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Greenhouse gas emissions and material flows

PART I: Analysis of the literature

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The approach, results and conclusions of the entire project can be found in the summary report *Greenhouse gas emission reduction and material flows. Final report*, edited by Institut Wallon.

The detailed results of the research of Vito are written down in three reports:

- *Greenhouse gas emissions and material flows. Part I: Analysis of the literature.*
- *Greenhouse gas emissions and material flows. Part II: Production and use of beverage packaging.*
- *Greenhouse gas emissions and material flows. Part III. Materials used for packaging and building: plastics, paper and cardboard, aluminium.*

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0 EXECUTIVE SUMMARY

This report is a result of the research project *Greenhouse gas emissions and material flows*, a joint project of Institut Wallon, Institut pour un Développement Durable and Vito, co-ordinated by Institut Wallon. The approach, results and conclusions of the entire project can be found in the summary report *Greenhouse gas emission reduction and material flows. Final report*, edited by Institut Wallon.

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In this report the recent literature dealing with material flows and greenhouse gas emissions is analysed. The starting points of the research on *Material Flows and Greenhouse Gas Emissions* were kept in mind: the life cycle approach, the final consumer perspective, the focus on specific emissions or impacts (in this case greenhouse gas emissions), the dynamic approach, the link with political decision-making, hence the inclusion of cost aspects, and finally, the focus on Belgium.

A short overview is given of different types of material flow studies. Two studies dealing specifically with material flows and greenhouse gas emissions were analysed in more detail.

Some conclusions could be drawn on the relation between material flow analyses and the study of specific emission or impacts over the entire life cycle of specific products:

The system boundaries used for evaluating material flows are not always consistent with a life cycle perspective. Many material flow studies leave out the use phase of the products and their post-use treatment. The distinction between material flows related to production or to consumption is not always clear either.

Many of the material flows studies (sometimes implicitly) have the objective of looking at ways of diminishing environmental impacts related to production and/or consumption patterns. However, many of them do not consider environmental impacts explicitly.

Specific material flow analyses can be helpful in identifying the importance of the flows. They can give an idea of the relation between the final consumption of specific materials (in products) and the domestic production system for these materials. They can also be helpful in quantifying the magnitude of actual and future flows, waste flows and the import and export flows of specific materials. However, when assessing life cycle impacts related to the consumption of specific products, material flows analyses are not an end in their own right.

Two comprehensive efforts to link material flows to greenhouse gas emissions are the MATTER-BRED project and the work done at FhG-ISI by Patel *et al*. They conclude that there is a potential for reduction of greenhouse gas emissions through materials strategies. However, some of these strategies only become cost-effective when high greenhouse gas emission taxes are applied.

For evaluating emissions two different perspectives can be taken:

- a *life cycle emissions from end use perspective,* in which the life cycle emissions related to the end use of specific products (functions) within a specified region are studied;
- a *direct emissions from processes perspective* in which the impacts caused by the transformation and end use processes within a specified region are studied.

Both perspectives are valuable and sensible. However, for open economies they lead to large differences in system boundaries.
In an open economy changes in consumer choices do not necessarily lead to changes in production in the country itself. Equally so, changes in production are not only determined by changes in consumption within the system, but also by demand on external markets.

The evaluation of both *life cycle emissions from end use* and *actual emissions from processes* within one comprehensive and unique model was possible in the MATTER study because Western Europe was considered as a relatively closed economy.
However, the Belgian economy is extremely open. Moreover, the focus in our study is on specific end uses (packaging, housing, livestock products). Hence, the model does not represent the entire economy, and becomes even more 'open'.

It was concluded that the development of a comprehensive Belgian energy and materials model is not useful for our purposes. Specific approaches had to be developed for each of the product groups studied in this project.

1 INTRODUCTION

This part of the report gives an outline of the literature on greenhouse gas emissions and material flows and puts the study on Material Flows and Greenhouse Gas Emissions in a larger perspective. The purpose is not to be exhaustive, but rather to draw practical conclusions for analysing greenhouse gas emissions related to Belgian material flows.

For an overview and an evaluation of the existing literature on material flows the following basic issues for the study on Material Flows and Greenhouse Gas Emissions will be kept in mind:

- life cycle approach (or chain analysis approach): to avoid problem shifting within the chain, to look for the most efficient improvement options in the entire chain, to look at the global impact of consumer choices;
- final consumer perspective: energy and material flows have to be linked to consumption, to final demand, hence to functions; changes in final demand are also considered;
- emissions, impacts: the goal of the study is not to analyse material flows as such, but the possible (reduction of) impacts that can be associated to (changes in) material use;
- assist in political decision-making: for political decision-making, a crucial question is always: how to use the scarce resources in the most effective way? which actions have the highest positive effect at the lowest (financial and social) cost? different improvement options have to be compared; this calls for an optimisation approach;
- taking into account the evolution in technology and demand calls for a dynamic approach;
- finally, the focus is on Belgium; hence, the previous questions have to be answered at the Belgian level.

2 MATERIAL FLOWS STUDIES

2.1 Overview and definitions

Several tools have been developed for the analysis of energy and material flows or the chain analysis of products: substance flow analysis (SFA), material flows analysis or material flows accounting (MFA), life cycle analysis (LCA), energy system analysis, combined energy and material system analysis, input/output analysis.
In some analyses quantification of material use or material flows is an end in itself. In others it is a step in the assessment of environmental impacts related to material use.

