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Creating global scenarios of environmental impacts with structural economic models

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Arjan de Koning

Creating Global Scenarios of Environmental Impacts with Structural Economic Models

Arjan de Koning

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Creating Global Scenarios of Environmental Impacts with Structural Economic Models

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with Structural Economic Models

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Chapter 1

Introduction

1.1 Research area

One of the important contributions of environmental sciences to policy making is to analyse how future economic development might impact our natural environment. Examples are the report for the Club of Rome project (Meadows et al., 1972), OECD environmental outlooks (e.g. OECD, 2001) or the series of Dutch national environmental outlooks (e.g. RIVM, 1988).

Two concepts are central in this research area: economy and natural environment. To be able to analyse how future economic development might impact our natural environment we first have to describe what is meant by “economy” and “natural environment” and how they interact. Therefore we start by describing the economy, how we can see how the relationship between economy and natural environment and how the natural environment changes as a result of the interaction with the economy and how finally the changing natural environment can influence the economy in a recursive relationship. This broad conceptual view is necessary to be able to see the simplifications and aspects not covered when analysing future economic development and resulting impacts on our natural environment.

After describing conceptually economy and natural environment our vision on a model for the economy and its interaction with the natural environment is laid out. For the purpose of this thesis it is essential to create models, because we want to investigate how future economic development might impact our natural environment, a situation that cannot be observed. A model is by definition a simplification and partial view of the real world. Our model will therefore not be able to cover all the forms and aspects of interaction that occur between economy and natural environment.

Having laid out our view on economy, natural environment, and models to analyse the interaction between economy and natural environment, the specific research questions related to future economic development and impacts on our natural environment will be presented.

1.2 Economy and natural environment

1.2.1 The economy

The economy describes a certain aspect of our society (Polanyi, 1944). Society can be seen as the human constructed physical and non-physical artificial environment which is contrasted here with the natural environment that was briefly mentioned in Section 1.1 and that will be discussed in more detail in Section 1.2.3. The physical artificial environment is our houses, roads, cars, knives and spoons and the energy sources that drives our machinery. It is all the land that is in use for agriculture and forestry. It is the excavated mines and quarries. Our physical artificial environment covers a substantial part of the earth. In 2007, cropland, permanent meadows and pastures covered about 39% of the global land surface and built-up land covered about 7% (Hooke, 2012). In the Netherlands these numbers are 67% for agricultural land and 16% for built-up area (CBS, 2017a).

The non-physical part of our society are our economy, institutions and culture. The economy is how we organize our set of interrelated production and consumption activities. The interrelated production and consumption activities within an economy work together to create our (non-)physical artificial environment¹. The economy itself is regulated by and embedded within institutions and culture (Polanyi, 1944; Blyth, 2002). When referring to economy we limit the meaning of this word to the set of interrelated production and consumption activities happening within our society in this thesis. Economic development is thus defined as the changes in interrelated production and consumption activities through time.

This thesis research does not investigate how cultural or institutional developments might change our natural environment. That is not because of lack of appreciation of the importance

¹ Services such as maintenance, education, and insurance are non-physical.

of institutions and culture. On the contrary; they are important because they define how we organize and control our economy (Douai & Montalban, 2012 and references therein). This thesis research assumes that there is a certain economic development but how this development materializes or how this development has to materialize is not investigated.

1.2.2 The relationship between economy and natural environment

The operation of the economy depends on the natural environment in which it is embedded as conceptually shown in Figure 1.1. The natural environment provides living space, water, air, biotic, and abiotic resources. This is indicated by the arrow pointing from the natural environment to the economy in Figure 1.1. The arrow represents physical flows but not only materials. Taking heat or energy from the natural environment is non-material but it is physical.

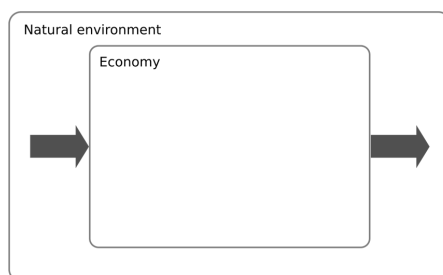


Figure 1.1: Relationship between economy and natural environment.

The economy also uses the natural environment to discard wastes that are, at a given time and place, not of interest for the economy. Therefore there is an arrow pointing from the economy to the natural environment. Again the arrow represents something physical but not necessarily material. Waste may be heat or another form of radiation somewhere in the electro-magnetic spectrum. Waste may also be land that is not economically productive or mining areas that do not contain economic valuable resources. For example, many nature or recreation areas in the

Netherlands are peat, sand or gravel excavation pits that have been “given back to nature”. It can be seen that 19 out of the 163 Natura2000 areas in the Netherlands were used for peat or clay excavation.

The clause “at a given time and place” is important. Frequently, waste is discarded into the natural environment that at another place or time might be of great interest for the economy and is re-absorbed into the economy. A typical example might be the reworking of old mine tailings or the salvage of discarded ships. A famous example is the recovery of materials from the scuttled German High Seas Fleet from Scapa Flow after WWI (Booth, 2011). Another example which receives quite some attention nowadays, is the use of CO₂ from air for the production of chemicals or the reworking of mine tailings (Schemme et al., 2017; Johnson, 2014).

In this research any uptake from the natural environment and any waste discarded into the natural environment is collectively called environmental intervention (Heijungs, 1997; Guinee et al., 2002)¹.

1.2.3 The changing natural environment

The natural environment consists of the geosphere, the biosphere, the hydrosphere and the atmosphere. It is part of the world that is influenced but not controlled by the economy. The natural environment has changed as a result of its interaction with the economy. A natural environment that has not changed by actions of mankind does not exist anymore on earth.

¹ Accidental releases from the economy should be considered waste as well. Accidental releases are often overlooked in models of the economy and natural environment. However accidental releases can have large and lasting environmental consequences. To name a few examples, mining spills such as the Aznalcollar toxic spill (Hernández et al., 1999) or large accidental releases of radioactive material such as Hanford, Kyshtym, Chernobyl and Fukushima (Norman, 1983; Cambray et al., 1987; Smith et al., 2000; De Koning & Comans, 2004). If the material released was of interest of the economy, the accident should have been prevented. If there was an accidental release there has been a choice (implicitly or explicitly and not necessarily rational) between the economic benefits of preventing the release and the economic benefits of not taking preventive measures. Accidents are a normal occurrences in the operation of the economy (Perrow, 1999) and should be considered as such in our research.

Perhaps before the industrial revolution and before anthropogenic emissions of greenhouse gases in the atmosphere reached such levels that they started to make a marked influence on the global climate there were parts of the world that could be considered untouched by humans. Currently, I cannot think of a natural environment that has not been changed more or less by human action.

The changing climate has transformed and will further transform the natural environment in a profound way. The IPCC reports (IPCC, 2014) and a plethora of other scientific literature describes the observed changes and the changes that are likely to happen. To name a few changes caused by the emissions of anthropogenic greenhouse gasses: higher average global temperature, retreating glaciers, melting of the Greenland ice sheet, melting of the West Antarctic ice sheet (Lenton et al., 2008; Pritchard et al., 2009), acidification of the oceans (Hoegh-Guldberg & Bruno, 2010) and changing rainfall patterns (IPCC, 2014). No part of the earth will be left untouched by these changes.

The oceans covering about 71% of the earth, with a mean depth of 3.68 km containing $1.33 \times 10^9 \text{ km}^3$ of water (Charette & Smith, 2010) with large unexplored areas (Griffiths et al., 2010) is also influenced throughout by mankind. The ocean floor is littered with clinker from the days that ships were powered by coal (Wei et al, 2012). At the surface and within the water column floats an unknown but substantial amount of plastic (Derraik, 2002). In the deep ocean traces of radionuclides released during above ground nuclear tests provide a convenient way to observe ocean circulation patterns (Pickart, 1992). Acidification and increasing surface water temperatures affects coral reefs which are a biodiversity hotspot in the natural environment (IPCC, 2014).

Global cycles of nitrogen, phosphorous, sulphur and metals have changed and are sometimes dominated by human activities (Galloway et al., 2004; Filippelli, 2008; Rauch, 2009). The world's biological diversity is in a major decline as a result of human activities. The present rate of extinction has probably accelerated to 1000 - 10000 times the natural rate (Wilson, 1985; May, 2011).

That our economy changes the natural environment in profound ways is not something new. Humans like many other species on this earth have influenced the natural environment for their own survival and have done so for a very long time. With the development of agriculture ca 10000 BC started the alteration of the landscape and associated impacts on the natural environment (Delcourt, 1987; Kahn et al., 2015; Yu et al., 2016). Land development for agriculture can be seen as taking land from the natural environment. Land development is seen as a resource taken from the natural environment and bringing it within the economy and thereby under control of the economy. Agriculture then becomes the economic activity controlling that area of land.

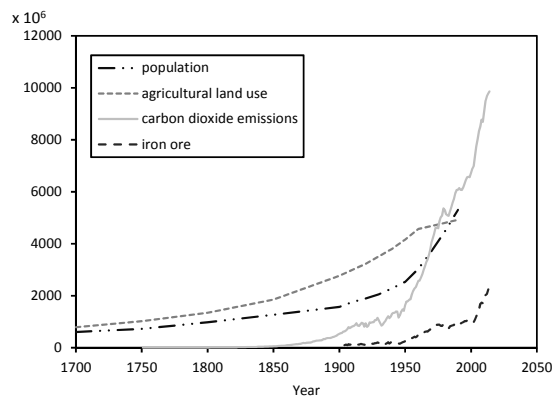


Figure 1.2: Long term development of human population, agricultural land use (million hectares), carbon dioxide emissions (million ton C/yr) and iron ore production (million ton gross weight/yr). For references, see text.

The severely eroded landscape of Greece is testimony of the changes to the natural environment caused by the economy in antique times (Van Andel et al., 1986; Hughes, 1994; Runnels, 1995). Sedimentation in the Rhine floodplain over the past 6,000 years has largely been attributed to changes in land use in the upstream basin (Middelkoop et al., 2010). Agricultural practice during the Bronze Age and at the end of the Roman period led to gully erosion on the loess plateau in Belgium. Landscape changes as a result of agricultural practice

did not only happen in Western Europe. On the eastern North American floodplain, maize-based agriculture lead to increased sedimentation in valley bottoms in the period 1100 - 1600 (Stinchcomb et al., 2011).

Hunting by humans already drove species to extinction in prehistoric times. Hunting probably caused the extinction of birds on Pacific islands (Duncan, 2002). Small vertebrate were driven to extinction by human-caused environmental degradation on Antigua (Steadman et al., 1984; Grayson, 2008).

From the start of the industrial revolution the volume of environmental interventions impacting the natural environment has increased due to an increased availability of energy sources, compounded by an exponential growth in world population (Ayres & Warr, 2009). Population has increased from about 0.75 billion in 1750 to 7.6 billion in 2015 (Durand, 1974; UN, 2017). Since 1750 CO₂ emissions from fossil fuel burning, cement manufacture and gas flaring have increased from 3 million per year to 9855 million tons of carbon per year (Boden et al., 2017). Agricultural land use has increased from 789 million ha in 1700 to 4822 million ha in 1990 (Klein Goldewijk, 2001). The amount of iron ore being mined has increased from 69 million ton per year in 1904 to 2280 million ton per year in 2015 (Kelly et al., 2014). Especially after 1950 the use of materials and emission levels has increased (Steffen et al., 2015). An estimate of the amount of anthropogenic erosion from prehistoric times until 2000 by Wilkinson (2005) indicates that current levels of erosion are at their highest. Figure 1.2 shows CO₂ emissions, agricultural land use and iron ore use over time reflecting the increase of the exchanges between economy and natural environment together with human population development. Because mankind has such a large influence on the natural environment by now, the current epoch has been coined the Anthropocene (Crutzen, 2000).

Given that the natural environment is changing fast, additional exchanges between economy and natural environment may have different environmental impacts because the state of the natural environment has changed. For instance an ecosystem may have disappeared already due to historical environmental interventions. This disappeared ecosystems is not taken into account when assessing impacts of additional environmental interventions. This can lead to a

situation where the environmental impacts of additional environmental interventions are assessed as being limited because sensitive ecosystems have already disappeared.

1.2.4 A recursive relationship

As argued above, our economy needs resources from the natural environment and at the same time discards waste into the natural environment thereby altering the natural environment. As a result the natural environment changes at a faster pace than seen in the last few thousands of years¹. The influence of the economy on the natural environment is now so large that it threatens the natural resources that form the basis of the economy.

The threat to the natural resources that form the basis of our economy forms a recursive relationship between the economy and the natural environment. For instance, anthropogenic greenhouse gas emissions lead to climate change and this climate change has an effect on the ability of the economy to use resources from the natural environment (Moore & Diaz, 2015). With average global temperatures in 2016 about 1.1 °C above pre-industrial levels (WMO, 2017) the recursive effects are starting to show. Sea level rises due to increased melting of ice sheets and glaciers affects low lying coastal areas (Zhang, 2004; Hansen et al., 2016;). Effects include increased flood risks and increased coastal erosion. For some countries it means that additional money has to be spent on flood defences or that coastal areas have to be abandoned.

While changes in the natural environment in itself may provide incentive to reduce the effect of the economy on the natural environment, it is the repercussions on the economy that seems to trigger most societal response. Adaptation measures for global warming are almost invariably related to the protection of the economy, not the natural environment. In the climate change 2014 synthesis report, in an overview of adaptation approaches, out of the ten categories discussed only one explicitly addressed ecosystems (IPCC, 2014).

¹ Abrupt climate changes during the last ice age changed the natural environment drastically. These changes occurred in a time frame of decades (Severinghaus et al., 1998; Alley et al., 2003). Since about 10000 years the earth has seen a relative stable climate.

1.3 Modelling economy and natural environment

1.3.1 The need for models

In the previous paragraphs our concept of economy and natural environment and their interaction has been described. The main message is that the influence of the economy on the natural environment is unprecedentedly large, that the change of the natural environment as a result of economic activity is growing, and that these changes in the natural environment have repercussions on the economy.

There are reasons to expect that the influence of the economy on the natural environment will continue to grow in the coming decades. The size of the human population is forecasted to grow to 9.7 billion in 2050 (UN, 2017) and the global economy is expected to grow from 34 trillion Euro in 2000 to about 109 trillion Euro in 2050 (OECD 2012a, 2012b). On the other hand many technology developments such as renewable energy technology and agricultural developments, may lower the influence of the economy on the natural environment.

In numerous cases, technology development has successfully reduced environmental interventions in the past. Some examples at different geographical scale can be mentioned. Local water quality has improved substantially in the Netherlands over a period of 100 years. Introduction of flushing toilets, sewer systems, connection of houses to sewers (even in remote places) and last but not least waste water treatment technology developments have reduced impacts of the discharge of household wastewater on surface water. Surface water quality improved against a backdrop of population growth and economic growth (Puijenbroek et al., 2010; CBS, 2017b). On a regional scale, SO_x emission reduction measures have been successful (Vestreng et al., 2007). Emissions of SO_x dropped from 55 Tg SO₂ in 1980 to 15 Tg SO₂ in Europe. On a global scale SO_x emissions are decreasing as well but some regions, such as India and Bangladesh, see increased SO_x emissions. On a global scale the Montreal protocol which came in effect in 1987, reduced emissions of ozone depletion substances to such a level that the ozone layer is starting to recover (Mäder et al., 2010). Of course it was not only technology that made these successes possible. The creation of policies, laws and institutions made it possible to successfully apply the technology.

As observed from the previous examples, it is ultimately the interplay between economic development, population growth and technology development that determines what the influence of the economy on the natural environment will be. Often this relationship is given as the Impact = Population $\times$ Affluence $\times$ Technology or IPAT equation (Ehrlich & Holdren, 1972; Chertow, 2000; York et al., 2003) where affluence is often expressed as GDP per capita and technology as impact per GDP.

We are interested in how far technology development aimed at reducing impacts per GDP can counteract the increasing environmental interventions from economic growth in terms of increasing GDP per capita and population growth. Can long-term technology development be fast enough to reduce our exchanges with the natural environment such that the resulting changes of the natural environment does pose a threat to the natural environment itself and the repercussions of these changes is not a threat to the economy?

Economic growth and population growth are not investigated as means to reduce environmental interventions in this thesis. The projections/forecasts by authoritative institutes such as the OECD and UN population division are followed. What is investigated in detail, is the uptake of resources by and emissions from the economy due to changes in the technology.

To be able to assess how future technology developments may alter exchanges between economy and natural environment a simplified model of the workings of the economy and natural environment is needed.

1.3.2 Modelling the economy

The workings of the economy as it is embedded and shaped by society is complex. Individual decisions by millions of unique producers, consumers, financial and regulatory bodies are influenced by the decisions of millions of other unique economic actors. The end result of all these actions is in its most simple description a circular flow in the economy in the form of goods and services being produced by producers and the monetary value of labour provided by the consumers. In turn the wages being paid to the consumers is used to buy the goods and services from the producers, see Figure 1.3. Such a simple picture of the workings of the

economy was already introduced by classical economists, but it was Wassily Leontief (1928, 1941) who made it into a model of the economy that is used to this day.

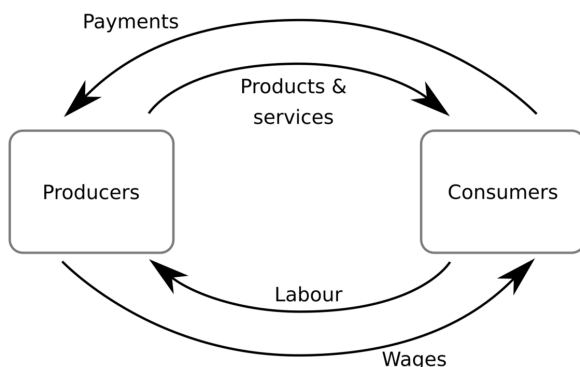


Figure 1.3: Circular flows of money and goods & services in an economy, modified after Leontief (1928).

Leontief proposed to describe the circular flow of goods and services in a so called input-output (IO) table. An input output table is a comprehensive account of all the economic flows within a national economy in a given period, usually 1 year. The IO table allows us to measure the quantities involved in the circular flow and it can be used to examine structural developments in an economy by comparing IO tables from different time periods. The IO table and the conventions used for compiling data to fill this IO table forms what we call the IO framework. This framework later formed the basis for national accounting methods (Stone, 1961). An advantage of the use of the IO framework in our research is that the description of the economic flows is closely related to the aggregate physical flow of products through the economy. The flows in the IO framework can be expressed in monetary or physical units and mixtures thereof (Weisz & Duchin, 2006). The in- and outputs of each sector as recorded in the IO framework are also a reflection of the technology used in the sector.

The IO framework, originally used to measure the structure and development of (regional) economies was later extended to include information about environmental interventions

(Leontief, 1970). In the Netherlands, the National Statistical Bureau (CBS) pioneered the extension of the IO framework with information about exchanges of the economy with the natural environment (De Haan & Keuning, 1996).

