Paper	Manufacture of pulp, paper and paper products
22	Printing	Publishing, printing and reproduction of recorded media
23	Ref. Pet.	Manufacture of coke, refined petroleum products and nuclear fuel
24	Chemical	Manufacture of chemicals and chemical products
25	Rubber	Manufacture of rubber and plastic products
26	Non-met	Manufacture of other non-metallic mineral products
27	Metals	Manufacture of basic metals
28	Fab. Met.	Manufacture of fabricated metal products, except machinery and equipment
29	Machinery	Manufacture of machinery and equipment n.e.c.
30	Computers	Manufacture of office machinery and computers
31	Electrical	Manufacture of electrical machinery and apparatus n.e.c.
32	Communic.	Manufacture of radio, television and communication equipment and apparatus
33	Optical	Manufacture of medical, precision and optical instruments, watches and clocks
34	Cars	Manufacture of motor vehicles, trailers and semi-trailers
35	Tran. Eq.	Manufacture of other transport equipment
36	Furniture	Manufacture of furniture; manufacturing n.e.c.
37	Recycling	Recycling
40	Electricity	Electricity, gas, steam and hot water supply
41	Water	Collection, purification and distribution of water
45	Construction	Construction
50–52	Trade	Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods
55	Hotels	Hotels and restaurants
60	Land T	Land transport; transport via pipelines
61	Water T	Water transport
62	Air T	Air transport
63	Aux T	Supporting and auxiliary transport activities; activities of travel agencies
64	Post	Post and telecommunications

(*Table continued*)

Appendix B. Continued

65–67	Financial	Financial intermediation
70–74	Business	Real estate, renting and business activities
75	Public	Public administration and defence; compulsory social security
80	Education	Education
85	Health	Health and social work
90	Sewerage	Sewerage and refuse disposal, sanitation and similar activities
91	Members	Activities of membership organization n.e.c.
92	Recreation	Recreational, cultural and sporting activities
93	Other	Other service activities