This field of study has also been grouped under the heading ‘industrial ecology’: *the analysis of energy and material flows through the economy to define strategies to improve the efficiency and decrease the impact of materials and energy use*.[i]
Patel justifies the interest in industrial ecology and in material flow studies by the fact that *industry in OECD countries accounts for 33 % of total energy use in primary energy terms. Of this, approximately 72 % is related to basic industry, i.e. materials production only*. Hence, more efficient production, use and waste management of materials will lead to a decrease in energy demand and in environmental impacts.

According to Van der Voet[ii] the above mentioned tools have in common that they envisage an *integrated chain management*: the basic idea is to make economic material chains *from cradle to grave* the subject of policies. Pollution can be traced to its causes and finally linked to the use of resources, thus the question of responsibility can be addressed more adequately. When analysing abatement strategies, focusing on the integrated chain offers openings to spot various mechanisms of problem shifting. In addition, chain analysis can reveal improvement options that remain unnoticed when only looking at the final product.

However, there are also several differences related to e.g. the objectives, the scope or the system boundaries, which makes some tools more apt to respond to specific questions than others.

Material flow analysis has gained interest in European and national research efforts. Methods for analysing material flows have been developed through the EUROSTAT Project *Material Flow Accounts of Selected Products and Substances Harmful to the Environment*[iii], carried out by the Wuppertal Institute, and through the ConAccount Network.
Until now, except for some work done at Vito, especially on substance flow analysis of aluminium, cadmium, chromium and nitrogen (see §2.4), an inventory of nitrogen and phosphorus flows in Flanders by the University of Gent[iv] and the actual OSTC project on Greenhouse gas emissions and Material Flows, carried out by Institut Wallon, Vito and IDD, no references were found of Belgian research centres working on material flows, and in linking them up to environmental effects in general or greenhouse gas emissions more specifically.

The ConAccount network (*Coordination of Regional and National Material Flow Accounting for Environmental Sustainability*) was started in May 1996 (coordinated by the Wuppertal Institute for Climate, Environment and Energy). It functioned as an international platform for discussions on Material Flow Accounting (MFA).

One of the objectives of the ConAccount network was to provide the basis for the development of a coherent framework of MFA methodology, and to define the future needs for research and development for policy relevant MFA tools that foster decision making towards sustainability. *It seemed necessary to make the methodological ties between the concepts and the results most transparent, and to clarify the reasons for the similarities and differences of the various MFA approaches.*[v]
An *Inventory of MFA Activities* has been established and four ConAccount workshops were organised[vi], the last in April 2001. Next to many practical accounting exercises, discussions focused on issues of system definitions and boundaries, the relation between MFA and other tools and on the policy relevance of MFA.

MFA, as defined by ConAccount, refers to accounts in physical units (usually in terms of tons) comprising the extraction, production, transformation, consumption, recycling, and disposal of materials (e.g. substances, raw materials, base materials, products, manufactures, wastes, emissions to air or water). It covers approaches such as substance flow analysis, product flow accounts, material balancing, and bulk material flow accounts.
ConAccount restricted its activities to studies of (supra-)national and regional scope, thus leaving out product LCA.

This definition and the need for developing a common framework already indicates that the field is diverse and still in development. However, some lines can be drawn.

2.2 Total materials use

One of the problems when trying to get an overview of the field designated as MFA, is the confusing use that is made of the term ‘materials’. The term ‘material flows’ is used for different type of flows.
One group of studies focuses on the quantification of the total direct and indirect material inputs of an economy. The term ‘material’ in this case refers to raw materials or primary resources (including energy carriers), rather than to materials ready for processing (such as plastics, steel, cement, …).
In the methodology originally developed by the Wuppertal Institute, the Direct Material Input (DMI) of an economy is defined as the flow of natural resource commodities that enter the industrial economy for further processing. Hidden Material Flows are defined as the portion of the total material requirement that never enters the economy. It is the natural resources use that occurs when providing those commodities that do enter the economy. The Total Material Requirement (TMR) is the sum of the total material input and the hidden or indirect material flows.[1] It is the total material requirement for a national economy, including all domestic and imported natural resources (besides water and air).[iii, vii]

The Federal Statistical Office of Germany has established the first physical input-output table (PIOT) for West Germany in 1990. The European Environmental Agency (EEA) is

[1] The data on domestic material requirement are provided by statistics on industrial production, agriculture, forestry and fisheries. The physical data on imports are provided by foreign trade statistics. Imports are grouped into raw materials, semi-manufactured products and final products. The semi-manufactured products are classified according to their main constituent (e.g. steel, aluminium) and combined with data on cumulative material requirements. The final products are only accounted for by their own weight.

stimulating the use of material flow accounts as indicators of progress towards sustainability.[viii]

Thus, TMR accounts for global material requirements, including energy carriers and non-energy materials. It is a highly aggregated indicator, whereby all resource flows are aggregated in tonnes. It is used to calculate an overall Material Intensity Index (TMR/GDP) or a Direct Materials Input Intensity Index (DMI/GDP).