A simplified environmentally extended input-output framework is shown in Figure 1.4, and it contains five elements¹. The intermediate table describes all the inter-industry flows as monetary transactions². The columns in this table represent production recipes of industries. Each element in a column expresses how much of a certain input from a particular industry is needed to make the output of the industry. The final use table describes final demand by final consumers among which households. The factor inputs table contains payments of an industry to factors of production, including but not necessarily limited to labour and capital. Finally the input-output table is augmented with environmental extensions for the intermediate user and final user. Each column in the environmental extensions matrix shows the environmental emissions and environmental resource use directly connected to the activity of the industry and the activity of the final users.

¹ Only the very basics are shown here. The framework can be set-up in different ways, taking for instance into account that a country has imports and exports. For more information please consult the text book of Miller & Blair (2009) on input-output analysis.

² Input-output tables are either expressed in an industry by industry ($i \times i$) format or product by product ($p \times p$) format. For ease of discussion it is assumed that the table is in $i \times i$ format.

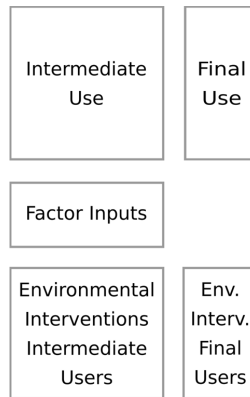


Figure 1.4: Simplified input-output framework.

The IO framework as depicted in Figure 1.4 represents the observable economy. A model is needed if we want to attribute environmental interventions to final use or calculate how environmental interventions are affected by changes in final demand. The model used for this analysis is the so-called demand driven Leontief model. It is called demand driven because the basic assumption in this model is that everything that happens is a result of the demand for goods and services¹.

A crucial assumption in this model is that the inputs per unit of output of the industries do not change if the final demand for goods and services changes. Another crucial assumption is that the factor inputs and environmental interventions per unit of output of the industries does not change if final demand changes². Having created the Leontief model from the values in the IO table, the model can be used for Input-Output Analysis (IOA). The equations for the

¹ A supply driven model based on the same observations depicted in Figure 1.4 exists as well. It is called the Ghosh model (Ghosh, 1958). It is seldom used because it is considered unrealistic from an economics point of view (Oosterhaven, 1989).

² When using the Leontief demand driven model, changes in final demand will by definition lead to changed production by intermediate users and hence changed environmental interventions. Special care shall be taken to ensure the emissions from final users are scaled to the changed final demand as well.

derivation of the Leontief model from the data contained in the input-output table (IOT) can be found in standard text on IOA such as Miller & Blair (2009).

Having created the input-output model it is possible to track back how for instance the final demand for cars is related to the inputs necessary to make these cars and which industries supply the sheet metal that is necessary for making the cars. Further up the supply chain the sheet metal making industry may need iron ore and coal. In the end all of the industries are somehow involved in the production of the cars because of the inter-connectedness of the industries. Knowing the inter-industry relationships, it is possible to calculate the output of all the industries that are necessary to create the products consumed by households. If the required output of the industries is known also the environmental interventions from the industry sector can be calculated and hence the environmental interventions associated with the production and consumption of a product.

Initially the environmentally extended input-output analysis (EIOA) studies were based on national environmentally extended input-output tables (EIOT). It was an unsatisfactory state of affairs. By using national tables, only the environmental interventions within the national boundaries could be included and environmental interventions outside the national boundaries had to be estimated, see for several estimation approaches Peters (2008). This shortcoming of IOA was addressed by creating global multi-regional (E)IO tables. EXIOBASE is one of the multi-regional IOTs (Wood et al., 2015) but other multi-regional IOTs exist as well, each with their own strength and weaknesses, for an overview, see (Tukker & Dietzenbacher, 2013).

When using the data in multi-regional EIO tables to create a multi-regional input-output model it is possible to carry out multi-regional input-output analysis (MR IOA). This analysis allows us to picture the connections between consumption in one part of the world and environmental interventions in other parts of the world. Examples of this type of analysis can be found in Tukker et al. (2014, 2016). This type of analysis is very useful for analysing the current state (ex post or retrospective analysis) of the economy and its environmental interventions in the world. Time series of multi-regional input-output models can also be used to understand how past changes in the economy affected emissions and resource use.

Because the economy is very complex, different aspects of the economy can be of interest and different questions have to be answered about the operation of the economy, there is a plethora of other economic models besides the IO model. Macro-economic models that may overlap with the IO models are computational equilibrium models (e.g. Burniaux & Truong, 2002; Burfisher, 2011) and macro-econometric models (e.g. Conway, 1990; Meyer & Lutz, 2007; Pollitt et al., 2014).

The MR IO framework can be used for ex ante analysis as well. A very attractive feature of the MR IO framework is that it covers relations between economic sectors and countries in the global economy at a high level of spatial and sectoral detail. If the sector description in the MR IO framework is specific enough, the in- and outputs of sectors might easily be changed such that these in- and outputs reflect a (future) technology change. A model is necessary to implement the changes. If such a model is available, it makes the MR IO framework very well suited as a basis for the analysis of economy-wide implications of large scale introduction of renewable energy systems, including trade-offs in environmental pressures. In the context of this thesis, it is hence interesting to see how a model can be developed using the MR IO framework as a basis that can be used in scenario modelling of future economic and environmental change. Because the scenario model would use the structural relationships between the sectors to make changes in the MR IO framework we coin such an approach “creating global scenarios of environmental impacts with structural economic models”.

1.3.3 Modelling the natural environment

The inner workings of the natural environment are probably even more complex and less understood than the economy. In this thesis it is not the inner workings as such that are of interest but it is the connection between environmental interventions and (marginal) changes in environmental processes. These changing processes can lead to environmental impacts. The impacts are finally related to environmental problems, i.e. the “undesiredness” of the environmental impacts as perceived by society (Heijungs, 1997). As noted in Section 1.2.3 we can only assess environmental impacts based on the current state of the natural environment. A fundamental problem that will not be solved in this thesis.

Modelling in detail the pathway from environmental intervention to environmental impact is complex especially because it often needs to be done at high temporal and spatial level. Impacts depend on the timing and location of an environmental intervention and the level of all other environmental interventions taking place at the same time. However, from the point of view of environmental impact calculation, knowledge about the temporal and spatial nature of environmental interventions calculated by our MR IO model is limited¹.

In an IO model we do not know exactly when and where environmental interventions take place. Partly this lack of knowledge is fundamental because it is impossible to univocally cut-up the intricate inter-industry connections into a single supply-chain (Heijungs & De Koning, 2018). A second fundamental reason is that the IO model covers observations in one year. A supply chain that uses historically built-up infrastructure (for instance a hydro-power plant) does not fully take into account the environmental interventions associated with the historically built-up infrastructure. A practical issue is the limited spatial detail available in IO models. We do not know if an environmental intervention is a single event at a particular location or if the environmental intervention is a diffuse emission over a large area happening over the course of a year. We also do not know the real extent of the emission because in the IO model the intervention can be related to a hypothetical final use of a product. This problem is similar to the situation in life cycle assessment (LCA). Only in cases when the environmental interventions associated with total global consumption are calculated, the full quantity of emissions is known. Because real environmental interventions are not known, the modelled environmental impacts are better called potential environmental impacts to distinguish them from real environmental impacts estimated in risk assessment.

The properties of the environmental interventions calculated with MR IOA as described above are similar to the properties of environmental interventions in LCA. The approach to modelling potential environmental impacts is therefore borrowed from life cycle assessment (LCA). During the life cycle impact assessment (LCIA) phase, environmental interventions are transformed into potential environmental impacts (Udo de Haes, 1996). Many LCIA

¹ From an economic point of view the MR IO model based on the MR IOTs contained in EXIOBASE is among the most detailed models available.

methodologies do exist that provide a set of potential environmental impact indicators. To name a few: the eco-indicator '99 method (Goedkoop & Spriensma, 1999), the so-called CML method (Guinée et al., 2002), the IMPACT 2002+ method (Joliet et al., 2003) and the more recent ILCD method (EC-JRC, 2011). A recent overview of best practice in LCIA is given by Hausschild et al. (2013). A discussion of all the intricacies of life cycle impact assessment methodologies is beyond the scope of this introduction but the LCIA methodology for the global warming impact indicator is discussed in somewhat more detail because this thesis is mainly concerned with climate change, an important case application in this thesis.

Best practice LCIA indicators for global warming (Hausschild et al., 2013) are based on the baseline model of 100 years of the IPCC (IPCC, 2007) with radiative forcing as a global warming indicator. The global warming potential (GWP) is used as a so-called characterization factor that expresses the relative contribution of a GHG to potential global warming impacts with respect to CO₂. The characterized GHG emissions are subsequently summed up into a global warming impact category indicator. The global warming impact category indicator result associated with the consumption of a country is often called the carbon footprint of a country (Fang et al., 2015). The use of GWPs means that there is a linear relationship between quantity of emission and potential environmental impact is assumed. It also means that the environmental model cannot take into account that the environment is changing. An emission in 2000 is characterized in the same way as in 2050.

1.4 Research context

One of the global environmental problem areas where the effect of economy on the natural environment has already global repercussions on the economy is climate change. Under the Kyoto protocol countries have agreed to set targets to reduce global GHG emissions to a level that would prevent dangerous anthropogenic interference with the climate system (UNFCCC, 1998). In Cancun, countries agreed to limit their GHG emissions to a level such that the

average global temperature increase remains well below 2 °C¹ since pre-industrial measurements (UNFCCC, 2010, 2012).

The 2 °C limit means that substantial emission reductions should be realized already by 2050. The IPCC (2014) RCP2.6 scenario reduces CO₂ emissions to around 12 Gt in 2050. These reductions are in the order of 50% relative to 1990 levels (Van Vuuren et al., 2011; Boden et al., 2017).

How these emission reductions should be achieved is unclear. Many scenarios have been published such as the RCP2.6 scenarios (IPCC, 2014), blue map scenario (IEA, 2008) and OECD scenarios (OECD, 2012a). At least it is clear that the use of fossil fuels should be reduced. Our fossil based technologies should be replaced by nuclear energy, bio-energy or renewable energy technologies together with efficiency and life style changes. Remaining fossil fuel energy generation is to be combined with carbon capture and storage (Deetman et al., 2014; IPCC, 2014).

The introduction of renewable energy technologies on such a massive scale as necessary for the required GHG emissions reductions by 2050 takes time (Kramer & Haigh, 2009). There are many reasons why this transformation may not be implemented quickly even when the technology is available to make this transformation. One of the reasons is the amount of investments in fossil fuel infrastructure that will not be written off at once (Davis & Socolow, 2014).

It is of high importance to know if indeed the introduction of the renewable energy technologies can achieve the deep GHG emission reduction that are required in 30 years' time against a backdrop of population growth and economic growth. In this, we want to focus on

¹ A global average 2 °C limit as a boundary where major environmental effects are probably avoided is questionable. At an average 2 °C global warming (above pre-industrial temperatures) there is a possibility that the Greenland ice sheet will disappear leading to 2 - 7 meter sea level rise. This impact would be felt > 300 years from now. On a much shorter timescale the Arctic ocean will become ice free. Scientists have advocated to limit the global average temperature increase to 1.5 °C to avoid surprises. The “well below” has not been defined and pre-industrial means average temperatures from the period 1850-1900, well after the industrial revolution started.

the following point. Renewable energy technologies have substantially lower GHG emissions compared to fossil fuel based energy technologies. However many environmental interventions associated with renewable energy technologies such as land, water or metal use are higher compared to fossil fuel based technologies (Kleijn, 2011). Perhaps the introduction of new energy technologies solves the climate problem but other problems may arise or might even make large scale introduction of some of the energy technologies impossible (Alonso, 2012). Of particular concern are available metals and biomass. In this thesis we will specifically have a look at availability of metals related to the introduction renewable energy technologies. Water and land use related to the introduction of renewable energy technologies are not further investigated.

1.5 Objectives and research questions

To be able to address the concerns raised above, we set out to investigate the effect of the introduction of renewable technologies on GHG emissions and resource use until 2050. The tool of MR EIO is in principle suited for this, since it has the potential to link all economic processes in a systematic way globally, at a high level of detail in terms of products and sectors. This in principle allows for an economy-wide analysis of the pressures on land use and resource use of, for instance, a broad implementation of renewable energy technologies as explained in Section 1.3.2. At the same time, an MR EIO is usually linked to relatively simple approaches to analyse the potential environmental impacts via characterization factors borrowed from LCIA (Section 1.3.3). Furthermore, MR EIOs as such are not forecasting models. This then leads to the following research questions central to this thesis:

1. How can an EIO framework be turned into a long term global quantitative scenario model that allows us to investigate environmental interventions and their effect on natural environment and economy?
2. What are the strengths and weaknesses of such an EIO based scenario tool compared with other quantitative scenario modelling approaches that use for instance econometric modelling, integrated assessment modelling, and computable general equilibrium modelling?

3. What is the appropriate spatial and economic sector resolution for a successful implementation of scenarios in the developed scenario model?
4. How can this quantitative scenario model be used to investigate:
 - a. If the introduction of renewable energy technologies can reduce GHG emissions in 2050 to a level in line with the 2 °C limit?
 - b. If the introduction of these renewable energy technologies might be constrained by the supply of metals until 2050?
5. How can, also given experiences in case applications, the EIO based scenario model developed in this thesis, be adapted to overcome certain weaknesses it has compared with other quantitative scenario models?

1.6 Reading guidance

Chapter 2 starts with an investigation of the advantages and disadvantages of using the IO framework for scenarios that typically look several decades into the future. The investigation consists of describing and comparing the characteristics of several archetypical model groups that are all macro-economic models used in climate change scenario modelling. This chapter addresses the question which economic modelling approach is useful for the type of questions that we would like to answer in our research (Question 2).

Chapter 3 addresses the question of optimal spatial and sectoral level to use in IO frameworks like the one developed in Chapter 4. It is a methodological study that may direct future efforts in developing detailed multi-regional input-output tables. Because creating a high level of detail in IO tables is a lot of effort, focusing this effort on crucial parts is important (Question 3).

In Chapter 4 we will be using the IO framework for the implementation of long term scenarios aiming at limiting greenhouse gas emissions in 2050 below the 2 °C climate target. This research addresses a crucial question raised before: can technological progress reduce environmental interventions fast enough while the economy and population are growing (Question 1 and 4a)?

Chapter 5 builds further upon the IO framework presented in Chapter 4. In this case the developed scenario model is used to investigate if the greenhouse gas mitigation measures in that scenario (typical mass introduction of renewable energy technologies) are actually possible given a limited supply of metals. Renewable energy technologies often require more metals per unit of energy than fossil fuel based energy technologies (Question 1 and 4b).

Chapter 6 answers the research questions by integrating the results of the different studies and reflecting upon the knowledge gained. It further points to some of the scientific problems that need to be solved for further development of scenario models in an IO framework (Question 5).

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Chapter 2

Models for socio-economic scenario analysis and climate change

Abstract

Global climate change scenario studies employ models that range from simple regression models to computable general equilibrium (CGE) models, macro-econometric models and integrated assessment models (IAM). Recently global multi-regional environmentally extended input-output tables (MRIOT) have also been used to model the greenhouse gas (GHG) emissions until 2050 in different socio-economic scenarios. This type of scenario modelling is a new approach in global climate change scenario studies that has recently become possible with the recent creation of global multi-regional input-output tables. In this study it is investigated what the contribution of the global MRIOT based scenario tool can be in this mature research area. For this purpose different model types were evaluated in terms of their description of the economic system, environmental system, the solution mechanism used to calculate the GHG emissions for a particular scenario and how accessible the models (results) are to external researchers. The evaluation shows that all modelling approaches rely on extrapolation of past trends and that they do not contain or have a very limited description of the effects of climate change on the economy. A strength of the global MRIOT based scenario tool is its consistent and comprehensive description of 129 economic activities in each country/region but a weakness is its simple description of the economy. It is recommended to examine if the global MRIOT based scenario tool might be extended with a hard-linked environmental model that is capable of estimating feedback effects on the economy.

2.1 Introduction

Climate change is one of the key challenges that humanity is facing in the coming decades (UNFCCC, 2012). Countries worldwide agreed in the Paris Climate Agreement (UNFCCC, 2015) to keep global average temperature increase to well below 2 °C and preferably even below 1.5°C. Several studies investigated the global emissions targets needed to keep within this 2 °C limit and found that GHG emissions should be reduced about 60% by 2050 (Van Vuuren et al., 2011; UNEP, 2016) compared to 2010 levels. In 2016 global GHG emissions were about 49 Gt CO₂ eq. (Oliver et al., 2017). According to the latest IPCC report the net

carbon emissions should approach zero by 2050 for staying below the 1.5 °C target (Clarke et al., 2014). Such large emission reductions require major changes in production and consumption patterns (Akenji et al., 2016; De Koning et al., 2015). How our global production and consumption will evolve in the coming decades cannot be predicted. Instead of trying to predict the future, scenario studies can be used to investigate possible pathways that brings us upon a route towards meeting that Paris Agreement's climate targets.

Scenarios in the context of this article can be described as "...a coherent, internally consistent and plausible description of a possible future state of the world..." (Parry & Carter, 1998). A way to explore such consistent descriptions of the futures, is to model the scenarios by means of computational abstractions representing a model of the socio-economic-environmental system. Qualitative evaluation of socio-economic scenarios is possible as well but are not considered in this study.

In climate change research, scenarios often describe plausible trajectories of climate conditions and other aspects of the future (Moss et al., 2010). They are built up in discrete steps. The starting point of climate change research is the formulation of so-called socio-economic scenarios. Subsequently models are used to estimate GHG emissions in agreement with these socio-economic scenarios. Emissions scenarios form the basis for the calculation of radiative forcing scenarios, climate change scenarios and finally impact & adaptation vulnerability studies (Moss et al., 2010). For this article, global models that can be used to calculate emission scenarios on the basis of socio-economic scenarios are being reviewed.

Socio-economic scenarios consist of a set of exogenous assumptions, assumptions that may be based on the output of different types of models (e.g. human population development models). These socio-economic scenarios are translated into inputs for the scenario model. The exact inputs of the scenario depend on the model (e.g. economic growth is in some models endogenously calculated, but an exogenous assumption in other models). Examples of key elements of socio-economic scenarios include the future performance of the energy and agriculture systems (Stehfest et al., 2014).

A plethora of different models have been used to calculate future GHG emissions based on exogenously defined socio-economic scenarios. They can strongly differ in their system boundaries, level of detail and core mechanisms. The models range from simple regression models to large coupled models such as integrated assessment models. Recently some new types of models have been used for the implementation of climate change scenarios that are based on detailed global multi-regional input-output tables (De Koning et al., 2015; Hertwich et al., 2015). In these models, multiregional input-output tables (MRIOTs) are constructed that reflect a socio-economic scenario. Given the myriad of other global scenario models available that have a much longer development history, we may ask ourselves what are the additional benefits of this new multi-regional input-output based modelling strategy in reference to all other scenario modelling strategies.

To investigate the role of the detailed global multi-regional input-output models an overview is made of scenario models used in climate change scenario assessment, focusing on selected characteristics of the different modelling strategies, their strengths and weaknesses and their most appropriate application area. From this overview recommendations will be given to which model type can be used for which purpose. In doing so, it shows the positioning of the global multi-regional input-output model in the field of scenario models for climate change.