The TMR has been calculated for a few European countries (Germany, the Netherlands, Finland, and Poland), the United States and Japan,[vii, ix] and recently for the European Union as a whole.[viii]
In a similar way the TMR of specific sectors have been analysed (e.g. for metal material flows in Finland[x]).

The use of the term materials is a bit confusing in this context. Normally, it is not only materials as such, but rather all natural resources that are quantified. What is meant by metal material flows in the paper of Juutinen and Viitanen[x] is quite different from the analyses of material flows (e.g. plastic flows) mentioned in the following paragraph (§2.3).

In this type of analysis the implicit assumption is that all material flows are carriers of environmental burdens and that any decrease in materials use is a step towards sustainability.
Total materials use as such is used as an indicator for environmental impacts and as an indicator of sustainability. In fact, this type of analysis can be interpreted as a kind of life cycle impacts assessment in which raw materials use is used as the sole indicator of environmental impacts. However, it can be doubted if this aggregated physical weight of all material inputs is always a good indicator for environmental impacts or for progress towards sustainability.

Moreover, TMR and DMI are not related to specific functions or to the consumption of a specific country or region. They comprise all primary resources required for the production side of an economy. A decrease in TMR/GDP for a given economy can well be caused by a (relative) shift in the economy to production of products with a high added value compared to a low material input (e.g. production of advanced communication technology), whereas low technology commodities are imported. The overall environmental burden will not have changed.

Besides this indicator function, a quantification of total material use does not give any information on which practical choices to make to reduce environmental impacts.

A similar concept is the Materials Intensity per Unit of Service (MIPS). In this case the materials use is related to a specific service or function.

2.3 Specific material flows

At a more detailed level, analyses are carried out of specific material flows. In this case the material is a *commodity produced by industry*[i] or a *base material* (e.g. plastics, steel).

In these cases the link between the material flows and eventual environmental impacts is so ambiguous that no practical conclusions can be based upon the magnitude of the material flows as such. To assess the environmental relevance, these flows have to be translated into emissions or impacts (e.g. linking steel flows to specific life cycle emissions during steel production), and these will depend on the processes used to transform the flows into final products. Furthermore, life cycle impacts depend on the actual use and post-use treatment of the final products for which the materials are used.

The flows of specific materials in a specific economy (e.g. plastics in Germany) are quantified in their different forms (e.g. primary plastics, plastic intermediates, plastic products, waste plastic). At each stage of the life cycle imports and exports can occur, and they have to be accounted for.
Problems arise when trying to find data on materials embedded in products in the form of components (e.g. the use of plastics in cars). A similar problem arises with packaging. The use of packaging by the industry is not final but intermediate use. In order to complete the flows of the considered material, ways have to be found to account for these materials embedded in products. Methods have been developed to estimate the material flows related to components and packaging and to relate them to final use (e.g. the STREAMS method developed by Joosten *et al*[xi]; the study on C streams of Patel *et al*.[i,xii]). This is especially useful when quantifying waste streams.

The STREAMS method, developed in the Netherlands, quantifies specific material flows starting from final consumption. As such it goes further than some other specific material flow analyses that stop at the production stage. It also proposes solutions for quantifying materials in packaging and components and materials embedded in products.[2]
Economic supply and use tables are used to calculate the amount of materials that enter the final stage of consumption. These tables are compiled annually by the national statistics office of a number of countries (e.g. the Netherlands, Germany). The method was used to quantify plastic flows and paper and wood flows.[xiii, xiv]

The possibility of deriving results highly depends on the aggregation level of the supply and use tables. If the aggregation level is too high the core materials and products become part of wide groups of goods. This is the case for Belgium. Moreover, in Belgium economic input-output tables are compiled only once every 5 years. The one for 1995 is actually not yet available.
The methodology includes the conversion of monetary data into physical data. The authors acknowledge that this conversion is a critical step. Statistics Netherlands has made an effort to construct physical supply and use tables for the Netherlands for some material flows. However, because a lot of work is involved in constructing these tables, it is very unlikely that they will become available for many materials and products, for many years and for many countries.

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[2] For each industry the purpose of the input of core materials and products is estimated and divided between packaging, components and final products. This estimate is based on the industry's supply of goods and general knowledge on packaging practices and product compositions. Subsequently packaging and components have to be allocated to the supply of materials and products and finally to the users of these materials and products.

Imported goods are assumed to be comparable to domestically produced goods, with regard to prices, composition and packaging method. The same assumption is made for exported goods. This is a very bold assumption, as shown by the example the authors give themselves of materials or products that are not manufactured in the Netherlands.

Patel *et al* have calculated the flows of plastics through the German economy. A specific question, which they address, is the assessment of future waste streams associated to today's consumption of plastics. (see also §0) They use the analysis of material flows as input in waste treatment scenarios.

2.4 Substance flow analysis

Substance flow analyses (SFA) focus on flows of one specific substance (often one element, such as Cd, N, P) or group of substances.[ii] The ConAccount proceedings contain several examples. At the recent workshop 'Economic growth, material flows and environmental pressure', 26 - 27 April in Stockholm also several papers were presented.
In Belgium Vito is developing a model for substance flow analysis and applying it to the problems of heavy metals and nutrients (Cd, Cr, N) in Flanders.

In the case of substance flow analysis the link between the studied substance and the potential impact (e.g. eco- and human toxicity of heavy metals, eutrophication caused by the inflow of nutrients (N and P), the release of CO_2 or CH_4 from C-containing materials, products or energy carriers) is stronger than for the other types of material flow studies. Substances are analysed because they are considered to be inherently dangerous or harmful and their proliferation into the economy or the environment has to be monitored or avoided. Sometimes substances are not harmful as such but there is a strong risk that the substance turns into an undesired emission into the environment (e.g. C). Thus, SFA provides relevant information for a region's management strategy regarding specific pollutants.

2.5 Conclusions

All three types of studies mentioned above have in common that they do not look at environmental impacts directly. For the study of specific impacts or emissions the analysis of material flows or substance flows is not an end in itself but serves the end of determining specific emissions or impacts, or strategies to avoid specific flows that are considered inherently harmful.

Material flows studies often are confined to territorial boundaries: the material flows induced by all the (production and consumption) processes in a country are studied. Most claim a life cycle perspective, but in practice few of them link the material flows to specific functions or to final consumption.

3 LIFE CYCLE ANALYSIS

A life cycle impact inventory is straightforward, and is a useful tool when inventorying the potential environmental impacts related to specific products or functions. Life cycle analysis (LCA) is often used to identify the improvement potential in the product system for a specific product. It is also used to compare several competing products or processes potentially fulfilling the same function. As such it is used by companies for decisions on which products to develop or use, and by policy makers for decisions on product policies (e.g. as a basis for discriminating taxes).

However, LCA lacks the dynamics and the costs analysis that are necessary for policy making and decision taking. An analysis of LCA for policy making can be found in a recent study of Wollny and Schmied[xv]. They compare 10 different studies on plastics recovery options. They conclude that "LCA studies for policy decision-making have to find methods in order to analyse cross-effects" and "waste management policy might be more effective if it is supported by a policy assessment using scenario techniques, change assessments and LCA-elements". To assess the total effect of specific policy measures that aim at changing production or consumption patterns, the results of LCAs have to be completed with analyses of the total technical, sociological and economic potential of these changes.

Moreover, normally, LCA is not bounded in space. The product system cuts across geographical boundaries. Results of a life cycle assessment can be hard to translate to regional or national policies because parts of the life cycle take place outside the territorial boundaries. Where the (improvement in the) process and its impacts take place, is not analysed in a life cycle assessment, but it is of interest for a policy maker.

4 MATERIAL FLOWS AND GREENHOUSE GAS EMISSIONS

4.1 The analysis of carbon flows

Patel *et al* [i,xii] studied fossil carbon use for materials in Germany. They look at how much the production and waste management of synthetic organic materials contribute to the release of CO_2 emissions and to what extent these emissions could be reduced in the short term by improved material management, including recycling, re-use, energy recovery and the use of bio-based resources and feedstock. They want to answer these questions for Germany.
They use a material flow simulation model, based on detailed input-output tables of chemical raw materials, intermediate and final products, to describe the production and foreign trade of plastics products, their use and their residence times in the economy, and finally to calculate the present and future volumes of waste. This is then used for an analysis of plastics recycling in Germany and CO_2 savings potentials related to carbon use for synthetic materials. They also analysed the production and use of surfactants in Germany and the CO_2 emission reduction by surfactant substitution.

Material flows are analysed up to the level of final products. Alternatives for plastics use at the level of final use are not considered. Neither is energy use during the use phase of plastic products.
The model uses mixed boundaries "reflecting the German situation". Whereas the flows analysis refers to production and use in Germany, and import and exports form Germany, CO_2 emissions are calculated during the entire process chain, starting with the extraction of resources and ending with the saleable material ('cradle-to-factory gate'), which means that part of the CO_2 emissions and the related improvement potential will be realised outside Germany. In terms of technology, production is modelled in Western Europe in the mid 1990s. As far feedstock use for ethylene production and ammonia production and the ratio 'high severity' versus 'low severity' cracking are concerned the calculations refer to the production in Germany in 1995.
The authors estimate that 60-80 % of the improvement potential will be realized in Germany. It is not clear however how they arrive at this conclusion.

4.2 Energy and materials system modelling (MATTER MARKAL)

Gielen[xvi] looks at the existing environmental systems analysis methods, among which material flows studies, and puts them into four groups:

1. Static energy analysis, life cycle analysis and material flow analysis of individual materials and products
2. Static integrated energy and material system analysis
3. Static economic input/output systems analysis
4. Dynamic energy systems analysis

He concludes that the requirement for dynamic modelling over a period of decades, taking technological change, changing demand and changing environmental policy goals into consideration, is problematic for existing environmental systems analysis tools such as energy analysis, LCA, MFA, Input/Output models and waste management models.

In the MATTER project, a joint project of 5 Dutch research institutes, co-ordinated by ECN in the framework of the National Research Programme on Global Air Pollution and Climate Change[xvii] a comprehensive West European materials and energy system model (MATTER MARKAL) in which a life cycle approach is combined with an energy system cost optimisation model (MARKAL, see), was developed.