Overviews of different modelling approaches have been made in the past. An early model review (Cole, 1987) distinguished between systems models, institutional models, de-institutionalized models, politico-economic models and modelling consortia models. Another model typology was introduced by Braat & Van Lierop (1987). The authors classified the models according their intended use, and distinguished between descriptive models, explanatory models, predictive models, prescriptive models and evaluative models. Van den Bergh (1991) made an analysis of dynamic models for sustainable development and used three criteria, i.e. completeness, aggregation and openness to distinguish 12 different classes of dynamic economic-environmental models. An overview of computable general equilibrium models for sustainability impact assessment was made by Böhringer & Löschel (2006). A survey of model approaches to integrated environmental assessment and management was carried out by Kelly et al. (2013). The five different model approaches were: system dynamics, Bayesian networks, coupled component models, agent-based models and

knowledge based models. A review of scenario models that follows a similar characterisation of models as in this research, but focussing on energy - climate scenario models only, was carried out by Krey (2014). A recent review of energy modelling tools by Després et al. (2015) categorise the models according to two dimensions. The first dimension distinguished between optimization and simulation models. The second dimension distinguished between bottom-up, top-down and hybrids thereof.

This overview will focus on global economic-environmental coupled models dealing with climate change impacts. The global focus is a necessity because any GHG emission to air anywhere on the planet contributes to radiative forcing. The economic activities that cause GHG emissions to air are also ever more globally connected through a global market (Krugman et al., 1995). Economic actions in one place of the world can have unforeseen environmental consequences in other parts of the world, for instance land-use change in Brazil due to the stimulation of corn-based ethanol use in the US (Searchinger et al., 2008). Global scenario models are therefore the most appropriate to study climate change.

Given the global focus, models that only address a particular region, or a particular economic sector are left out in the analysis. Among these models are partial equilibrium models such as CAPRI (Britz & Witzke, 2014), an EU wide agricultural sector modelling system, and pure energy sector models such the TIMES model, a descendent of the MARKAL based models (Loulou & Labriet, 2008). Models that analyse the effect of changes in a particular sector against a static background system are also not taken into account. Likewise the partial equilibrium models they do not implement global scenarios for the whole economy. Typically hybrid - IO such as combinations of MARKAL energy models with IO or integrated LCA - IO models fall in this category.

2.2 Methods

2.2.1 Model classification

First of all, the models that fall within the scope of this study are divided into several groups and subgroups. All models are at least used to estimate GHG emission following a set of more

or less detailed socio-economic scenarios. Some models cover further impacts along the DPSIR (Driving forces, Pressures, States, Impacts, and Responses) chain (Smeets & Weterings, 1999) as well. Dividing the models into different artificial classes has the danger that the continuous landscape of modelling approaches is seen as discrete and non-overlapping only. However to be able to get to grips with the variety of models in use, a certain classification and simplification is needed. Nonetheless, there will be a lot of models that do not exactly fit the classification and the classes represent stereotypes.

Introducing classes also has the danger that it sets the perspective for the analysis of the different models without realizing that other classifications and perspectives might be possible as well. For the purpose of this article we will classify the models based on their core working mechanism. The core working mechanism is the implementation of what is seen as a model concept to describe relations between socio-economic drivers and GHG emissions in the form of a computational model. That might be simple correlations, structural relations, chemical processes models, market equilibrium models, actor models etc. A stereotypical description of the core working mechanism is given for each class.

Other classification criteria could have been used as well. For example, a classification based on mathematical characteristics of models such as the distinction between linear and non-linear representation of relationships. Such a classification system might have led to a more strict division between models. However, instead of using these possible classification criteria as such, we will use it as defining characteristics of the different groups of models. These characteristics are the ones that set the models apart and define the stereotypic traits of the groups of models. Key characteristics of the model classes will be defined later. We first describe the stereotypical model classes on the basis of their core mechanism.

On the basis of the core working mechanism we distinguish the following groups:

Simple models These are regression models, characterized by the absence of mechanistic relationships. Usually, they predict one variable from two or more other known variables. They directly relate simple socio-economic parameters, to (global) emissions. The IPAT equation (Chertow, 2000) and variants thereof like the STIRPAT equation (York et al., 2003)

are typical representations, but also econometric models of eco-innovation and observed emission reductions (Mazzanti et al., 2014) fall into this group. These simple models have also been coined as empirical statistical models that are fitted to past data (Farmer & Foley, 2009). Other stereotypical model groups that are described later may also contain equations or descriptions based on regression analysis but these equations concern relationships between intermediate variables within the model and don't directly relate input parameters and model output. We will consider the STIRPAT model as stereotypical representation of the group of simple models.

Structural models These models use the structural relationships between industry sectors and final consumers to make an estimate of the emissions associated with final consumption of products (Duchin, 1998). The relationships between the industry sectors are the products that are being produced and consumed by the industries themselves as well as other final consumers. These relationships may be expressed in physical and/or monetary terms. At the same time the products consumed and produced by the industry (sectors) are a representation of the in- and outputs of an industrial process. Life Cycle Assessment (LCA) models, Material Flow Analysis (MFA) models and Input-Output Analysis (IOA) models and combinations thereof are typical representations of these models. The integrated LCA model THEMIS (Hertwich et al., 2015) and the IOA based model CECILIA (De Koning et al., 2015) are examples of combinations of structural models.

The structural models can be combined with linear programming models. A typical representation is the World Trade Model (WTM) (Duchin, 2005; Duchin, 2015). The CECILIA models is a comparative static model but dynamic structural models can be used for techno-economic scenario analysis as well (Faber et al., 2007).

Macro-economic models We coin macro-economic models as models that cover the whole economy. They are either computational general equilibrium (CGE) models or structural macro-econometric models. CGE models assume that the prices in an economy are determined at the multiple markets in which supply and demand are in equilibrium (Burfisher, 2011). The models analyse how the choices of economic agents are coordinated across all these markets. The models assume cost-minimizing behaviour by producers, average-cost

pricing, and household demands based on utility maximizing and cost minimization behaviour. The models may be comparative static or dynamic. An early example on an environmental relevant CGE model is the GREEN model (Burniaux et al., 1991, 1992). The GTAP model and its extensions such as GTAP-E (Burniaux & Truong, 2002) are typical examples of CGE models that have recently been used in climate scenarios (Nijkamp et al., 2005; Dandres et al., 2012)

E3ME (Pollitt et al., 2014; Barker et al., 2015) and Ginfors (Meyer & Lutz, 2007; Lutz & Meyer, 2009) are econometric based macro-economic models. The model combines econometric statistical analysis with input-output analysis embedded in a complete macroeconomic framework. Parameters of the econometric models are often estimated econometrically using time series data (Meyer & Lutz, 2007). The econometric models is a further development of the structural models adding behavioural relationships such as price elasticities and endogenous technology progress. In general econometric models differ from the CGE models by assuming demand-driven development of production outputs and using financial multipliers in the investment part. The models use historical data sets to estimate behavioural model parameters and they do not assume optimal behaviour like CGE models do (Barker et al., 2014; West, 1995). Early examples of the macro-econometric based models were called extended input-output models. The Washington Projection and Simulation Model (WPSM) is such an example (Conway, 1990).

Integrated assessment models Integrated assessment models (IAMs) are used extensively in the examination of the impacts of climate change and the search for socio-economic pathways that meet certain temperature targets. See for instance Smith & Bustamante (2014); Van Vuuren et al. (2010, 2011); Riahi et al. (2011); Thomson et al. (2011); Masui et al. (2011). We define an integrated assessment model broadly as any model which combines scientific and socio-economic aspects of climate change primarily for the purpose of assessing policy options for climate change control. Early examples of integrated assessment models include IMAGE v1 (Rotmans, 1990), the DICE model (Nordhaus, 1994) and RICE models (Nordhaus & Yang, 1996), the ICAM models (Dowlatabadi & Morgan, 1993; Dowlatabadi, 1995) and numerous others (Lempert et al., 1996; Manne et al., 1993; Matsuoka et. al., 1995). The

IMAGE version 3 model is currently used for the analysis of possible pathways leading to a two degrees warming (Van Vuuren et al., 2011).

A distinction can be made between two groups of IAMs. The first group concentrates on the trade-off between the level of mitigation, adaptation and climate impacts. These models include a description of the global economy and its relationships with the three costs categories mentioned above. The description of the different subsystems is often quite simple - and we refer to these models here as the cost benefit analysis type (CBA-type). The second category is more focused on providing an understanding of how the energy system and agriculture system functions in relation to earth system elements. These models are typically used to identify mitigation strategies. We refer to this type as the process IAMs. The DICE model family falls into the CBA type and the IMAGE model belongs to the process type.

IAMs typically consist of several loosely coupled, sometimes called soft-linked (Klaassen et al., 1998), models (see e.g. IMAGE 3.0; Stehfest et al., 2014). In that sense IAMs fall outside our classification scheme because it does not have a single core working mechanism. They are composed of parts, each having a different mechanism. For instance IMAGE 3.0 contains an energy simulation model (Timer; Vries et al., 2001) combined with a CGE model (GTAP/MAGNET model; Wolter et al., 2014) and a land-use model that is a regression-based suitability assessment for crop types (CLUMondo, Van Asselen & Verburg, 2013). Parts of the integrated assessment model might even be replaced by other types of models. The different IMAGE model versions indeed show that in the different versions subparts of the IAM were replaced. Nonetheless we have included the IAMs as a group into our analysis because IAMS are the only type of models that attempt to quantify the positive or negative feedback of rising temperatures on the production capacity of the economy. As an illustrative example, we will use the IMAGE 3.0 model. In Figure 2.2 we show a simplified overview of the landscape of models as we introduced above. Figure 2.1: Diagram showing the different modelling types as distinguished in this article (the last row provides individual models as example of each class).

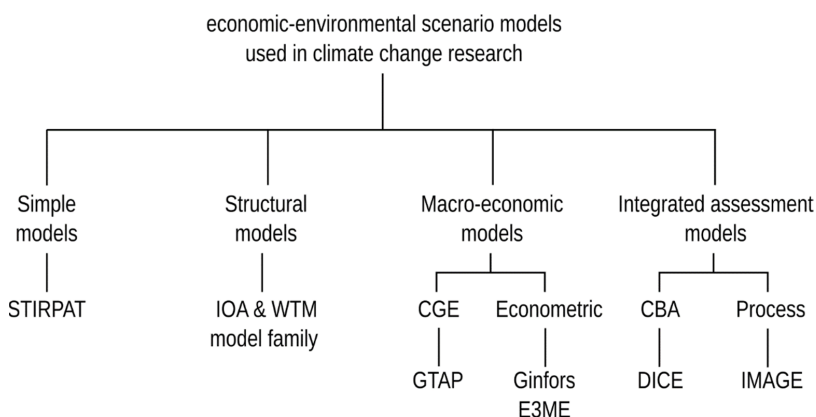


Figure 2.2: Diagram showing the different modelling types as distinguished in this article (the last row provides individual models as example of each class).

2.2.2 Model characteristics

Each of the different (stereotypical) model types will be characterized on the following aspects (1) system boundaries (2) resolution (3) solution mechanism (4) accessibility. Each of these aspects is discussed further below.

System boundaries The models differ in their coverage of the globally connected economy - climate system. The DPSIR chain refers to how economic activity leads to environmental interventions and how these interventions can lead to changes in the environment which can at the same time impact the production capacity of the economy. A typical example would be changes in rainfall patterns (Shilong et al., 2010) that will affect agricultural production. A fully coupled environmental and economic model is necessary to be able to make an assessment of these feedbacks. If feedbacks from the environment to the economy are to be modelled, this request a certain spatial and temporal resolution because climate change impacts are very dependent on location.

We will use the theoretical conceptualization, as shown in Figure 2.2, of the coupled environmental - economics system to characterize the system boundaries for the model groups as shown in Figure 2.3.

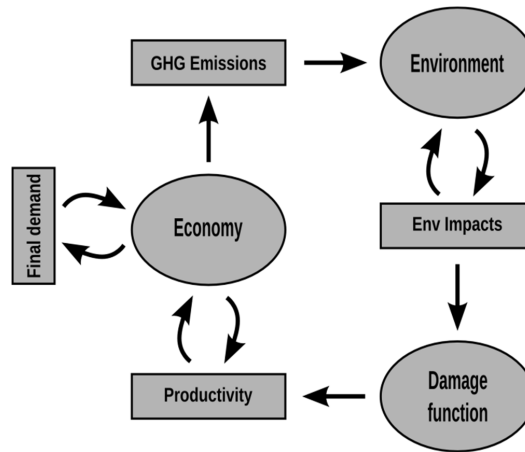


Figure 2.3: Conceptualization of the coupled environmental-economics system

The economy is based on a certain available production capacity, a production capacity that can be influenced by changes in the economy as well. The economy produces products for final consumption and changes in the economy might change final demand and vice versa. The operation of the economy has as a side-effect emissions of GHGs, notably CO₂, CH₄ and N₂O. There is no direct feedback from the emitted GHGs on the economy. However, the accumulation of GHGs in the atmosphere and oceans effects global climate and ocean acidification, which in turn leads to environmental impacts. These environmental impacts such as changes in rainfall patterns, increased CO₂ concentrations, higher average temperatures, sea level rise may in turn damage that production capacity of an economy. If we want to calculate the full effects of a certain socio-economic scenario we need to calculate the fully coupled economic-environmental model. Each of the model types discussed above cover part of this coupled economic-environmental model as will be shown later.

Resolution The resolution is an expression of the level of detail by which the economic and/or environmental systems are modelled. A distinction is made between resolution within the economic system and resolution in the environmental system.

For the economic system the resolution has a temporal and spatial component. The spatial resolution is the amount of regional detail considered. The economic system might be divided into individual countries or into several larger economic regions. The economic system might even be just a single entity without further spatial resolution. The temporal resolution of the economic system is in most cases on an annual basis but some models might have a higher or lower temporal resolution.

Another aspect of economic resolution is the level of detail in economic actors. How many production, consumption and financial sectors are distinguished? Given that the behaviour of each economic actor has to be modelled and data are needed to describe that behaviour, an economic model that has high geographical resolution and high actor resolution needs a large amount of data. This means it is likely that there is a trade-off between actor resolution (and associated economic behaviour modelling) and geographical resolution. Often an actor of interest is modelled in higher resolution than other actors in the economy. For instance, energy sectors are often modelled at higher resolution.

Also the environmental system resolution has a temporal and spatial component. The global warming potential (GWP) which is a measure of the increased radiative forcing by the emission of a substance (Lashof & Ahuja, 1990) is most often used to assess the relative impacts of GHG emissions used in the models discussed later. There is no spatial resolution and often only the GWPs with a hundred year time horizon are being used, offering no temporal resolution. The IAMs are models that have (much) higher temporal and spatial resolution in their environmental systems models. Besides a temporal and spatial resolution also the resolution in the diverse environmental ecosystems can be characterized. Because the IAMs is the only model type that may include specific models for the assessing more detailed ecosystem impacts it is not a distinct feature upon which the models can be differentiated.

Solution mechanism The solution mechanism characterizes the models in relation to four questions: Does the model have a deterministic or stochastic outcome? Is the model static or dynamic? A static model does not contain an endogenous time evolution component in the model. Is the model linear or non-linear? Linearity means that there is a linear dependency between input and output parameters. It does not mean that every equation in the model must

be linear and finally does the model include optimization behaviour. Examples of optimizing model behaviour include optimal distribution of resources, utility maximizing consumers and cost-optimal selection of energy supplying technologies. We find this an important characteristic because it is a core part of a scenario. If a scenario is quantified with a model that is centred around optimal behaviour of economic agents, this optimal economic behaviour is a key ingredient of the requirements to achieve such scenarios as well.

Accessibility Another characteristic of the model is accessibility of the model. Is it possible to obtain, inspect, adapt and run the model? Is it possible to obtain the source code of the model and is this well documented? Can the model be run on current desktop hardware or does it need more powerful hardware such that running the model might not be so easy even though the model itself is available? Accessibility is important for scientific results that depend on computation, because not releasing such code raises needless, and needlessly confusing, roadblocks to reproducibility (Ince et al., 2012). Accessibility is also important because the scenarios are used to suggest policies to mitigate climate change that might have far reaching implications for production and consumption. If the scenarios models are available to others, they might be improved and confidence in the results may improve (Voosen, 2016).

2.3 Results

2.3.1 Simple models

Description The STIRPAT model (Stochastic Impacts by Regression on Population, Affluence and Technology (Dietz & Rosa, 1994, 1997; Rosa & Dietz, 1998) as described by (Chertow, 2000) is an analytical tool which has been used to disentangle the effect of population growth, increased affluence and changing technology on a range of environmental impacts. For instance it has been shown that there is no evidence of an environmental Kuznets curve for total CO₂ emissions (York et al., 2003). The STIRPAT model relates total productivity in an economy to GHG emissions as shown by its equation (York et al., 2003):

$$M_i = aP_i^b A_i^c T_i^d e_i$$

Where M is emission, P , A and T are expressions for population, affluence and technology. The coefficients a , b , c and d have to be estimated and e is an error term. The subscript i denotes that the equation varies across observational units. Typically the equation is fitted to observations from a particular country.

System boundaries The system boundaries of the simple model may be depicted as in Figure 2.4. The size of the economy often expressed in GDP is related to the amount of GHG emissions.

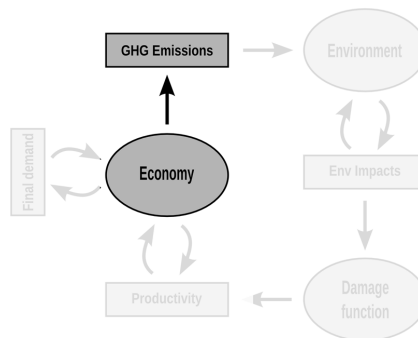


Figure 2.4: Conceptualization of a simple model

Resolution The economic resolution is low both from a spatial and temporal point of view as well as from the number of economic actors point of view. The spatial cover is typically a country or region and covers the whole economy. The model does not distinguish between economic sectors and the measure used for economic activity is GDP.

Solution mechanism The model is calibrated against a set of empirical data. The uncertainty of the model is quantified. Making predictions with the model outside of the range of available empirical data is questionable because no mechanisms are captured by the model.

Accessibility The STIRPAT model can easily be reproduced and adapted to other case studies because the model consists of a single equation only. The STIRPAT model is particular useful for retrospective analysis.

2.3.2 Structural models

Description The CECILIA model (De Koning et al., 2015) is based on global multi-regional supply use table for the year 2000 which is transformed into an input-output table.

A scenario for the CECILIA model consists of exogenous information on population growth, supply and use of energy, general efficiency improvements, and development of specific technologies such as electric vehicles and GHG emission reduction measures such as carbon capture and storage (CCS). This exogenous information is used to adapt the existing supply-use table. For each different scenario a new supply-use table needs to be developed. The new supply-use table incorporating the scenario is subsequently transformed in an IO tables that can be analysed using the familiar Leontief equation (Miller & Blair, 2009):

$$M = B (I - A)^{-1}y + E_{hh}$$

In which M are emissions, B is the matrix of emission per unit of output of each sector, I is the identity matrix, A is the technology matrix that specifies all the inputs per unit of output of each sector, y is final demand and E_{hh} are emissions from household activities. The technology matrix as created in each scenario may be seen as the structural model of the economy and each column in this matrix is a production recipe for each sector.