The integrated energy and materials model is used to extend the analysis of greenhouse gas emissions mitigation to substitution between production processes and/or materials. The materials system includes industrial processes, products use and waste treatment (collection, disposal, recycling and energy recovery).
The model allowed estimating the potential contribution of materials strategies to reduction of greenhouse gas emissions. It was concluded that approximately one third of all greenhouse gas emissions could be attributed to the materials system. Changes in material flows can influence the greenhouse gas emissions significantly. By including the materials system, more cost-effective greenhouse gas reduction strategies could be identified than in the case where only improvements in the energy system are considered.[xvi]

More recently, in the context of the BRED (Biomass for Greenhouse Gas Emission Reduction) project[xviii], the MATTER MARKAL model was extended with a detailed agriculture and biomass module that allowed the analysis of biomass (bio-energy and bio-materials) strategies for greenhouse gas reduction[3]. The input and output data of the MATTER 4.2 MARKAL model are available on the MATTER web site[xvii].

The MATTER MARKAL model allows analyses at two levels:
- For the economy as a whole the effect of greenhouse gas taxes on the overall energy and materials system and on the resulting greenhouse gas emissions can be analysed.
- The comprehensive energy and materials model can be used to focus on specific sectors, functions, products or materials within it (e.g. petrochemicals[xix], biomass[xviii]). The specific outcomes are the result of the optimisation of the entire system.

The MARKAL energy and material flows model has some clear strong points:
- The dynamic nature of the model allows taking into account changing energy and product service demand, resource availability and resource prices, new technologies and changing technology characteristics, assessing (long term) improvement potentials and taking into account the time lag between production and disposal.
- Optimisation of the entire system allows selecting the most cost-effective technologies as a function of constraints, comparing improvement options in different sectors and analysing interactions between changes in the energy system and changes in the materials system. Recycling and reuse are integrated in the entire system. Outcomes (costs, emissions) are given for the entire system, thus no allocation problems arise.[4]
- Finally, costs are taken into account in evaluating emission reduction options.

[3] The actual MATTER 4.2 MARKAL model is the result of 20 man-years of work in the context of the MATTER project, and 12,5 more man-years in the context of the BRED project. Next to the input data for 35 technologies producing electricity and heat and 50 energy carriers, it contains the input data for 788 processes producing other than electricity or heat, 295 end use technologies, 150 materials, more than 100 products and 30 categories of waste materials.
[4] Multiple inputs and outputs, costs and benefits of recycling, reuse or energy recovery

However, some critical remarks can be made.
Some of the above-mentioned theoretical advantages are no longer valid in an open economic system, or in a system that does not represent the entire economy of a region or country (mainly because the assumption that the productive system changes according to (changes in) the demand is no longer valid).

System boundaries for the MATTER MARKAL model were chosen on the basis of the end use of products[5]. In the model it is implicitly assumed that the demand within the system (the end use) is to a large extent fulfilled by supply by the system. The closed character of the West-European economy[6] justifies this assumption. The geographical and the functional system boundaries (see also §5.2) do more or less coincide. Conclusions drawn from the life cycle perspective (e.g. potential greenhouse gas emission reductions) can roughly be allocated to the West-European transformation system and be compared to the West-European greenhouse gas reduction targets.[7]

Gielen acknowledges that "because of the political change in eastern Europe, the materials trade between Eastern and Western Europe will significantly increase over the next few decades. At the present time however, the importance of this is still rather limited." Considering the 50 years time frame of the study and considering the perturbing effects greenhouse gas taxes might have (delocalisation to countries without stringent greenhouse gas policies), this last argument is rather weak.
He also acknowledges that "an analysis of separate countries may seem a more appropriate approach for policy-making but the international dimension of material flows would complicate such an analysis". Even before the MATTER project ECN developed a Dutch energy and materials model in a similar way.[xx] However, in an open economy, the functional (product system) boundaries do not coincide with the geographical boundaries, and the implicit assumption in the MARKAL model that changes in consumption automatically lead to changes in the production system is not valid. Although it is acknowledged that it is difficult to translate the conclusions of the study in practical policy recommendations, the full consequences of the open character of the economy on the results are not analysed and results are presented as being valid for The Netherlands.
In the model standard European technologies are used to describe the Dutch production system.

The experience acquired within the MATTER and the BRED project also shows that the advantage of developing a comprehensive model is somehow counteracted by the fact that the more global and comprehensive the model gets, the more difficult the interpretation of the results in terms of significant insight for policy making becomes.

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[5] Gielen refers to a definition of end-use as *the total amount of material consumed by West European product manufacturers plus the net import (import minus export) as semi-finished and finished products minus the process waste from product manufacturers. In other words, end-use is defined as materials used for products consumed within Western Europe.*
However, both cited definitions are only identical in a closed economic system. The *total amount of material consumed by West European product manufacturers* includes the consumption of materials for the production of export products, thus intermediate use and not end use.
[6] The 15 countries of the European Union, Norway, Iceland and Switzerland
[7] West-European production is roughly equal to West-European consumption. *A maximum of 20-25 % of steel and wood, and less than 5 % of cement and petrochemicals is imported or exported from Western Europe*.[xvi]

The model itself is very elaborate and contains many assumptions. The interactions and trade-offs taking place between improvement options in different sectors are very complex, difficult to understand without detailed knowledge of the model and all its assumptions, and difficult to explain. On the other hand, the overall solution given by the model assumes rational decision-making (system cost optimisation) based on full foresight and full transparency (see Annex 1). The more complex the model and the interactions, the less plausible this assumption is. In the MATTER and the BRED project many scenario and sensitivity analyses have been carried out to assess the impact of several assumptions (e.g. on technical and cost coefficients or on macro-economic parameters). However, the influence of this basic and very crucial assumption on the final results is not analysed.