System boundaries The CECILIA model does not model explicitly environmental impacts as a result of the GHG emissions except that it uses GWP₁₀₀ for characterisation of the substances. The system boundaries of this structural model may therefore be depicted as shown in Figure 2.5.

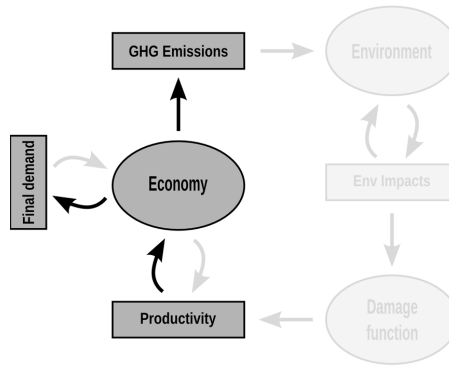


Figure 2.5: Conceptualization of a structural model

Resolution The model consists of four regions, and each of these regions is divided into 160 different industry sectors. It can be used for comparative static analysis.

The core of the CECILIA model is the mechanism by which the exogenous information is incorporated in the supply-use tables and how changes in a particular sector affect the inputs and outputs of the other sector. This macro-economic framework may be depicted as shown in Figure 2.6.

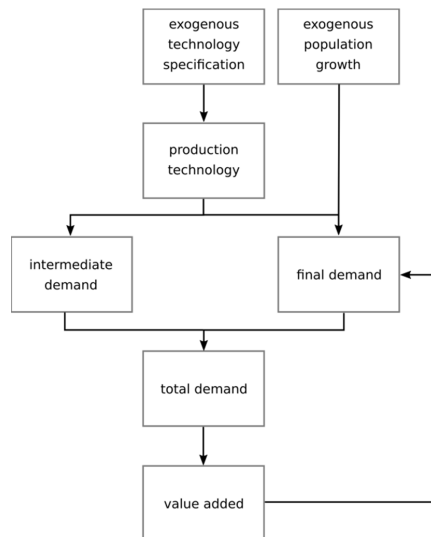


Figure 2.6: Macro-economic framework of CECILIA, inspired by West (2006)

The inputs into CECILIA are technology specifications and expected economic and population growth. The technology specification embodies a technology scenario containing items such as efficiency improvements in industry sectors, expected electricity supply mix, but also changes in the technology used by households. The changes in the technology and population growth leads to changes in the total demand which in turn changes total value added which leads to changes in the total final demand. This structural model assumes that a changing income does not affect spending patterns and the model does not take into account that there may be constraints on the availability of factor inputs. In that sense the CECILIA model contains little additional economic behaviour. Moreover the CECILIA model contains only information on the quantity of goods and services, not about the price of goods and services.

Solution mechanism Equilibrium in the CECILIA model is achieved by balancing demand and supply of products. We classify the economic model in CECILIA as being very simple. As such the model does not allow for the evaluation of economic policy measures such as cross border taxation or subsidy schemes.

A typical application for CECILIA is the implementation of long term technology development scenarios. These scenarios can be used to examine how technology (not necessarily optimal technology) would influence resource use and a broad range of other environmental interventions. The CECILIA model is not suitable for forecasts or predictive scenarios because it lacks mechanisms that model the short term behaviour of economic agents in response to market changes.

Accessibility A proper uncertainty analysis or validation of the model by comparing modelled results with historical time series has not been made yet. It does reproduce some of the GHG emission scenarios calculated through with other and well established models (De Koning et al., 2015). The model is freely available in the form of a collection of Matlab files and

accompanying input and output data¹. It can easily be run by a single user and does not pose special hardware or software.

2.3.3 Macro-economic models

2.3.3.1 Computable general equilibrium models

Description CGE models can be comparative static or dynamic. Dynamic means that the CGE model explicitly traces each variable through time, often at annual intervals. The GTAP model has a comparative static as well as dynamic variant called GDyn (Ianchovichina & McDougal, 2000). This description is based on the original comparative static model.

The theoretical underpinnings and the operation of the GTAP model has been documented extensively (Ianchovichina & McDougal, 2000; Burfisher, 2011). The GTAP model is the basis of many specific scenario models (Burniaux & Truong, 2002; Nijkamp et al., 2005; Adams, 2005; Dandres et al., 2012) It is also an important part of the IMAGE3.0 model (Stehfest et al., 2014). The behaviour of the model is well studied.

System Boundaries An energy extended version of the GTAP model, called GTAP-E (Burniaux & Truong, 2002), incorporates carbon emissions from the combustion of fossil fuels. The CGE models do not explicitly model environmental impacts. As such the system boundaries may be depicted as shown in Figure 2.7.

Notice that in comparison with structural model the difference lies in the interaction between production capacity and final demand. In an IO model a given final demand leads to higher production. In a CGE model demand and production change as in response to price changes.

¹ See <http://cml.leiden.edu/research/industrialecology/researchprojects/projects/cecilia.html>. Accessed 12 October 2017

Resolution The latest version of GTAP database (GTAP 9), a set of social accounting matrices (SAM), distinguishes 140 regions and 59 sectors. The SAMs are used to parametrize the GTAP model. The GTAP models are however never run at the dimensionality provided by the GTAP SAMs. Typically the SAMs are aggregated based on the application of the model. While we do not know every application of the GTAP model, in GTAP-E 8 sectors and 8 regions are distinguished (Burniaux & Truong, 2002) which is at a much lower resolution than multi-regional IO models and lower than the macro-econometric models, see Section 2.3.3.2.

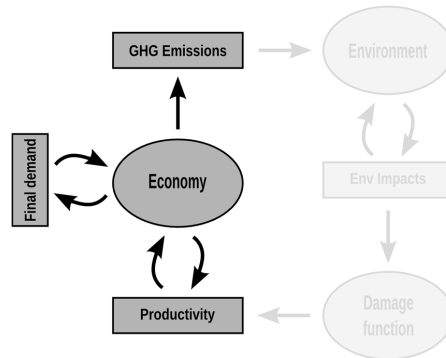


Figure 2.7: Conceptualization of a CGE model.

GTAP contains (non-linear) models for consumption, production, capital and labour markets, international trade, and taxation. It is both a quantity and price model. The prices are established by demand and supply and these prices in return determine for instance the choice between the use of domestically or imported products, see Figure 2.8. Substitution elasticities are the exogenous parameters in the CGE model that describe the responsiveness of supply or demand to a change in prices or incomes. Final demand is governed by demand functions that describe the quantity of goods bought in response to price changes and income changes. In GTAP model different demand functions can be chosen based on the application of the CGE model.

In GTAP, commodity demand by consumers is determined by maximizing utility under a given consumption budget. If the consumers buy domestically produced commodities or

imported commodities is determined by minimizing the commodity cost and producers are cost-minimizing their production (Burfisher, 2011).

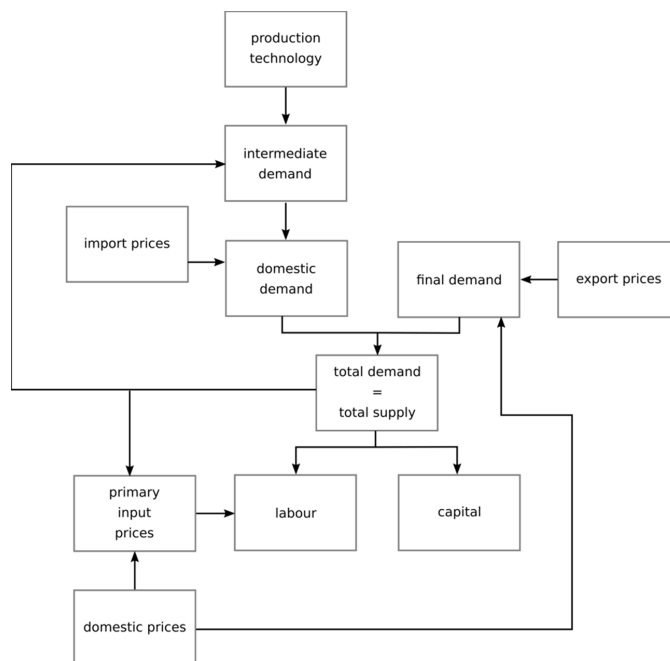


Figure 2.8: Conceptualization of a CGE model, After West (2006).

Solution mechanism CGE models have optimizing behaviour of economic agents and market equilibrium as a core mechanism in the model. The behaviour is described in differential equation. The solution of the set of non-linear equations (differential equations) in GTAP is done by the software package GEMPACK (Harrison & Pearson, 1996). GEMPACK will solve the set of non-linear equations by making a linearized representation of the model and approaching it as an initial value problem (Harrison & Pearson, 1996).

Accessibility The GTAP model and many of its variants can easily be run by a single user and does not pose special hardware but often does have special software requirements. All equations describing the CGE models have been described (Hertel & Tsigas, 1997) and ready-made software is available.

2.3.3.2 Macro-econometric models

Description Macro-econometric models combine econometrically estimated demand equations with input-output analysis embedded in a complete macro-economic framework. An econometric model is a step away from the structural models discussed earlier by encapsulating the IOTs in a macro-economic framework but retains the sector detail and much of the rich detail in environmental accounts. The macro-econometric model is different from the CGE models discussed earlier because they do not assume market equilibrium, optimal economic behaviour and supply-side constraints. We use here GINFORS as a typical example of this type of models, since GINFORS has been frequently used to analyse questions around climate change and resource-efficiency (e.g. Stocker et al., 2011; Distelkamp & Meyer, 2017). The GINFORS macro econometric model can be characterized as an evolutionary model based on bounded rationality of the economic agents and imperfect markets (Meyer & Lutz, 2007).

System Boundaries Like the CGE models the macro-econometric models focus on the economic system and processes in the environment are not modelled. The system boundaries of the macro-econometric models are similar to the CGE based models, see Figure 2.9.

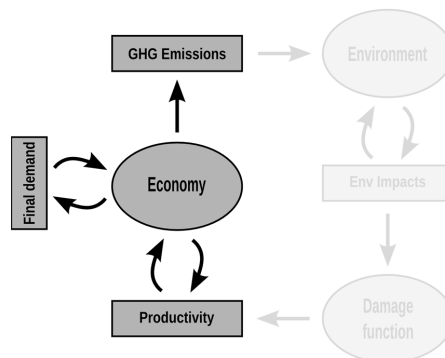


Figure 2.9: Conceptualization of a global macro-econometric model.

Resolution In the macro-econometric model GINFORS covers the whole world distinguishing 50 countries and 2 regions (Meyer & Lutz, 2007). These are all connected with bilateral trade matrices for 25 products. The input-output of each of the countries and regions

are connected through the trade matrices. The input-output tables of a country are connected to a macro-economic model for that specific country. It also contains a detailed energy model and materials model. Energy emissions, land use, material input are all estimated with the GINFORS model (Meyer & Lutz, 2007). The resolution of this macro-econometric model is comparable to that of the structural model. It has more geographical detail but less sector/product detail.

Accessibility The GINFORS model has been well-described in the literature (Meyer & Lutz, 2007). The model itself is not freely available.

2.3.4 Integrated assessment model

2.3.4.1 Process based integrated assessment models

Description The IMAGE3.0 model is a state of the art integrated assessment model. The model is well documented (Stehfest et al., 2014). The IMAGE model is known for the construction of climate change scenarios leading to a radiative forcing of 2.6 W/m^2 (Van Vuuren et al., 2011) consistent with an average global temperature increase of 2°C , the so-called RCP2.6 scenario (Moss et al., 2010). Other integrated assessment models used for the construction of climate change scenarios are RCP8.5 based on the IIASA modelling framework (Riahi et al., 2011), RCP6.0 based on the Asia-Pacific Integrated Model (AIM) (Masui et al., 2011) and RCP4.5 based on the global integrated assessment model (GCAM) (Thomson et al., 2011). Key inputs into the model, so-called drivers of the model can be divided into eight groups: 1) population projections, 2) economic development 3) trade regimes, tariffs and barriers 4) environmental and other policies 5) technological change in agriculture and forestry 6) technological change in the energy system 7) life style parameters 8) energy and land resources.

The IMAGE3.0 model consists of several soft-linked modules that cover the so-called human system, earth system and environmental impacts. Soft-linked means that the model are not run together as a single system, but instead information exchange occurs via input and output files. A module produces output and another module treats the 1st module's output as input. The economic system, in IMAGE called human system, consists broadly of two groups of

models covering agriculture & land use and energy supply & demand. The output of these two groups of models are 1) land cover and land use and 2) GHG emissions.

Subsequently the land cover and land use and the GHG emissions are inputs for models that estimate effects on carbon, water and nutrient cycles and climate. Finally based on the estimated changes in the environment impacts on biodiversity, land degradation, ecosystem services and human development are calculated.

System boundaries The process based IAMs incorporate economic as well as in the environmental system models. IAMs are also in principle capable to model the effect of the emitted GHGs and subsequent climate change on the production capacity of an economy. In Figure 2.10 a conceptual picture of a global process based IAM is shown. Some feedbacks are included in IMAGE while others are not. An example of a (positive) feedback incorporated in the IMAGE model is the fertilizing effect of CO₂ on crops. In contrast, the feedback of a changed environment on the economic system in the IMAGE model is not covered. In the last case, uncertainty has been an important reason not to fully include this impact. Second because the IMAGE model is a soft-linked model it is impossible to iteratively model the full feedbacks. As we will see later cost-benefit type IAMs iteratively try to model full feedbacks.

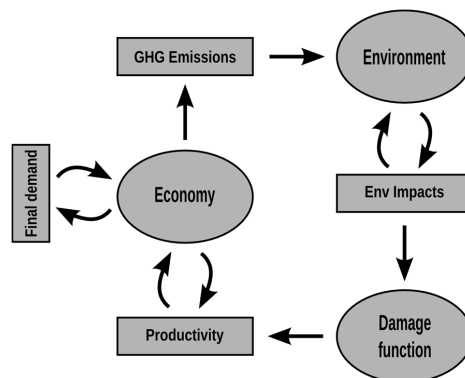


Figure 2.10: Conceptualization of a process based integrated assessment model.

Resolution The IAMs being the only global models incorporating an economic and environmental system, the resolution in the economic and environmental system are discussed separately.

The economic system of the integrated assessment model covers the world, subdivided into 26 regions with a relative high degree of coherence within each region. The economic system model consists of the energy simulation model TIMER that describes 12 primary energy carriers. Output of the model is long-term development of bio-energy production and energy demand and production. Another part of the economic system model is the agricultural economy model. The MAGNET model is used which is based on the standard GTAP model, discussed earlier. The MAGNET model covers the entire economy but has a special focus on agricultural sectors and further distinguishes a few¹ other aggregate sectors (Stehfest et al., 2014). Everything said about the GTAP model applies to the MAGNET model as well. See Figure 2.8 for an overview of a CGE model. The output of the MAGNET model is demand for crops livestock, forest products and all other commodities. Subsequently the location of crop production is modelled using a spatially explicit land use allocation model on a 5x5 minute resolution.

The environmental system is modelled at different resolutions by the different model components. The global vegetation growth model LPJmL distinguishes 12 crop types on a 5x5 minute resolution. Climate impacts are modelled with MAGIC6.0 which calculates the effect of GHG emissions on CO₂ concentration, ocean carbon uptake, radiative forcing, global mean temperature and precipitation. From there on GLOBIO model assesses biodiversity impacts, flood risk and a number of other impacts.

Solution mechanism IMAGE is run in a simulation environment. In this simulation environment, the baseline scenario results are driven by year to year decisions such as development of population, demand for energy services and GDP. There are two major exceptions. The MAGNET model (run via a soft-link) is run on the basis of its optimisation assumptions. Second, in climate policy runs information on the option to reduce emissions in

¹ Unfortunately texts describing IMAGE3.0 are unclear about the number of sectors distinguished.

different part of the system is forwarded to the policy-model FAIR that optimises the reductions in various sectors.

Accessibility The IMAGE3.0 model and its sub models have been well documented (Stehfest et al, 2014). Sensitivity and uncertainty analysis have been performed. The IMAGE3.0 model is a collection of complex models which require large amount of external data. Therefore, it cannot be run by a single person and requires specialized hardware and software. Scenario modelling with IMAGE is a multi-institute effort. The models and data are not freely available. The IMAGE model might be seen as the most inaccessible model of all climate scenario models discussed in this paper.

2.3.4.2 Cost-benefit analysis type integrated assessment models

Description The DICE model is a dynamic model which was used to calculate the economic costs and benefits of climate mitigation scenarios. To be able to do so, first the damage costs to the production capacity of the economy by unmitigated climate change had to be estimated. Second the costs of climate mitigation scenarios had to be estimated.

The DICE model calculates the quantity GHGs emitted by economic activity based on the rate of economic activity and the amount of GHG emissions per output of that activity. The GHG emission intensity decreases over time. A climate change mitigation scenario leads to faster decreases in GHG emission intensity. The development of economic activity over time is influenced by the exogenous input parameters population growth and technological development. The GHG emissions lead to a higher concentration of GHGs in the atmosphere. A simple relationship was used to estimate mean global temperature on the basis of the accumulated GHGs. Finally a damage function expressed the damage done to the production capacity of the economy (Nordhaus, 1994). This whole system of equations is solved at once.

System Boundaries The DICE model incorporates both the economic and environmental system although in a superficial manner. Its system boundaries can be shown as in Figure 2.11.

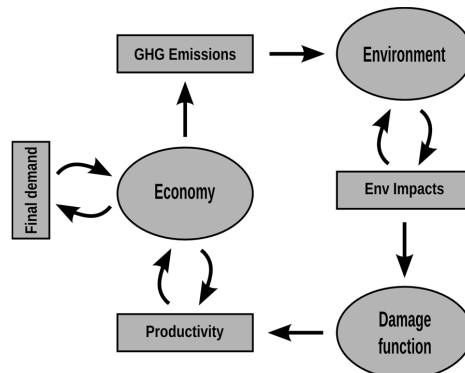


Figure 2.11: Conceptualization of a CBA type integrated assessment model.

Resolution The DICE model does not subdivide the global economy and as such its spatial resolution is low. There is also no further modelling of interactions between actors such as done in the IO, CGE and macro-econometric models where changing output of one sector affects the output of other sectors. The economic model in DICE is very simple indeed. Just as simple as in the simple models category.

The environmental model is also simple. There is a simple model that accounts for the half-time of GHGs in the atmosphere. GHG emission rate and half-time of GHG emissions determines the evolution of GHG concentrations.

Solution mechanism The model consists of a few (non-)linear functions that have to be solved for each time step.

Accessibility The model is simple enough to be reproduced as demonstrated by Kaufmann (1997).

2.4 Discussion

2.4.1 System boundaries

It is quite clear that IAMs are the only type of models that potentially are capable of exploring the full effect of a particular climate change scenario because they are the only models that include feedback mechanisms from the environment to the economy. Critical here is climate feedbacks on agriculture and forestry. Agriculture and forestry sectors are needed to support the increasing demand for biofuel, biofuel that is critical for the climate change scenarios in which the well below 2 °C target is met. The simple, structural, and macro-economic models do not take climate feedbacks into account (unless their input parameters somehow take it into account).

Although the CBA type IAMs take climate feedbacks into account, it is modelled in such a simple manner that no additional insight is gained into for instance the effect on agricultural productivity. In the process type IAMs the large number of soft-linked models and the limited climate feedback mechanism incorporated prevent a full assessment of the climate feedback mechanism. An example is feedback effects on crop productivity. In the IMAGE model elevated CO₂ concentrations are expected to lead to higher crop yields. However any other effects of climate change such as extreme weather events, increased susceptibility to insect damage, increased nutrient limitation are not taken into account (Stehfest et al., 2014). Furthermore the increased crop productivity does not lead to further chain effects in the economic system.

Climate feedbacks on agriculture and forestry are not a theoretical possibility that does not happen at average global temperature increases of 1.5 - 2 °C. Even at current level of temperature increase, Canadian pines forest are decimated by pine beetles that now thrive due to increasing temperatures (Kurz et al., 2008).

This indicates that there is a need for an integrated economy - environment model in which climate feedback mechanisms can be modelled to the fullest extent to be able to assess effects on at least agricultural and forestry productivity. This is becoming even more important now that there is a real threat that the 2 °C cannot be met (Tollefson, 2015). At least it should be

established that climate change mitigation using bioenergy in combination with CCS is not hampered or obstructed by climate change itself.

Fully integrating economic and environmental models likely means sacrificing some of the highly detailed environmental process modelling against the ability to solve a full coupled economy-environment model at once. This also means that this model cannot be soft-linked because it would be time consuming to iteratively solve the combined set of models.

The structural models with their simple description of the economy but very detailed sector resolution, especially in the agricultural and energy sectors might be used for such a model if they would be extended with a sufficiently detailed environmental model that can reasonably model feedback effects on the economy.

2.4.2 Economic model resolution

The simple models have a very low resolution. As such they can be used for interpretation of past trends. Their aggregated nature prevents makes them unsuitable for the implementation of meaningful socio-economic climate scenarios. Given that the DICE model relies on a very simple economic model as well, it is doubtful that such a CBA type IAM is very useful to inform us about the optimal economic climate mitigation measures.

The CGE and macro-econometric models are capable of investigating the effect on the economy and GHG emissions of all kinds of (economic) policy measures. The CGE model typically distinguishes fewer sectors and fewer regions than the macro-econometric models. The CGE and macro-econometric models calculate economic effects from a different point of view. The CGE models assume an economic optimal operation of the economy. The econometric based models are empirically grounded. A side by side comparison of GINFORS with the EXIOMOD CGE model (Meyer & Ahlert, 2017) concluded that the core paradigms of the econometric models and CGE models had decisive consequences when it came to evaluation of environmental tax reforms.

The economic model within the process based IAM is not meant for economic analysis but is used to quantify the amount of activities taking place in an economy under different scenario

assumptions. The economic model can be in the case of IMAGE as complex as the MAGNET CGE model and it is further enriched by inputs from the energy simulation model TIMER. However the soft-linked TIMER and MAGNET CGE model does not provide the detailed and integrated view on inter-industry connections and industry outputs as available in a structural model.

All the economic models discussed above have more or less elements that are extrapolations of past trends. For the simple model it is obvious because it represents a regression line fitted to past data. For the more complex models the extrapolation is found in endogenous factors incorporated in the model. For instance the structural models have the input-output coefficients that were observed in a certain year. CGE models and econometric models additionally use for instance observed price and substitution elasticities. These endogenous factors represent our understanding of the world as we know it today.

When investigating long term explorative scenarios we must be aware that the world might function quite differently from the way it functions today. On time scales of decades' inventions and innovations may strongly alter what is being produced and consumed and how is being produced and consumed. In such a future world, with new classes of technology, it is not known how price elasticities and consumer preferences will look like for products and technologies that are currently in their infancy or do not exist at all. If these (endogenous) factors are not known - factors that are crucial for the modelling of economic behaviour - modelling of economic behaviour becomes difficult. Models in which it is easy to identify and alter endogenous factors based on exogenous information or scenarios would support long term explorative modelling. Structural models with their simple structure fulfil an important role here.

The structural models which are based on combinations of linear functions. The assumption of linearity in economic systems might be seen as a weakness of the structural models. However, while the specification of economic mechanism in CGE models is done using (non-linear) differential equations, the solution of CGE models (among which the MAGNET model used in IMAGE) is done on the basis of a linearized version of these equations. The linearity of structural models is therefore less of a drawback compared to CGE models.

The CGE models and the economic models in the process based IAMs all contain mechanisms where optimal economic behaviour and/or optimal allocation of resources is assumed. A scenario analysis with these models will therefore contain as a major assumption that this optimal behaviour will take place. The results of CGE models and IAMs are therefore to be interpreted likewise.

2.4.3 Environmental model resolution

The IAMs are the only type of models that include a model of the environmental system. The CBA type IAM examined here (DICE; Nordhaus, 1994) has a rather simple environmental system model. A distinct feature of the model is the inclusion of a damage function that expresses the effect of changed mean global temperature on the economy. The CBA type IAMs can in principle calculate the full economic effect of a scenario but as argued before they fall short of that goal because they are too simple.

The process based IAMs incorporate very complex environmental models. Part of the environmental models have a high level of spatial resolution and environmental mechanisms are modelled in great detail. Some effects of increased GHG emissions in the atmosphere on the economic system have been incorporated into the modelling framework. One such an effect is the fertilizing effect of CO₂ on crop growth. However only this positive fertilizing effect has been taken into account, none of the possible negative effects of crop growth have been taken into account making the model biased. A full analysis of the feedback effects is not possible as described in Section 2.4.1.

We have seen that the CGE model and the economic models incorporated in the process based IAMs contain elements of optimal economic behaviour. Given that the environmental models in the IAMs cannot analyse the full feedback effects of the environment on the production capacity of the economy, we conclude that CGE containing process based IAMs can be optimistic about the effort needed to reach a certain climate target.

2.4.4 Accessibility

If a model becomes more complex, more information is needed and it takes more effort to run the model and hence the model becomes less accessible. It is an inherent problem. The structural models are relatively easily accessible because the required data are available, the software is available and they do not require special hardware and software. Accessibility also means that the model has been described and the behaviour of the model is well understood. Typically this means that sensitivity, uncertainty analysis has taken place and the model has been validated. Most of the models (or parts thereof) have to a certain extent been validated. The CECILIA model has not seen such a validation yet. This is clearly a drawback of the model.

2.4.5 Combinations of models

The discussion above centred on the stereotypical representations of the model categories. Model categories with their own strength and weaknesses. By combining/integrating the different models types, one can try to overcome the limitations of the individual model categories. The number of combined models that have been used in scenario analysis is enormous, we just name a few interesting examples of these model combinations to show that almost any combination between model categories is possible.

For instance Manne & Wene (1992) made a combination of a macro-economic model and a MARKAL model. The paper summarizes the development of a new hybrid MARKAL-Macro (M-M) energy system model for the UK. This hybrid model maintains the technological and sectoral detail of a bottom-up optimization approach with aggregated energy demand endogenous and GDP impacts from a single sector neoclassical growth model (Strachan & Kannan, 2008). This paper has demonstrated the feasibility of a formal hard link between MARKAL (a systems engineering model) and MACRO (a long-term macro-economic growth model). The merger combines MACRO's aggregate view together with MARKAL's detailed analysis of technical options for future energy systems.

An example of an LCA model in combination with a partial market equilibrium is the U.S. Forest Products Module (USFPM). The LCA is used to analyse an energy demand scenario in

which wood use increases to 400 million cubic meters in the United States for ethanol production (Earles et al., 2013).

An example of an IOA model used in combination with a partial equilibrium model is the combination of the EIPRO IOA model with the CAPRI model (Tukker, et al., 2011; Wolf, et al., 2011). The agricultural CAPRI model was linked to the static IOA model and used to investigate changes in agricultural production as a response to changes in the final demand for agricultural products in the EU.

2.4.6 Positioning the structural model

The CECILIA model, as a specific example of a structural model, focusses on technical and supply chain relationships within the global economy. Its sector resolution, especially in the agricultural sectors and energy sectors, is in general higher than in any of the other model types. This makes the CECILIA model well suited to examine the industry interrelationships in a comprehensive and consistent manner. Process based IAMs like IMAGE lack this full integration of linkages between different economic sectors, but treat for instance agriculture and energy in separate model modules. Most CGE and Econometric models discern just one agricultural and resource-extraction sector, implying they cannot analyse well how a higher use of biofuels impacts land use or how a higher use of solar cells impacts the level of extraction of specific metals (De Koning et al., 2018). Another example is that in the energy - CGE model combinations a direct link is lost between for instance the output of coal power plants and coal mining with all its associated inputs (including demand for that same electricity), because two separate models are used for the energy sectors and the rest of the economy.

There are no endogenous economic model mechanisms within the structural model. They lack for instance price elasticities and endogenised relations between capital savings and investment, and how productivity changes due to investments. Econometric and CGE models contain such information, and hence are better suited for modelling the impacts of economic policy measures and other predictive analyses, particularly on the short to medium term. For scenario analysis several decades ahead, it is questionable if the build in endogenous mechanism in econometric and CGE models, parametrized using historical data, are still a

reasonable representations of a future world. On this point, the lack of endogenised information in structural models in fact may be an advantage. In the structural models without endogenous mechanisms all information on the future state of the world has to be exogenously supplied. This makes it transparent what the assumptions are on which the scenario rests. When doing long term what-if analyses, this is in our view a clear advantage of the structural models over CGE or Econometric models.

The linearity of the structural models cannot be seen as a drawback of these types of models compared to CGE models. The widely used CGE models are in practice also often linearized.

Compared to both process and CBA IAMs, CECILIA has the advantage of a comprehensive, detailed and integrated economic coverage, but misses endogenised economic mechanisms, modelling of environmental processes, and feedback of environmental change to economic sectors. Part of these limitations of structural models like CECILIA can be overcome by hard-linking it to an environmental systems model that includes a feedback on economic production. Of particular interest is the full feedback of increasing global mean temperature on agricultural and forestry sectors.

The CECILIA model has not yet been validated by comparing modelled results with historical time series. Recently a time series from 1995 to 2011 of supply-use tables have become available. This time series would allow the CECILIA model to be validated. For further use of structural models in climate change scenario studies this validation is an important next step. At this point this structural model hence must be used with caution in modelling future climate scenarios. At the same time there is reason for optimism. Some of the CECILIA model results were compared to other climate change scenario models. These first comparisons showed that the CECILIA model reproduced (almost spot on) the BAU scenarios from RCP 8.5 (De Koning et al., 2015).

2.5 Conclusions and recommendations

This research examined the position of structural economic models in relation to other model types used in climate scenario studies. The structural model takes up an interesting position with respect to the partial equilibrium and CGE models. Structural models may particularly be used for long term what-if scenario analysis and a consistent approach towards modelling the economy without optimality assumption. The apparent drawback, i.e. that various parameters like economic growth have to be brought in exogenously, is in fact a strength for such long term scenarios since such assumptions are made transparent. The structural models can however not replace IAMs because they model only the economic system and lack modelling of environmental processes and feedback of these on the economy. To overcome the last drawback, it is recommended to examine if the structural models might be extended with a hard-linked environmental model that is capable of estimating feedback effects on the economy. At this moment there does not seem to be a process based IAM that fully takes into account feedback effects on the economy. Further, it is recommended to execute, as a first step to further use in climate scenario studies, to carry out a validation of the CECILIA model by checking how good the model is able to match historical time series of economic development and emissions and resource extraction.

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Chapter 3

Effect of aggregation and disaggregation on embodied material use of products in input-output analysis¹

Abstract

Consumption based material footprints calculated with multi-regional Input-Output (mrIO) analysis are influenced by the sectoral, spatial and material aggregation used in the mrIO tables and the lack of disaggregation can be a source of uncertainty. This study investigates the effect of the resolution of mrIO databases on consumption based material footprints. The effect of aggregation was investigated by making different input-output tables with different spatial, product and material category resolution and comparing the calculated material footprints. Our results indicate that the material footprints of countries calculated with the different spatial and product aggregations are in general in the order of a few percentage with outliers in the order of 25% difference. The use of IO models with a low product category resolution (e.g. 60 product categories) to calculate the embodied material use of individual products will likely result in estimations of the total embodied material that are for some product categories inaccurate. The effect of having aggregated material categories as extensions to the mrIO is more influential on the material footprint of countries, the difference can be in the order of 30% when aggregating the original 46 material categories into 16 material categories. This result strongly suggests that the material data used for to create the extensions for the IO framework should be collected at the highest resolution that is practically feasible.

3.1 Introduction

Multi-regional IO systems are currently recognized as constituting a state-of-the art system for the calculation of economy-wide environmental impacts of consumption, including carbon, water, land and material footprints (Bruckner et al., 2012; Tukker et al., 2014; Eisenmenger et al., 2015; Bouwmeester, 2014; Wiedmann et al., 2014). Different multi-

¹ This chapter has been published as: De Koning, A., Bruckner, M., Lutter, S., Wood, R., Stadler, K., and Tukker, A. (2015). Effect of aggregation and disaggregation on embodied material use of products in input-output analysis. *Ecological Economics*. 116, 289-299. DOI: 10.1016/j.ecolecon.2015.05.008

regional IO systems (mrIOs) exist, and they differ in their level of resolution with respect to material categories, products/industries and countries/regions (Tukker & Dietzenbacher, 2013). Much of this work on consumption-based accounts with mrIOs has focused on the carbon footprints of countries and products (Hoekstra, 2010; Ahmad & Wyckoff, 2003; Hertwich & Peters, 2009; Davis & Caldeira, 2010), and increasing attention is devoted to factors causing uncertainty in such footprint estimates (e.g. Peters et al., 2012; Wilting, 2012; Lenzen et al., 2010; Moran & Wood, 2014; Stadler et al., 2014). Currently, efforts are being made to use similar approaches to estimate footprint type indicators of material usage for policy applications (EC, 2011; OECD, 2011). An important example of such efforts is the ongoing work of the United Nations Environment Program International Resources Panel (UNEP IRP)¹ and OECD (2008) to develop a harmonized resource extraction database covering almost all countries in the world. In this context, the question is what factors are relevant when creating robust estimates of material footprints. Since the UNEP IRP effort will harmonize much of the primary extraction data, the question we focus on in this paper is: what is the impact of data resolution and aggregation on estimates of material footprints using mrIOs? We focus on this specific question within three particular domains: (1) the resolution of information on material extracted from the environment; (2) the resolution of product groups tracked in the input-output system; (3) the geographic resolution. By investigating these aspects, we have sought to identify a reasonable level of resolution for mrIO work in order to get representative results, and to identify the areas that are most critical to provide detail on when either creating or utilizing mrIO data.

Tukker & Dietzenbacher (2013) provided an overview of the latest developments in mrIOs. Previous work has shown that the resolution in an input-output table (IOT) affects the results obtained. As early as in 1949, Leontief discussed the influence of aggregation (Leontief, 1949). Hatanaka (1952) and McManus (1956) showed that aggregated input-output tables are very likely to yield outputs that differ from that of the original table. The impact of the resolution of IOTs and mrIOTs on footprints of countries and products has until now mainly been investigated for CO₂ or greenhouse gas emissions (e.g. Su & Ang, 2010; Su et al., 2010;

¹ See the website of the UNEP IRP (<http://www.unep.org/resourcepanel/>) for completed work and ongoing research.

Lenzen, 2011; Bouwmeester & Oosterhaven, 2013; Steen-Olsen et al., 2014). The conclusion of this work is that a greater level of sector and country resolution generally improves the accuracy of carbon footprints estimates. Bouwmeester & Oosterhaven (2013) concluded that the effect of sectoral aggregation is much larger for water footprints than for CO₂ emissions, highlighting the need for a separate investigation of the influence of aggregation on material footprints. Wood et al. (2015) compared multipliers and impacts embodied in the trade of labour and carbon dioxide, finding significantly enough variation to warrant further research into disaggregation. Lenzen (2011) empirically analysed the question, again for carbon dioxide, finding a clear indication that disaggregation is always preferred to aggregation. Steen-Olsen et al. (2014) concluded that more work is necessary to investigate the relationship between the level of resolution of IOTs and multipliers for other environmental extensions, such as materials. Huysman et al. (2014) looked at the need for disaggregated material extraction data in order to characterize the material footprint by means of a secondary indicator (exergy in this case). Linking pressure indicators such as material extraction to impact indicators that require a characterization of resource use will create a further argument for material disaggregation, which we acknowledge, but do not analyse here.

Work on understanding the uncertainty in material footprint calculations with mrIO is still in its early stages. Eisenmenger et al. (2015) and Giljum et al. (2014) presented comparisons of the material footprint for Austria, the EU-27, the US and China, calculated using different mrIOs: WIOD (Dietzenbacher et al., 2013; Timmer, 2012), Eora (Lenzen et al., 2013), GTAP (Narayanan et al., 2012), OECD-GRAM (Bruckner et al., 2012) and EXIOBASE (Wood et al., 2015). The material footprints calculated with these mrIOs ranged from 29 to 33 tons per capita for Austria (Eisenmenger et al., 2015), and from 10 to 11 billion tons for the EU-27, 7.5 to 12.5 billion tons for the US, and 7 to 19 billion tons for China (Giljum et al., 2014). It is likely that this range of outcomes is principally due to basic differences in, for example, the material extraction data used (an issue that will be solved by the aforementioned work of the UNEP IRP). However, as was found for carbon footprints, some of the differences can be

attributed to differences in resolution, at the level of countries, industry and products, and material categories, as used in the different mrIOs¹.

Until now the effect of resolution in mrIOs on the material footprint has not been studied in detail. The specific novelty of the present study is its focus on material footprints and the effect of using more or less detail in material categories. As indicated above, the effect of material category resolution is especially interesting for the ongoing discussions at UNEP regarding the set-up of a world-wide material accounting database. While the incorporation of this database in a detailed mrIO can definitively be an argument for a high level of detail, issues such as copyrights or the demand for less detailed data by the majority of users argue for the use of less detailed material extraction data. This paper aims to specifically offer guidance on the effects of having higher or lower resolution in the material data.

We place this research question in a broader context by calculating both material and carbon footprints, and comparing the results regarding the variance of the calculated material footprints with the calculated carbon footprints of countries and products/industries. The carbon footprints serve as a reference with which the material footprints are compared. Is the effect of resolution on the material footprint smaller or larger than on the carbon footprint? The carbon footprint is a useful reference because of the wealth of other studies examining the effect of resolution on carbon footprints. In addition, greenhouse gas emissions are also emitted by many sectors of the economy, in contrast to material extraction, which is by and large concentrated in the agriculture, forestry and mining sectors, leading to much higher concentrations in supply chains.

This study used the recently published version 2 of EXIOBASE (Wood et al., 2015; Tukker et al., 2014). The available multi-regional supply-use tables (mrSUTs) at the highest level of

¹ As summarized by e.g. Tukker et al. (2013), not only the mrIO approach but also various other approaches, including coefficient approaches, can be used to estimate (material) footprints of countries. A coefficient approach for the material footprint looks at the weight of an imported product according to trade data, and then uses life cycle inventory data to estimate the primary material extraction needed to produce that product (cf. Eurostat, 2012b). Comparison of mrIO and coefficient approaches is beyond the scope of this paper – see Schoer et al. 2013.

detail were used as the starting material. Subsequently, this set of mrSUTs was transformed to four different mrIOs, each representing a scenario. These scenarios allowed us to investigate the effect of (1) reduced product resolution, (2) reduced spatial resolution, and (3) reduced material category resolution. The basic comparison between the scenarios regards the total material and carbon footprints of countries/regions and the embodied material use and carbon emissions of products per million Euro of the product. In specific cases, the result was broken down into different material categories for further explanation and interpretation.