The model is suitable for analysis of broad strategies but not for decisions on specific technologies.

5 CONCLUSIONS

5.1 Materials and life cycle approach

The life cycle concept (*cradle to grave*) is necessarily linked to a specific function or to the final use or consumption of an end product. Materials are not related to functions. They are intermediates in the product system. Essential elements in a life cycle approach are the use phase of the end products (i.e. its energy consumption) and their post-use treatment.

When comparing options for minimising environmental impact, the full life cycle has to be taken into account. Hence, life cycle environmental impacts should be related to products and functions, not to materials or sectors. When assessing life cycle impacts, material flows analyses can be helpful, but they are not an end in their own right.

Nevertheless, many studies adopt an intermediate perspective. They do not trace materials use up to the level of the final consumption, but up to the level of materials production or materials use in industry in a specified region or country.

Possible reasons for this are the following:
1. Some studies take the national industry (the transformation[8] processes) of a country or a specific sector as focal point (e.g. the iron and steel industry in Belgium), and look at minimising the (life cycle) environmental impact of these transformation processes. The outcomes of such a study might be very relevant for improving the environmental record of this industry, but from a life cycle perspective they are incomplete.
2. The availability of data. Data on materials production and (intermediate) materials consumption can be found in national statistics. However, data on materials embedded in products as components or packaging are nor readily available.
3. System boundaries for an analysis based on final consumption do not coincide with territorial boundaries.

5.2 Life cycle approach, end use and system boundaries

Although many material flow studies claim a life cycle perspective, the system boundaries used for evaluating material flows are not always consistent with this perspective. The distinction between material flows related to production or to consumption is not always clear either. The same applies for emissions or impacts.

Two different perspectives can be taken for evaluating emissions[9]:
- a *life cycle emissions from end use perspective,* in which the life cycle emissions related to the end use of specific products (functions) within a specified region are studied;

[8] We will use 'transformation' to cover not only production processes but also post-use treatment of used products.
[9] We look at emissions here that contribute directly to a specific global impact (in this case Global Warming). The same reasoning also applies to other emissions or to other environmental burdens caused by the considered processes, possibly having a local, a regional or a global impact.

- a *direct emissions from processes perspective* in which the impacts caused by the transformation and end use processes within a specified region are studied.

The first perspective starts from the final demand for products consumed within a region and looks at the whole life cycle of these products (all processes involved in the production, use and post-use treatment starting from the extraction of raw materials to final disposal). Transformation processes for export in the considered region are not included.

The second perspective only looks at the processes (both transformation and end use processes) taking place in the specified region. Upstream life cycle impacts of imports and downstream life cycle impacts of exports are not included.

Other terms have been proposed for making this distinction. Van der Voet calls these perspectives the *functional approach* and the *regional approach* respectively.[ii]

> The *functional approach*: the point of departure is the fulfilment of functions for the population of a given region. The first step is to establish consumption within the region. This serves as the basis for the processes to be included into the system. Any relevant steps taking place outside the region must then also be included. Processes taking place within the region for the benefit of other regions (e.g. production for export) are not part of the system.
>
> The *regional approach*: the point of departure is the area itself as a geographically bounded system and what actually takes place there. The location determines which processes (extraction/production/consumption/waste processing) take place within the system.

Gielen[xvi] calls them the *end-use principle* and the *'regional border' principle*.
The terms used by both authors are somehow confusing because the *functional approach* or the *end-use principle* also refer to a region for defining the end-use.

Patel *et al*[xii] also make the distinction between a life cycle approach (*Prozesskettenprinzip*) and a regional approach (*Standortprinzip*). The German *Standortprinzip* reflects more clearly the idea of processes and emissions taking place in a specific region.

Both perspectives are valuable and sensible. They both correspond to specific policy options. The former would provide a basis for acting on (final) consumer responsibility (*"you bare responsibility for what you consume"*). The latter corresponds to the concept of national responsibility as actually in use for evaluation of national greenhouse gas emission levels (*"you are responsible for the emissions on your territory"*). It is easier in terms of defining responsibilities and policies, but does not necessarily lead to the highest global benefits. It may even lead to problem shifting from one country to another.

For open economies both perspectives lead to large differences in system boundaries. Setting boundaries for one perspective does not allow drawing sensible conclusions for the other perspective.

In an open economy there is a weak link between the production system and consumption. Changes in consumer choices that reduce the life cycle emissions related to the consumed products do not necessarily lead to changes in production in the country itself. While the

global benefits of such a policy might be clear, it does not necessarily help a country in reaching its internationally agreed greenhouse gas reduction targets.
Equally so, changes in production are not only determined by changes in consumption within the system, but also by demand on external markets.

5.3 Material flows analysis and the analysis of specific emissions

It seems there is a gap between material flows studies (at sector, regional or national level) on the one hand and detailed LCA type analyses on the other hand.

Many of the material flows studies mentioned above (sometimes implicitly) have the objective of looking at ways of diminishing environmental impacts related to production and/or consumption patterns. However, many of them do not consider environmental impacts explicitly. Approaches in which total materials use is calculated are not very helpful in analysing specific environmental impacts and ways to reduce them.

The case of material flows and greenhouse gas emissions is a bit special because carbon is both a major constituent of specific materials (synthetic organic materials, biomass materials) and of specific emissions. In this sense it comes close to substance flow analysis. Carbon contained in materials can give rise to CO_2 emissions when it is incinerated in its waste stage or when it is oxidised in case of emissions of volatile products, or to CH_4 emissions when it is landfilled.
For all other materials the use of the materials indirectly contibutes to the release of greenhouse gas emissions mainly through the combustion of fuels or in some cases through specific process emissions.

Specific material flow analyses, especially those including the final use of materials in products, can be helpful in quantifying the magnitude of actual and future flows, waste flows and the import and export flows of specific materials. As such, they do not give any information on specific emissions or impacts, but they can be helpful in identifying the importance of these flows, and they can give an idea of the relation between the final consumption of specific materials (in products) and the domestic production system for these materials.

The only two comprehensive efforts to link material flows to greenhouse gas emissions are the MATTER-BRED project and the work done at FhG-ISI by Patel *et al*. The latter focuses on flows of fossil carbon embedded in materials and on the associated final net release of CO_2 in the atmosphere, which can be reduced through increased recycling or through the use of biogenic feedstocks. The former has a wider scope. It is an integrated energy and materials analysis. Changes in materials use can result directly or indirectly (through the embedded energy consumption or process emissions) to the reduction of greenhouse gas emission.
The MATTER and BRED studies conclude that there is a potential for reduction of greenhouse gas emissions through materials strategies. However, some of these strategies only become cost-effective when high greenhouse gas emission taxes are applied.

5.4 Using MARKAL for modelling Belgian energy and material flows

For several of the reasons mentioned in the previous paragraphs the development of a comprehensive Belgian energy and material flows model, based on the Belgian transformation system, does not seem to respond to the objectives of the actual project.

The objective of using MARKAL for energy and material flows modelling is to have a tool for analysing the (actual and future) greenhouse gas emissions related to the production, the consumption and the post-use treatment of specific products or product groups in Belgium and the impact of potential greenhouse gas emission reduction measures.

The evaluation of both life cycle emissions from end use and actual emissions from processes within one comprehensive and unique model was possible in the MATTER study because Western Europe was considered as a relatively closed economy.
The most important specificity of the present project, compared to the MATTER study, arises mainly from the geographical scale adopted. The MATTER project studied Western Europe while the present project focuses on Belgium. As illustrated by the analyses of material flows (see *Greenhouse gas emission and material flows. Part III*), the Belgian economy is extremely open. For many materials, semi-finished products, final products and even waste products import and export streams are predominant, so that the amount of related "imported" and “exported” greenhouse gas emissions is significant. For many materials and products analysing the improvement potential of the Belgian production processes only, as originally planned, leaves out the largest part of the product life cycle.

Changes in consumer behaviour will not automatically lead to equivalent changes in the Belgian production system. Changes in consumer behaviour aimed at reducing life cycle greenhouse gas emissions will not necessarily lead to reductions of the Belgian greenhouse gas emissions.

Moreover, the focus is on specific end uses (packaging, housing, livestock products). Hence, the model does not represent the entire economy, and becomes even more 'open'.

We can conclude that the development of a comprehensive Belgian energy and materials model is not useful, and that specific approaches have to be developed for each of the product groups studied in this project.

Annex 1

MARKAL

MARKAL (MARKet Allocation) is a dynamic techno-economic energy system optimisation model developed in the framework of the "Energy Technology Systems Analysis Programme" (ETSAP) of the International Energy Agency (IEA)[xxi].

The multi-period linear programming model selects the least cost combination of processes and flows that satisfies the exogenously defined demand for energy services over a given time period (typically several decades) under given exogenously defined constraints, starting from an existing exogenously defined transformation system. It calculates the resulting total system cost, total or specific emissions, energy flows, process activities, and shadow prices for produced goods.
In that time period demand will change, costs and technical parameters of technologies will change, existing capacity will gradually be replaced, new technologies will become available. As a consequence the least cost combination of technologies will also change.
MARKAL optimises the system over the entire time period. It supposes rational decision making based on full foresight and full transparency.

Although MARKAL allows imports and exports the implicit assumption in MARKAL is that the productive system changes according to (changes in) the demand. In fact imports and exports are defined as processes that are part of the system and provide an alternative to transformation within the system. If no constraints (minimum, maximum, fixed, ratio) are put on import and exports they will be evaluated according to the same criterion of least cost combination for the entire system.

MARKAL allows the evaluation of greenhouse gas emission reduction policies. Emissions can be associated to processes or to fuel consumption. A constraint or a cost can be put on these emissions.

MARKAL had to be adapted to allow modelling material flows. The most important structural difference is that storage of materials in products had to be modelled by including a time lag between input and output of the products during the use phase. Analogous with the demand for energy services demand for product services has to be defined exogenously.

In the actual Belgian MARKAL model, the Belgian energy system is modelled. This includes all energy flows and related air emissions (notably CO_2, SO_2 and NO_x) occurring in Belgium, resulting from primary energy production, energy transformation and final energy consumption in the different activity sectors.

REFERENCES

[i] Patel M. (1999) *Closing carbon cycles. Carbon use for materials in the context of resource efficiency and climate change*, thesis, Utrecht University, Utrecht (the Netherlands).