3.2 Material and methods

Most of the studies mentioned in the introduction investigated the effect of aggregation of the IOT. However, since the work of Stone and co-workers (UN, 1968) it is generally accepted that the best route to arrive at an IOT is to compile data in the form of a supply-use table (SUT) first. This SUT is then transformed into an IOT for analytical purposes. The purpose of examining the influence of aggregation is to assess the implications of having less detailed data available. Since the basic data for an IOT is given in the form of a SUT, the investigation preferably starts by aggregating the SUT and transforming the aggregated SUT into an IOT. As is shown below, aggregation at the level of an SUT usually results in an aggregated IOT that is different from an IOT created by aggregating the IOT in the same way.

Various SUT to IOT transformation models exist, see for instance Miller & Blair (2009) and Eurostat (2008), but the most commonly used model for product-by-product tables uses transformation according to the industry technology assumption (PxP-ita), which is also recommended by the UN (1993). The PxP-ita IOT always gives positive values and can work with rectangular SUTs like those used in this study. We therefore used the PxP-ita model in this research to transform the SUT into a symmetric product-by-product table.

The basic data used to construct all four scenarios consists of mrSUTs exported from EXIOBASE version 2.2.0¹. This set of tables represents the EXIOBASE mrSUT data at their highest level of detail for 48 countries/regions, 200 product categories, 163 industry sectors

¹ EXIOBASE version 2 can be downloaded free of charge from www.exiobase.eu.

and 46 different material categories. See the Supporting Information for a full specification of these classifications. Also included in the set are the three major greenhouse gases (CO₂, CH₄ and N₂O). These were used to calculate consumption-based carbon footprints of countries as well as carbon footprints of individual products, and served as a reference with which the material footprint can be compared.

The total material footprint is based on the sum weight of all the individual material categories (only the “used extraction” categories were taken into account. The “unused extraction” data have not been used). The carbon footprint was calculated based on the global warming potentials of CO₂, CH₄ and N₂O with a 100-year time frame (GWP₁₀₀). These values are given in the Supporting Information.

The construction of the four different scenarios is described below, while a graphical overview is provided in Figure 3.1.

Default scenario. This is the scenario at the highest level of detail, where the mrSUT is transformed into a product-by-product IO system according to the industry technology assumption (PxP-ita), distinguishing 48 countries/regions, 200 products per country/region and 46 different materials. The algorithms for the transformation of the mrSUT into an mrIOT can be found, for instance, in Eurostat (2008) and Miller & Blair (2009).

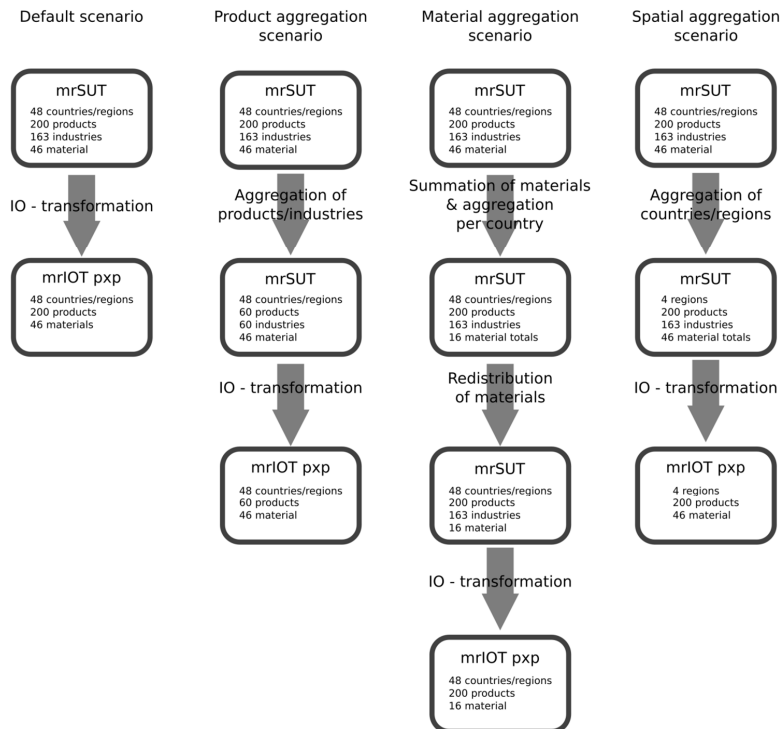


Figure 3.1: Overview of transformation steps used to create the different scenarios.

Product aggregation scenario. This scenario investigates the effect of working with a reduced product resolution on the calculated material and carbon footprints. First, the mrSUTs at the highest level of detail are aggregated into a mrSUT with a 60 products by 60 industry sectors dimension. This reduced resolution mrSUT is then transformed into a PxP-ita mrIO. The detailed product and industry classification can be found in the Supporting Information. The 60 product groups represent the product resolution at NACE rev 1.1 level 3 (EC, 2002) which is the level of detail of the SUTs supplied by Eurostat¹ for the years 2000 – 2006 (more recent years are available in a NACE rev 2 classification). This scenario thus typically represents a study in which mrIOs are constructed without further disaggregation of standard available SUTs.

¹ Available at epp.eurostat.ec.europa.eu, accessed 29 September 2014.

Spatial aggregation scenario. This is a scenario in which the original 48 countries and regions are aggregated into 4 large world regions, i.e. European Union (EU), high income countries (HI), fast developing countries (BX) and a rest-of-the-world region (WW). The definitions of these regions can be found in the Supporting Information. Comparing this scenario with the default scenario shows to what extent spatial aggregation may affect the overall material footprint calculations. For products, there exists a hierarchical classification in which product groups are defined at different levels of aggregation. These aggregated product groups combine more or less similar products. Such a standard hierarchical classification does not exist for countries. We decided to at least distinguish the European Union as an area of interest, and defined the other regions based on their current economic development, constrained by the countries distinguished at the lowest level of detail in EXIOBASE. The implications of this choice are examined below when discussing the results of the spatial aggregation scenario.

Material aggregation scenario. This is a scenario that assumes that the material extraction data are available at an aggregation level of 16 different categories, rather than at the default level of 46 categories. The 16 material categories¹ represent the two-digit level of the material categories defined in Eurostat's economy-wide material flow accounts (EW-MFA) guide (Eurostat, 2012a). The correspondence between the two-digit EW-MFA material categories and the 46 EXIOBASE material categories is given in the Supporting Information.

The multi-regional material extensions table was not simply aggregated into 16 material categories before the transformation into an mrIO system. Such an operation would not change anything relative to the default scenario when calculating the total material footprint of countries or products. Instead, the aggregation of the material categories was carried out in such way that it mimicked the difficulties that arise when attributing the extraction of specific material categories to specific industry sectors when the material categories are much more

¹ The official EW-MFA classification at the two-digit level distinguishes 17 categories. However, two of these categories (A.3.2 - Chalk and dolomite and A.3.6 - Limestone and gypsum) fall into a single EXIOBASE material category (Non-Metallic Minerals - Limestone, gypsum, chalk, dolomite), see Supporting Information. Therefore, the two EW-MFA categories are treated as one.

aggregated. In the course of the construction of EXIOBASE, total domestic extraction of the 46 material categories could quite easily be attributed to the production of specific products. For instance, domestic extraction of rice can be attributed to rice output, iron ore to mined iron output etc. When all agricultural products are lumped together into a single “crop extraction” category, simplistic assumptions have to be made about the distribution of this crop extraction over the different agricultural products, if no further information is available. This scenario assumes that the distribution of material categories that can be attributed to more than one product category is proportional to the monetary value of these product outputs.

The material aggregation was done in the following steps. The material extensions table per country that is available in the SUT system in the form of material category use per industry sector was first used to calculate the total material extraction in a country for 46 material categories. Subsequently, these totals were aggregated into the 16 EW-MFA categories. Each of the aggregate material categories was then allocated to the production of one or more products using an allocation matrix which is described in detail in the Supporting Information. The allocation matrix and supply table of a country were then used to redistribute the total material extraction over the different product outputs and were subsequently transformed into a new material extensions table at the 16-category level for the mrSUT. This mrSUT was then transformed into a PxP-ita mrIO at the level of 48 regions, 200 products and 16 material categories. A full mathematical description, including an example of the material aggregation, allocation and redistribution operation can be found in the Supporting Information.

The four different scenarios resulted in a set of four different mrIOs. These mrIOs were used to calculate the material and carbon footprints of countries. We also calculated the materials and carbon emissions embodied in the individual product groups, expressed in thousands of tons per million Euro and kg CO₂ equivalents per million Euro, respectively. Subsequently we calculated the percentage change going from the default scenario to one of the other scenarios with reduced. A change of 50% means that the scenario resulted in a footprint that is half as much higher than that of the default scenario resolution e.g. from 56 to 84 kg CO₂/million Euro. A change of -50% means that the scenario resulted in a footprint half as low as that of the default scenario, e.g. going from 46 to 23 kg CO₂/million Euro. Notice that calculating the

percentage change means a transformation of scale, where the highest negative change possible is -100% and the highest positive change is unlimited (in theory).

The distribution of differences obtained from the calculations was described with the usual statistical metrics such as the median, as well as the 1st and 3rd quartiles. The standardized unitless measure of kurtosis was also calculated, which is important to detect if the differences resulting from the aggregation have a larger influence on the material footprint than on the carbon footprint and vice versa. Kurtosis is a measure reflecting the degree to which a distribution is peaked, or more specifically, it provides information regarding the height of a distribution relative to its standard deviation (Sheskin, 2007). Distributions may be divided into three categories: mesokurtic, leptokurtic and platykurtic. The mesokurtic distribution can be represented by a normal distribution and has a kurtosis of approximately 0. A leptokurtic distribution has a higher degree of peakedness compared to the mesokurtic distribution, and its kurtosis is much larger than 0. The platykurtic distribution is much more spread out than the mesokurtic distribution, and its kurtosis is much less than 0, and we may expect a high probability of extreme values (Sheskin, 2007).

Note that to ensure a fair comparison between carbon footprint and material footprint, and in order to focus on the influence of resolution, the direct GHG emissions associated with the consumption phase of products (also called household emissions) were not taken into account. There are two reasons for not doing so in this study. Firstly, domestic extraction of materials only occurs at the level of industry sectors, not at the household level. Secondly, it is not very simple to allocate the total GHG emissions of households to the final consumption of a product. The calculation of the carbon footprint of products thus represents only the emissions occurring within industries. As a consequence, the carbon footprints of countries presented in this paper should not be interpreted as comprehensive, and they are not comparable to results presented elsewhere.

3.3 Results

In the following tables and figures we present the results of the analyses carried out, which are then discussed in more detail. Table 3.1 presents an overview of the percentage changes of the

material and carbon footprints of countries resulting from aggregation. The calculated material and carbon footprints of all the individual countries are given in the Supporting Information. Table 3.2 provides an overview of the percentage changes of the material and carbon footprints of products/industries. Box-and-whisker plots of the same results are shown in Figure 3.2, while the corresponding histograms are given in the Supporting Information.

Table 3.1: Statistical measures describing the differences (expressed in percentages) observed between the material and carbon footprints of countries, under different assumptions about the resolution in the Supply-Use table.

Metric	Effect of spatial aggregation		Effect of product aggregation		Effect of material aggregation
	Material FP	Carbon FP	Material FP	Carbon FP	Material FP
Count	4	4	48	48	48
Min	-2.67	-0.25	-28.7	-10.1	-18.6
Max	2.10	0.56	13.7	46.7	30.7
Median	-0.40	0.27	2.88	0.65	2.08
25% quartile	-2.14	0.08	0.43	-1.57	-0.65
75% quartile	1.39	0.39	5.03	1.75	5.67
interquartile range	3.52	0.31	4.60	3.31	6.32
In range -25% to 25%	100	100	98	98	98
Kurtosis	-4.8	1.2	5.02	28.81	6.07

3.3.1 Product aggregation scenario

Calculating the carbon footprint of countries with the product aggregation scenario leads in most cases to less than 10% increase or decrease of the calculated carbon footprint. The exception is Luxembourg, with a 47% higher carbon footprint (see Table 3.1). The influence of reduced product resolution on the material footprint of countries ranges from -29% to +14% (see also Figure 3.3). Examination of the effect of the reduced product resolution for individual products (Table 3.2) shows that for some product groups, it is as large as +1151% for the material footprint and +692% for the carbon footprint. Thus, in the most extreme case the footprint calculated with 60 product groups is about a factor 10 higher for a specific product group than that calculated with an IO model using 200 product groups. Notwithstanding these extreme cases, the change is less than 25% for 90% and 93% of the product groups for the material and carbon footprints, respectively. The kurtosis value indicates that the distributions are leptokurtic.

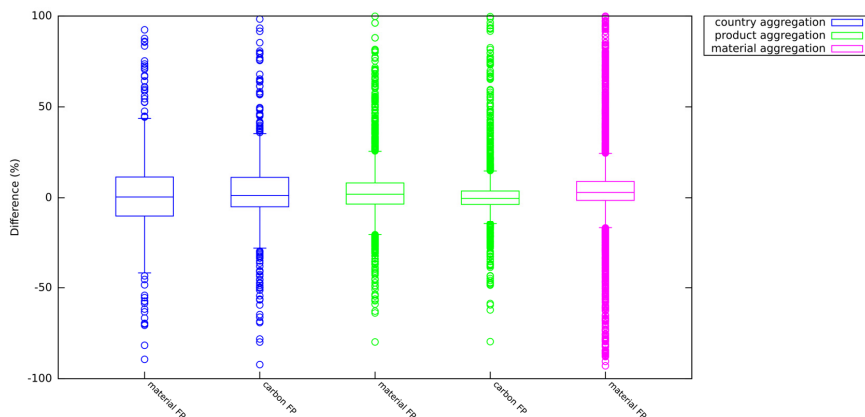


Figure 3.2: Box-and-whisker plots of the differences between the embodied material use and carbon footprints of products calculated under the different scenarios. The box indicates the interquartile range; the lower whisker is defined by the 1st quartile - 1.5 x IQR; the upper whisker is defined by the 3rd quartile + 1.5 x IQR; the median is indicated by the bar within the box. Outliers are indicated by the $\circ$ symbol. Outliers with a difference larger than 100% are not shown.

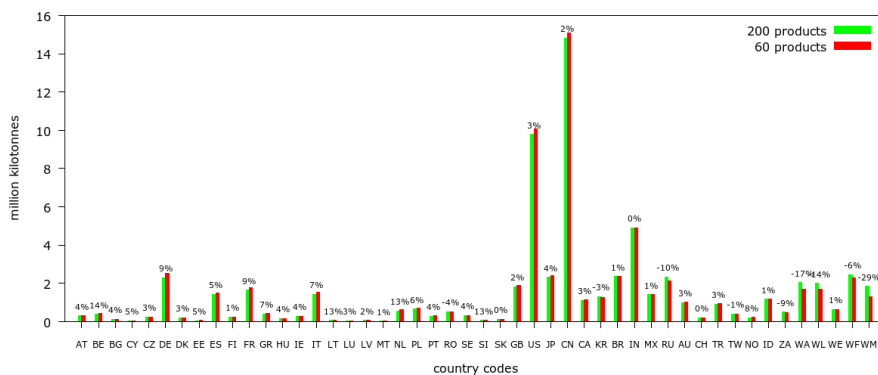


Figure 3.3: Product aggregation scenario: effect of reducing the product resolution from 200 to 60 products on the material footprint of countries. The percentage at the top is the percentage change between the default scenario (green bar) and the product aggregation scenario (red bar).

Table 3.2: Statistical measures describing the differences (expressed in percentage change with respect to scenario 1) observed between the material and carbon footprints of products under different assumptions.

Metric	Effect of spatial aggregation		Effect of product aggregation		Effect of material aggregation
	Material FP	Carbon FP	Material FP	Carbon FP	Material FP
Count	682	682	2644	2644	6677
Min	-89.4	-92.2	-79.8	-79.7	-93
Max	3560	1267	1151	692	22213
Median	0.4	1.3	2.0	-0.3	2.9
25% quartile	-10.0	-4.9	-3.4	-3.6	-1.4
75% quartile	11.4	11.3	8.2	3.8	9.0
Interquartile range	21.5	16.2	11.6	7.4	10.4
In range -25% to 25%	78%	80%	90%	93%	86%
Kurtosis	472	130	467	221	693

The data indicate that reduced product resolution has a greater influence on the material footprint than on the carbon footprint, as is shown by the interquartile range and the number of observations within the -25% to +25% interval. The difference in the distributions of material and carbon footprints was tested with the non-parametric Friedman test, which revealed that there is a significant difference ($X^2(2) = 101$, $p = 0.000$) between the mean ranks of the two distributions (Siegel and Castellan, 1988), see Table 3.3.

Table 3.3: Friedman test statistics to detect if the effect of aggregation for the material footprint is different from the effect of aggregation on the carbon footprint.

	material footprint versus carbon footprint	
	effect of spatial aggregation	effect of product aggregation
N	682	2644
Chi-square	9.859	101
df	1	1
Significance	0.002 **	0.000 **

** $p < 0.01$

A list was made of the 20 product groups showing the largest effect of product aggregation on the material footprint. Ten of these 20 products are summarized as “p14, Other mining and quarrying products”, which is an aggregation of the products “stone”, “sand and clay” and

“chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.”. Other composite products that occur multiple times in the top 20 are “p01, agricultural products” and “p16, tobacco products”. It appears that the effect of product aggregation is strongest for agricultural products and other mining and quarrying products, indicating that the embodied material use for sub-categories in these product groups is highly variable, and that the product groups where the actual material extraction takes place are most affected. The result for p16, tobacco products, whilst perhaps not significantly affecting macro-level results, is an interesting illustration of the nature of the aggregation effects. P16 is basically the manufacturing of tobacco products, and involves no direct material extraction from the environment itself, but instead involves inputs from the agricultural sector. The fact that the manufacturing process purchases a very specific agricultural product (tobacco) rather than a range of produce, and that tobacco is somewhat atypical compared to the rest of the agricultural sector (very high value to embodied weight ratio), causes it to show such high variability.

The patterns in the differences were further analysed by creating a “heatmap”, which shows the difference between the default and product aggregation scenarios for each country and each product group by means of a colour code. The most affected product groups show up in bright red or dark blue. The overall impression from Figure 3.4 is that white and nearly white colours dominate, which underlines the conclusion that for most product groups the differences resulting from product aggregation are small. Product groups p01, p14, and p16 show up as columns dominated by red. Interestingly, in product groups p21 - p26, the colours for the group of manufactured products indicate a moderate influence on the calculated material footprint.

It is known from earlier work (e.g. Tukker et al., 2014) that p45, construction work, is the product with the largest total embodied material use, with sand & gravel having the highest share. It is therefore interesting to see how the product aggregation has affected this key sector. Notice that the construction sector itself was not aggregated in our product aggregation scenario, but all the effects seen for this product result from the aggregation of products used as input for construction work. Figure 3.4 shows that the embodied material use of construction work in almost all countries decreases upon aggregation. This can be explained

by the fact that the original sand and clay mining sector, which has the highest material extraction multiplier in terms of kg/Euro, is aggregated with other mining sectors that have a lower material extraction multiplier.

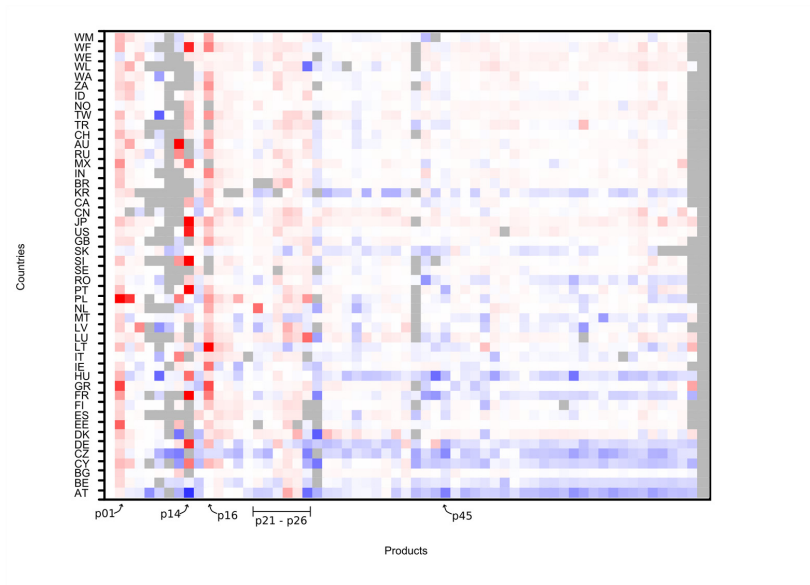


Figure 3.4: Heatmap showing the difference in embodied material use per country and per product for the product aggregation scenario, in the form of color codes. The differences are expressed as percentages. Dark blue means a difference of -100%. Dark red means a difference > 250%. The columns for product groups p01, agricultural products, p14, other mining and quarrying products, and p16, tobacco products, are dominated by red colors. p45 is construction work. Grey color means not available.

In addition, we prepared a list of the 20 product groups showing the largest effect of product aggregation on the carbon footprint. Six out of these 20 products are aggregated in “p26, other non-metallic products”, while a further five are in “p11, crude petroleum and natural gas services”. However, it is not obvious from the ranking of the product groups that the sectors with the highest emissions are most affected by the aggregation, as was observed for the material footprint.

3.3.2 Spatial aggregation scenario

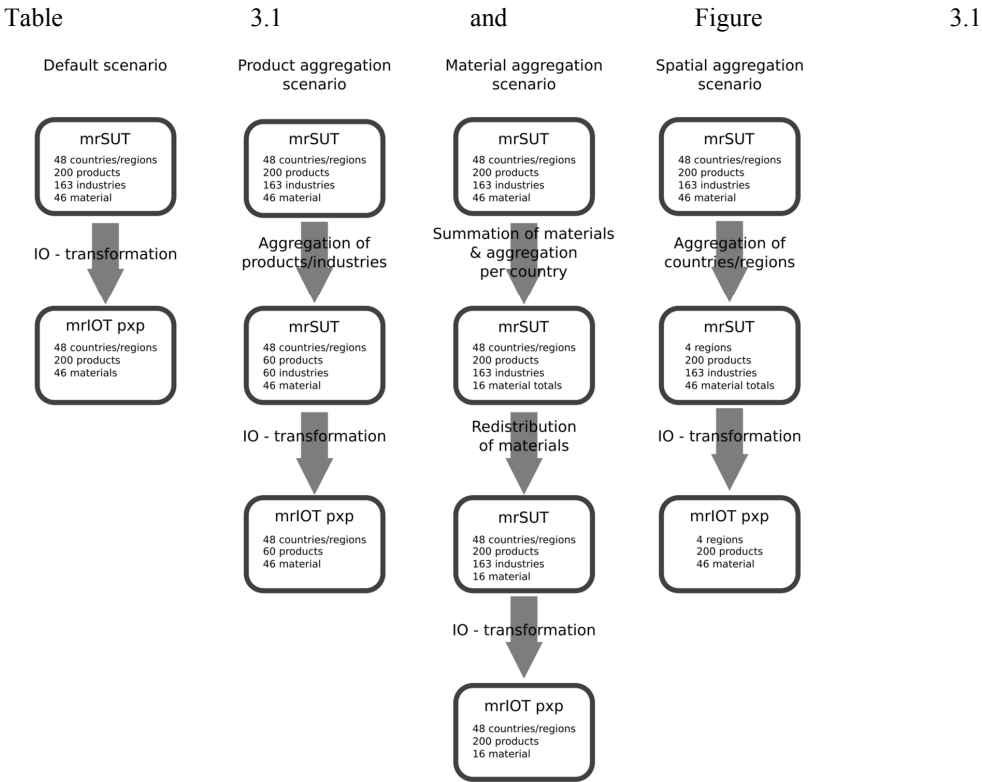


Figure 3.1 illustrate that the influence of reducing the spatial resolution on the calculated regional footprints is limited. The maximum differences for the footprints of the four regions are about 2% for the material footprint and less than 1% for the carbon footprint. If we focus on the embodied material use and embodied carbon emissions in individual product groups, the calculated embodied material use of products shows larger variation than the embodied carbon emissions, as is shown by the interquartile range. For the carbon footprint, 50% of the observed differences are in the range of -5% to +11%, while for the material footprint this is -10% to + 11%. We may conclude that the effect of reducing the spatial resolution is somewhat larger for the material than for the carbon footprint. The difference between the two distributions is significant ($X^2(2) = 9.859$, $p = 0.002$) according to the Friedman test (Table 3.3). The maximum percentage change observed when aggregating into 4 regions is 3560%

for the material footprint and 1267% for the carbon footprint, which is in the same order of magnitude as the maximum effect of the aggregation into 60 product groups.

Investigating the products that show the largest percentage change in embodied material extraction or embodied carbon emissions upon aggregation shows that no particular product seems to be specifically affected by the spatial aggregation, unlike the results obtained for the product aggregation scenario.

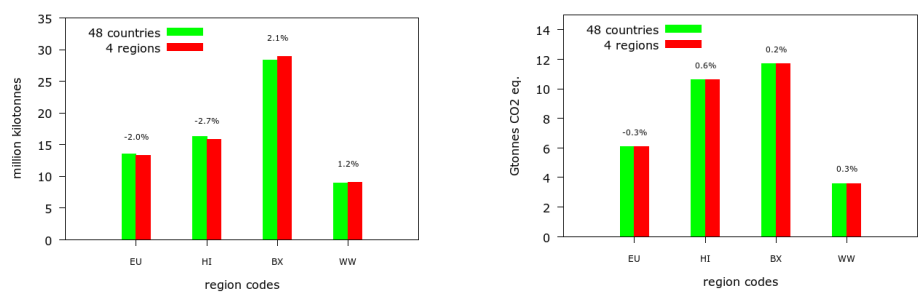


Figure 3.5: Spatial aggregation scenario: effect of spatial aggregation on the calculated carbon (right) and material footprints (left) of countries. The percentage change between the default scenario and the spatial aggregation scenario is given at the top of the bars.

The calculated carbon and material footprints are of course affected by the level of aggregation of the countries. Work by Stadler & Wood (2014) using the same data as our study and focusing on the product group of “wearing apparel: furs” showed that the material footprint of this product group was at most 25% smaller when considering an EU and aggregated world region. An aggregation into EU and main regions reduced the calculated material footprint by 5%. Stadler & Wood (2014) examined the effect of spatial aggregation on all products using different spatial aggregation scenarios, and found that the effect on the material footprint was much larger than on the carbon footprint, which corroborates our results.

3.3.3 Material aggregation scenario

The effect of aggregating the material categories from 46 to 16 categories on the material footprints of countries/regions ranges from -19% to +31% change, and is not significantly

different from the effect of spatial aggregation or product aggregation, according to the Friedman test (see Table 3.4). At the level of individual product groups, the effect of material aggregation is significantly smaller than the effect of spatial aggregation, in the same order of magnitude as the effect of product aggregation (but significantly different); see Table 3.2 and Table 3.5. If we take the effect range of -25% to +25% change as an acceptable change, the effect of the material aggregation scenario is slightly larger.

Table 3.4: Friedman test statistics to detect if the percentage change in the calculated material footprint of countries due to material aggregation is different from the effect of spatial aggregation and product aggregation.

	material footprint of products effect of material aggregation versus that of	
	spatial aggregation	product aggregation
N	4	48
Chi-square	1.000	.750
df	1	1
Significance	.317	.386
** p < 0.01		

If we look at the effect of material aggregation on the individual embodied materials in products (see Supporting Information), there is no effect at all for the categories of wood, fish, iron, marble, slate, clays & kaolin, salt, and chemical and fertilizer minerals. The effect on embodied sand & gravel in products is very small. The structure of the SUT and hence the IOT does not change in the material aggregation scenario, and some material categories are allocated to a single primary sector both in the EXIOBASE classification and in the corresponding EW-MFA 16-category classification. In such a case there will be no effect of the aggregation scenario on the embodied material use. This rule also applies to the sand & gravel category, yet we see a very small aggregation effect. This is the due to some of the manual tweaks that have been made to the original data, which were not applied in the aggregated material extensions¹. The effect on the individual material categories is largest for

¹ In the original data, sand & gravel extraction was connected to the production of p14.2, sand and clay in all countries and regions except in India. In the aggregated material data, the sand & gravel extraction was connected to the production of p14.2 without exception.

crops, chalk & dolomite, limestone and gypsum and other non-metallic minerals, as shown in the Supporting Information.

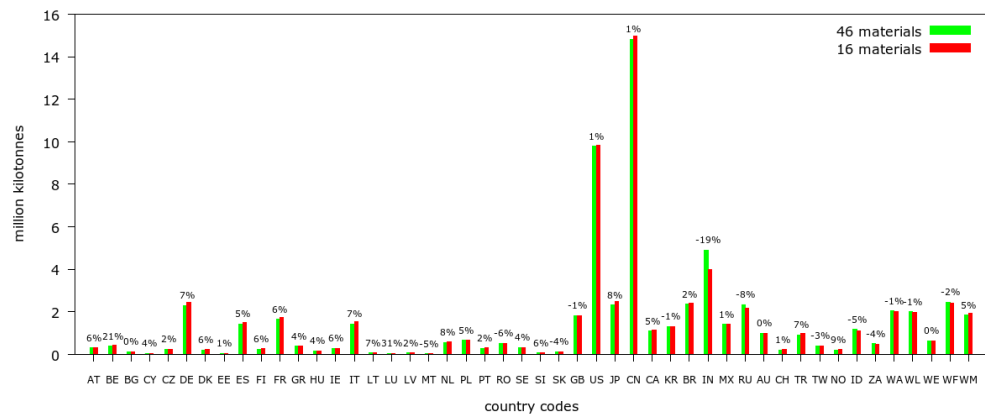


Figure 3.6: Effect of the aggregation of the 46 material categories into the 16 EW-MFA categories on the calculated material footprints of countries/regions. The percentage change between the default scenario and the material aggregation scenario is given at the top of the bars.

Table 3.5: Friedman test statistics to detect if the percentage change in the calculated material footprint of products due to material aggregation is different from the effect of spatial aggregation and product aggregation.

	material footprint of products, effect of material aggregation versus	
	effect of spatial aggregation	effect of product aggregation
N	682	2644
Chi-square	42.375	233.660
df	1	1
Significance	.000 **	.000 **

** p < 0.01

Eight examples of the effect of the material aggregation on the embodied material composition of products are shown in Figure 3.7. Four examples (DE p40.11b, DE p40.11.f, US P26.d, US p27.5, see figure for explanation of codes) were chosen such that they included a high share of the embodied material categories of non-ferrous metals, calcium carbonate

minerals and oil & gas. These are the material categories for which a large influence of the material aggregation scenario was observed. The other four examples (KR p14.3, SK p11.c, DE p11.c, ID p01.g) are the products showing the largest percentage change in embodied materials when the material categories are aggregated. The first four examples show that the composition of embodied materials of these four products is not much affected. In the most extreme case, a completely different embodied material composition is calculated, as illustrated by the last four cases.

We investigated if large percentage changes in the material footprint due to aggregation can be correlated with large percentage changes in the carbon footprint. This was done by creating scatterplots and calculating the Spearman rank correlation. Pearson's correlation coefficient was not calculated, as it is sensitive to outliers and assumes that the data are approximately normally distributed. The calculated Spearman correlation coefficients and two-tailed significance levels are given in Table 3.6. For spatial aggregation, a significant positive rank correlation was found between the changes in the material footprint and the carbon footprint. However, it is not possible to conclude directly that the percentage change in the footprints is correlated in these cases. A scatterplot of the rank-transformed data and the original data reveals that in both cases, the observed significant rank correlation is not an indication of correlation in general but is due to the nature of the data and the effect of rank transformation. We conclude that the percentage change observed in a material footprint is not correlated to the percentage change in the carbon footprint.

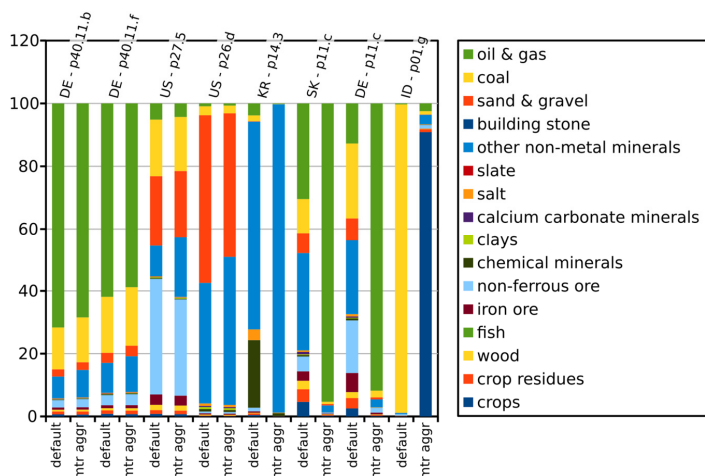


Figure 3.7: Some examples of the effect of aggregation of the 46 EXIOBASE material categories into the 16 EW-MFA categories on the embodied material composition of four different products. p40.11.b = Electricity by gas; p40.11.f = Electricity by petroleum and other oil derivatives; p26.d = Cement, lime and plaster; p27.5 = Foundry work services; p14.3 = Chemical and fertilizer minerals; p11.c = other hydrocarbons; p01.g = plant-based fibers; DE = Germany; US = United States of America; KR = South Korea; SK = Slovak Republic; ID = Indonesia.

Table 3.6: Measures of correlation between the percentage changes due to aggregation for the material footprint and carbon footprints of countries.

			Country footprint		Product footprint	
			Spearman rank correlation	Significance (2 - tailed)	Spearman rank correlation	Significance (2 - tailed)
Effect of	spatial		-0.400	0.600	0.469**	0.000
aggregation						
Effect of	product		-0.134	0.363	0.010	0.605
aggregation						

** $p < 0.01$

3.4 Discussion

Our findings show that aggregation of product groups from a high detail of 200 products to 60 product groups has a larger effect on the material footprint than on the carbon footprint. This is also true for our spatial aggregation scenario, where 48 regions are aggregated to 4 regions. This result can be explained by the fact that the variability of carbon emissions between sectors is smaller than the variability in material extraction. Carbon emissions occur in every sector, but material extraction is a very specific activity that occurs in the primary sectors only. When sectors are aggregated, it is likely that the sectors are more homogeneous in terms of the carbon emission multipliers than the material extraction multipliers.

No correlation was found between changes in embodied carbon emissions and embodied material use in products. Fossil fuel extraction is one of the material categories included in the total embodied material use indicator. Only for products where the embodied material use is dominated by fossil fuels that have been combusted can we expect an observable relation between the effects of aggregation on the embodied carbon emissions and the total embodied material use. This might be the case for the electricity sector.

The effect of product and spatial aggregation on the level of the mrSUT in this study, as well as in other studies investigating the effect of aggregation at the level of mrIOT, probably does not represent the full effect of having to work with aggregated (statistical) data. In our study, the aggregation of product groups and/or industry sectors was carried out at the level of the multi-regional SUT, after which this aggregated multi-regional SUT was transformed to an aggregated multi-regional IOT. We may call this approach half-way aggregation (see Figure 3.8). Many studies on the effect of aggregation have used an IO system as the starting point of their analysis (Hatanaka, 1952; Steen-Olsen et al., 2014; Su et al., 2010; Su & Ang, 2010) and aggregated the IO table, which means that the aggregation operation took place at a later stage. We call this approach late aggregation. Since we have access to the single-country SUTs in EXIOBASE, these single-country SUTs could also have been aggregated and used to construct a trade-linked mrSUT for further analysis. This route might be called early aggregation. Finally, the route in which the most detailed data are used to calculate indicators and the final indicators are aggregated to the desired resolution could be called final aggregation.

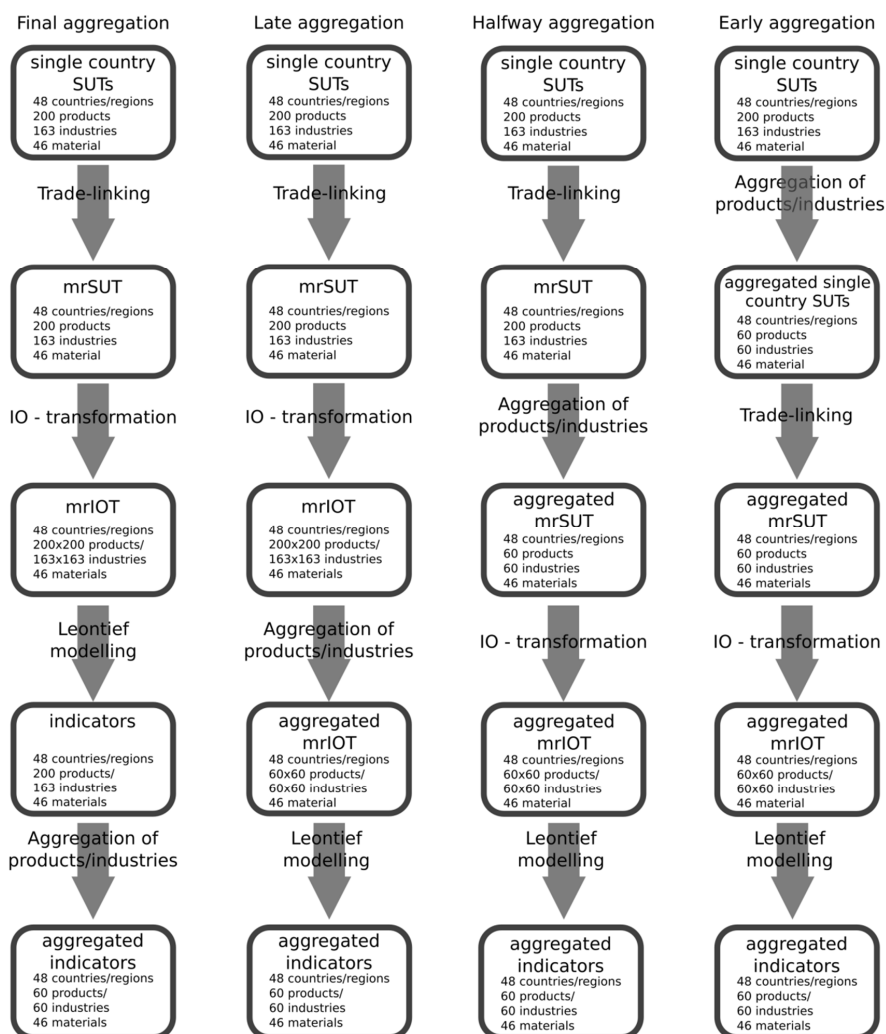


Figure 3.8: The four different routes towards aggregated environmental impact indicators calculated with a mrIO. By way of example, the default SUT available in EXIOBASE which distinguishes 200 products and 163 industry is aggregated to obtain aggregated environmental impact indicators distinguishing 60 products or 60 industry sectors.