[ii] Van der Voet E. (1996) *Substances from cradle to grave. Development of a methodology for the analysis of substance flows through the economy and the environment of a region*. Doctoral thesis, Centre of Environmental Science, Leiden University, Leiden (Nl.)

[iii] Bringezu S., Behrensmeier R., Schütz H. (1998) *Material flow accounts. Part I. General aspects, aluminium, national overall accounts. Final report of Phase I of the EUROSTAT Project "Material Flow Accounts of selected Products and Substances Harmful to the Environment"*, Wuppertal Institute, Dept. for Material Flows and Structural Change.

[iv] Viaene, X. Gellynck, K. Smis, N. Bracke (1999). *Onderzoek naar nutriëntenstromen in Vlaanderen*, Studie in opdracht van de VLM-afdeling mestbank, Universiteit Gent

[v] http://www.wupperinst.org/Projekte/ConAccount/index.html

[vi] Bringezu, S., Fischer-Kowalski, M., Kleijn, R., Palm, V. (1997). *Regional and national material flow accounting: from paradigm to practice of sustainability. Proceedings of the ConAccount workshop 21-23 January 1997*. Leiden, The Netherlands, Wuppertal Institute for Climate, Environment and Energy, Wuppertal.

Bringezu, S., Fischer-Kowalski, M., Kleijn, R., Palm, V. (1998). *Analysis for action: support for policy towards sustainability by material flow accounting. Proceedings of the ConAccount workshop 11-12 September 1997, Wuppertal, Germany*. Wuppertal Institute for Climate, Environment and Energy, Wuppertal.

Kleijn, R., Bringezu, S., Fischer-Kowalski, M., Palm, V. (1999). *ConAccount workshop. Ecologizing societal metabolism. Designing scenarios for sustainable materials management. November 21st 1998, Amsterdam, The Netherlands*. Centre of Environmental Science (CML), Leiden.

Economic growth, material flows and environmental pressure, 26 - 27 April 2001, Stockholm.

[vii] Adriaanse A., Bringezu S., Hammond A., Moriguchi Y., Rodenburg E., Rogich D., Schütz H. (1997) *Resource flows: The material basis of industrial economies*, World resources Institute, Washington D.C.

[viii] Bringezu S., Schütz H. (2001) *Total material requirement of the European Union*, European Environment Agency, Copenhagen.

[ix] Mäenpää I., Juutinen A. (2000) *natural resource use in the structures of the Finnish economy - an input-output analysis*, Paper presented at the Helsinki Symposium on Industrial Ecology and Material Flows, August 30th - September 3rd 2000.

[x] Juutinen A., Viitanen M. (2000) *Industrial ecology of the metal sector: metal material flows in Finland*, Paper presented at the Helsinki Symposium on Industrial Ecology and Material Flows, August 30th - September 3rd 2000.

[xi] Joosten L.A.J., Hekkert M.P., Worell E., Turkenburg W.C. (1999) *STREAMS: a new method for analysing material flows through society*. In: *Resources, conservation and recycling* 27 (1999) 249-266.

[xii] Patel M., Jochem E. Marscheider-Weidemann F., Radgen P., von Thienen N. (1999) *C-Ströme. Abschätzung der Material- Energie- und CO_2-Ströme für Modellsysteme in Zusammenhang mit dem nichtenergetischen Verbrauch, orientiert am Lebensweg - Stand und Szenarienbetrachtung. Band I: Abschätzungen für das Gesamtsystem*, Fraunhofer-Institut für Systemtechnik und Innovationsforschung (FhG-ISI), Karlsruhe.

[xiii] Joosten L.A.J., Hekkert M.P., Worell E. (2000) *Assessment of the plastic flows in the Netherlands using STREAMS.* In: *Resources, conservation and recycling* 30 (2000) 135-161.

[xiv] Hekkert M.P., Joosten L.A.J., Worell E. *Analysis of the paper and wood flows in The Netherlands*. In: *Resources, conservation and recycling* 30 (2000) 29-48.

[xv] Wollny V., Schmied M. (2000) *Assessment of plastic recovery options*, Öko-Institut, Darmstadt.

[xvixvi] Gielen, D. (1999). *Materialising dematerialisation. Integrated energy and materials systems engineering for greenhouse gas emission mitigation*. Thesis Delft University of Technology.

[xvii] http://www.ecn.nl/unit_bs/etsap/markal/matter/main.html

[xviii] Gielen, D., Bos, A., de Feber, M., Gerlagh, T. (2000), *Biomass for greenhouse gas emission reduction. Task 8: Optimal emission reduction strategies for Western Europe*, ECN, Petten.

[xix] Groenendaal B.J., Gielen D.J. (1999) *The future of the petrochemical industry. A MARKAL-MATTER analysis*. ECN, Petten (Nl.).

[xx] Gielen, D.J., Okken, P.A. (1994) *Optimisation of integrated energy and materials systems. Linked energy and material flows; methodological considerations and model calculations for the Netherlands beyond 2000*, ECN, Petten.

[xxi] Fishbone L. *et al* (1983) *User's guide for MARKAL (BNL/KFA version 2.0). A multi-period, linear programming model for energy systems analysis*, IEA ETSAP.