Late aggregation for the PxP-ita model leads to different environmental impact indicator results than halfway aggregation, except in the case that only products are consolidated in

aggregated groups (see Supporting Information for mathematical proof). In realistic cases, like those analysed in our different aggregation scenarios above, the aggregation concerns not only products but also industry sectors, so halfway aggregation results in an aggregated IO table that is different from a late-aggregated IO table. We know from the early work of Hatanaka (1952) that late aggregation and final aggregation also lead to differences. The cascade of effects from halfway aggregation to the final aggregated result is expected to be larger than the cascade of effects from late aggregation to final aggregated result.

Our results, showing the effect of aggregation on material and carbon footprint of countries and products, can therefore not be compared directly with those reported in studies of the effect of late aggregation. Moreover, our results probably underestimate the effect of aggregation, because in a “real-world” situation, where only aggregated SUTs of individual countries and materials can be collected and transformed into multi-regional SUT and IO systems, the early aggregation scenario would give the best description of the effect of having only aggregated data available. Trade linking (Bouwmeester, 2014) combines all the single-country SUTs into one multi-regional SUT system by combining trade data and the export/import data available in the single-country SUT systems, and reconciling all the differences between these disparate data sources. Having to work with aggregated data sources in this step will produce an aggregated mrSUT that is different from a halfway-aggregated mrSUT system and thus also from a late-aggregated mrIO system. The cascade of effects from early aggregation to final results will even be larger than the cascade of effects from halfway aggregation to final environmental impact indicator results. This means that the observed effects in the product aggregation and spatial aggregation scenarios underestimate the effects that would have been encountered if the primary data used to create the mrSUT had been aggregated.

3.5 Conclusions

This paper examined the impact of aggregation and disaggregation of material, product category/industry sector and country classifications in mrIOs on the calculation of the material footprint of countries and products. We found that the differences between the material footprint of a country as calculated with mrIO models that differ in product resolution and spatial aggregation are generally in the order of a few percent. However, outliers in the order of a 25% difference are possible. The effect of aggregating the original 46 material categories into 16 categories on the material footprint of countries can be in the order of 30% difference. This finding strongly suggests that the material data used to create the extensions for the IO framework should be collected at the highest resolution that is practically feasible. Since many of the original data sources used to compile material extension databases, like the International Energy Agency database (energy carriers), FAOSTAT (agricultural products) and the US Geological Survey (USGS; materials) are already at a high level of detail, we strongly recommend to stay as close as possible to the level of detail available in such original sources.

The effects of product aggregation, spatial aggregation and material category aggregation on the calculated total embodied material use of individual product groups is limited for many groups. For several individual product groups, however, the difference can be in the order of 100% or more. Particularly affected are primary sector products. The use of IO models with a low product category resolution (e.g. 60 product categories) to calculate the embodied material use of individual products will likely result in estimations of the total embodied material that are inherently inaccurate for some product categories. This limits the possibilities to use IOA in detailed MFA studies, if the IOA uses a relatively aggregated product resolution.

The effect of aggregation on the material footprints is larger than the effect on carbon footprints. This finding shows that it is important to specifically investigate the effect of aggregation on different indicators. An aggregation level that is acceptable for one environmental or economic indicator might be unacceptable for another indicator or purpose. When calculating footprints other than the carbon footprint, it is safest to do this at the highest level of detail and to aggregate results only at the very end.

The estimated effects of product category resolution and spatial resolution in this paper probably underestimate the effects that will be encountered when basic data to create the multi-regional SUTs are already aggregated, as in an early-aggregation scenario.

3.6 References

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Chapter 4

Scenarios for a 2°C world; a trade-linked input-output model with high sector detail¹

Abstract

In this study a scenario model is used to examine if foreseen technological developments are capable to reduce CO₂ emissions in 2050 to a level consistent with UNFCCC agreements, that aim at maximizing temperature rise to 2°C compared to pre-industrial levels. The model is based on a detailed global environmentally extended supply-use table (EE SUT) for the year 2000, called EXIOBASE. This global EE SUT allows calculating how final demand in each region drives activities in production sectors, and hence related CO₂ emissions, in each region. Using this SUT framework three scenarios have been constructed for the year 2050. The first is a Business-as-Usual scenario (BAU) which takes into account population, economic growth and efficiency improvements. The second is a Techno-Scenario (TS), adding feasible and probable climate mitigation technologies to the BAU scenario. The third is the Towards-2-Degrees Scenario (2DS), with a demand shift or growth reduction scenario added to the TS to create a two degrees scenario. The emission results of the three scenarios are roughly in line with outcomes of typical scenarios from integrated assessment models. Our approach indicates that the two degrees target seems difficult to reach with advanced CO₂ emission reduction technologies alone.

4.1 Introduction

Limiting temperature rise by to 2 °C compared to pre-industrial levels is broadly seen as necessary to avoid severe risks of climate change. It is the stated goal of UNFCCC negotiations (UNFCCC, 2011). To remain within this domain, greenhouse gas emissions are to be reduced substantially, while economic growth continues, especially in developing countries. Several modelling approaches and scenarios have been developed to give insight in

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how we may reach this climate stabilization goal. The scenarios in line with climate stabilization, limit climate forcing to 2.6 W/m^2 in 2100 (see van Vuuren et al., 2011 and the IPCC - working group III final draft report (IPCC, 2014) for a survey). The emission pathways towards 2100 in different scenarios may differ in the speed of emission reduction. However, substantial emission reductions should be realized already by 2050 to realistically remain within the 2-degrees rise domain. The IPCC (2014) RCP2.6 scenario reduces CO_2 emissions to around 11 Gt in 2050, which is roughly a 50% relative to 1990 levels, or a 60% reduction relative to 2000, the base year for our model. The goal of this paper is to see how such a reduction of global CO_2 emissions from industry and fossil fuel might be realized in 2050, by assuming the introduction of emission reducing technologies and changes in patterns of final demand, against a background of economic growth.

The scenario model developed is based on global supply-use tables (SUTs) with high sector detail, EXIOBASE, discerning four regions in the world. In a supply-use framework, the supply table contains the supply of products by industry sectors and the use table the use of products by industry and by consumers (Stone, 1961). Products produced by industries are either used as intermediates by other industries or are used by final consumers. The SUTs used in this study include information on the emissions of CO_2 , CH_4 and N_2O as so-called ‘Environmental Extensions’ for every industry sector. The SUTs give hence a complete picture of the structure of and particularly the relations within an economy, expressing the flow of products between industries and final uses in monetary terms. This allows calculating how final uses drives production – and hence emissions – in specific industries in specific regions (e.g. Miller & Blair, 2009). The SUTs also give a description of the technology used in every industry sector, in the form of monetary inputs and outputs, plus the emissions associated with that technology (Duchin, 1998). By systematically manipulating the supply-use tables (SUTs) exogenously, they can reflect changes in technologies, final demand, and economic activity part of the future scenario assumptions. Scenario assumptions lead to adjustments of these monetary inputs and outputs of industry sectors and their emissions and ultimately to a new set of SUTs. The new set of SUTs can then again be used to calculate GHG emissions of economy wide production and consumption.

Adapting monetary SUTs to examine the effects of techno-economic changes is nothing new. For instance, Cantono et al (2008) adapted an input-output table to examine the environmental effects of the introduction of hydrogen and fuel cell buses in the European economic system. Tukker et al (2011) showed how diet changes lead to structural changes in the European meat production sector and their effects on the environment. SUTs/IOT are also routinely adapted to make an estimate of a new year based on the SUT of a previous year, forcing the SUT to reflect some key economic indicators of the new year (see for instance Chapter 7 in Miller & Blair, 2009; Lahr & De Mesnard, 2004). The novelty of our approach is the combination of scale, technical detail and systematic approach to implementing techno-socioeconomic in the SUTs. All sectors in all regions, their inter-relations and emission coefficients will be changed and these changes are applied using a systematic approach implemented in a set of scripts which allows for easy analysis of different scenarios.

The scenario model used for this purpose in this research deviates substantially from integrated assessment and (partial) optimization models often used to investigate scenarios for the mitigation of climate change. Our scenario model has no endogenous dynamic relations like climate feedback mechanisms, no investment functions, no optimizations, and no learning curves. As far as desired, such factors need to be defined exogenously. In contrast, a major strength of our approach of implementing scenarios in a supply-use framework is the explicit introduction of new technologies with specific input, output and emission coefficients, and the inherent inclusion of chain effects at a level of detail that does not exist in general equilibrium models. If for instance the supply of electricity by coal power plants is reduced in a scenario by a switch to other technologies, also the supply by coal mines will be reduced accordingly including all related activities and emissions. All specifications of emission reducing technologies are based on options as specified in the literature as feasible or probable. This makes assumptions with regard to technical change transparent and the interpretation of the results straightforward.

The central question in this research is whether a feasible and probable technology development until 2050 alone can reduce CO₂ emissions to a level consistent with a less than 2 °C temperature increase above pre-industrial levels under a moderate population and

economic development scenario and, if not, whether additional demand side changes might reduce CO₂ emission to desired levels.

This paper focuses on CO₂ only, since technical emission reduction measures are better specified and policies targeted at CO₂ emissions seem more feasible than those for mostly difficult to measure and regulate emissions of other greenhouse gases, most notably CH₄ and N₂O from land use. Also indirect land use change and related emissions are not included. It is probably optimistic to assume that the emissions of such non CO₂- greenhouse gas emissions could be assumed as easily to be reduced as CO₂. Land use as a resource for food, feed and bioenergy production is included in the model but for this paper it will only be considered as a limit on the contribution of bioenergy.

4.2 Data and Method

Below an overview is given of the starting data for the scenarios, the scenario assumptions and the model framework in which they are used to implement the scenarios.

4.2.1 Supply - use tables

The EXIOBASE supply-use tables form the basis for specifying the scenarios. This world model distinguishes 129 sectors in 44 trade-linked countries and regions, including the individual EU27 countries (Tukker et al., 2013). In EXIOBASE, the national supply-and-use tables have been trade-linked. This means that all sectors in each country/region are linked to the supplying and using sectors in all other countries and regions. The trade-linkages are created by combining data from the national supply-use tables and trade data. Because these supply-use data and trade data will contain errors, the trade data are adapted to fit the supply-use data. A bi-proportional matrix balancing method, the so called GRAS method (Junius & Oosterhaven, 2003), is used to adapt the trade data such that consistency between supply-use data and trade data is achieved (Bouwmeester, 2014) with minimal adjustment of these data.

The EXIOBASE data for the year 2000 are some of the most detailed data public available now. A newer version of EXIOBASE for the year 2007 has recently been completed but these

data are not yet public available (Tukker et al., 2014). For the purpose of this study, the data from EXIOBASE have been aggregated into four global regions. They are the European Union (EU); other high income countries, like the US and Japan (HI); newly developing countries, like the BRICs (BX); and a Rest of the World, including most African and Middle Eastern countries (RoW). These regions are treated as internally homogeneous. Choosing to do the modelling on the four region aggregated level and at the 129 industry sector level has implications for the results which will be discussed.

The EXIOBASE emission data cover the major greenhouse gases CO₂, CH₄, and N₂O, next to non-GHG emissions. All our scenarios relate to these four world regions.

4.2.2 Scenarios

Three scenarios were developed. The starting point is the world as described in 2000 in EXIOBASE, stepwise transformed into possible worlds in 2050.

Business-as-usual

The BAU scenario assumes no specific additional climate policies. However, it follows trends in energy efficiency improvement and expectations on economic growth until 2050. Population growth, general efficiency improvement and productivity growth together lead to a more or less autonomous economic growth, already influenced by policies and other mechanisms. These general developments have been implemented in the SUTs in the following way. The trends in general efficiency improvement (influenced by current climate policies) of the last decade have been extrapolated, looking in detail into the country specific developments of the 30 most energy consuming sectors, as derived from the WIOD database (Timmer, 2012). These trends are not substantial in sectors like agriculture for developed countries, at roughly 1% efficiency improvement over the 50-year scenario period, and are much higher for some sectors in high growth developing countries leading to up to 36% efficiency improvement over the 50-year scenario period for e.g. the agriculture & food industry. The efficiency improvements already lead to a substantial economic growth as can be calculated from our model. GDP growth per region is further scaled up to meet the OECD prospects (OECD 2012a, 2012b) for economic growth. Figure 4.1 shows an overview of GDP and population development in the scenarios.

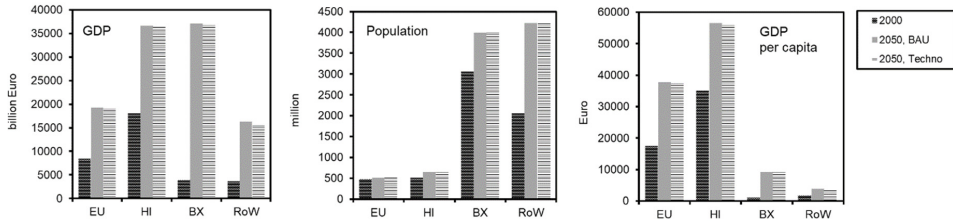


Figure 4.1: GDP, population and GDP per capita in the BAU and TS

In our scenario there is no shift in developed countries towards the secondary and tertiary sectors. Such shifts happened in the past for in the EU and other High Income countries which was partly due to shifting abroad of material production from developed to emerging countries. At a global level we assume that such a shift is not possible, the primary products needed for an expanding economy have to be made somewhere. Visions of re-industrializing Europe which entails “bringing back” primary industry like mining and manufacturing to Europe (EC, 2013) are also not included in our scenarios, as the structure of the global economy is not actively adapted in this sense.

Trade volumes tend to rise as a result of global specialization, economies of scale and reduction of trade barriers (Helpman & Krugman, 1985; Hummels et al., 2001). In the last decades this has led to high rates of growth in international trade, much higher than economic growth (Krugman et al, 1995). However, for the future it is likely that cost structures in different countries will become more similar when they approach similar levels of affluence (see also Figure 4.1 for GDP per capita in our scenario), with reduced global income inequality (Chen & Ravallion, 2004). Given that international trade barriers and international trade margins have already been reduced substantially, being a fraction of what they used to be (Krugman et al, 1995), we assume that trade volumes will not grow faster than GDP. Thus we did not actively adapt the share of international trade flows in global GDP.

Techno scenario

Next, on top of the BAU scenario, specific CO₂ emission reducing technologies are introduced, including a substantial shift to electricity use generated by fossil fuel power plants

equipped with carbon capture and storage (CCS) and a substantial share of wind and solar. The chosen technologies represent the large scale technology developments that can feasible and probable be implemented in a time frame until 2050. These technologies do not represent each and every emission reduction technology that is available but typically represent technologies that have proven themselves beyond the pilot scale. A detailed list of the technologies implemented in the Techno 2050 scenario in the transport sector, cement production, steel production, built environment, private households, commercial energy use and electricity supply sector is given in supporting information. Given the slow introduction of new (energy) technologies (Kramer & Haigh, 2009) it is very doubtful that technologies that are not well known by now will have a large contribution to carbon emission reductions by 2050. The scenarios assume a mix of low carbon technologies for electricity generation rather than the implementation of a specific technology such as full electricity generation by bio-based solar cells. They also do not represent potential disruptive technology developments that do not exist yet, e.g. nuclear fusion. Even though these disruptive technologies may come into existence the next few years, it is doubtful that within 30 year time they will substantially change the existing energy production and consumption system.

Shifts in primary energy for electricity production are substantial in our scenario (based on Jakeman & Fisher, 2010), with a substantial increase in the share of other renewables, enhanced use of biomass, and a relatively constant share of nuclear, see Figure 4.2. The electricity supply mix could have been chosen such that renewables would have a (much) higher share. However, based on rates of penetration of new renewable technologies (Kramer & Haigh, 2009), the long lifetime of coal power plants that are being built today and the shale gas revolution, it seems not unreasonable that even in 2050 fossil fuel based electricity generation still plays a substantial role. The role of biomass for electricity generation grows fast compared to the starting situation but stays in 2050 in absolute terms rather small (4.4 EJ or 2.7% of total electricity supply) compared to other models that implement a two-degrees scenarios (Rose et al., 2014). Our scenario choice is based on the strong indication that any increased land for biomass leads to increased competition for land which may induce substantial land use change and conflict with biodiversity protection and food supply. Even modest use of biofuels in the U.S. was connected to accelerated clearing of the Brazilian rain forest (Fargione et al., 2008; Searchinger et al., 2008). Even though the shares of some

electricity generation technologies stay the same (e.g. nuclear) it implies tremendous absolute growth compared to 2000, as electricity use expands so much, see Figure 4.2. In this technology oriented step, energy using industries adapt their source of energy in line with the overall assumptions on shifts in primary energy input.

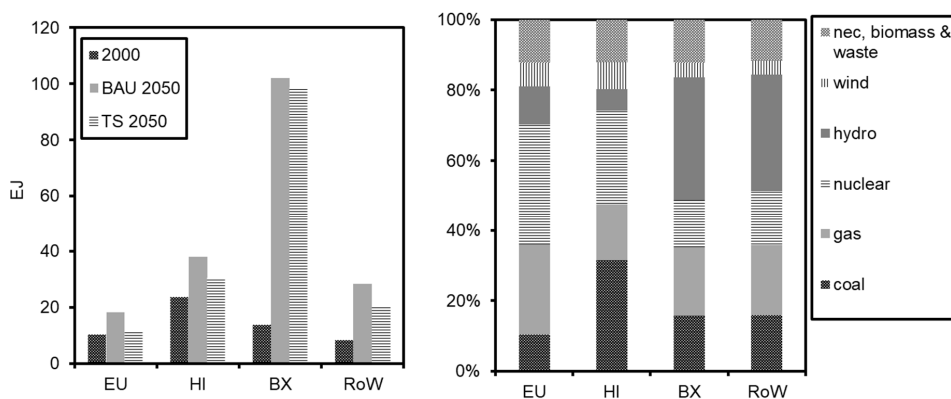


Figure 4.2: Total electricity supply in 2000, 2050 BAU and 2050 TS on the left hand side and the electricity supply mix in the 2050 TS on the right hand side of the figure

Electricity production technologies change substantially. By 2050 all coal and gas fired power stations (including those using biomass) are assumed to be equipped with CCS, reducing CO₂ emissions from these power plants with 80%. For that level of CCS, probably large scale transport systems are required to bring the CO₂ from the major sources of incineration to large saline aquifers. Such details have been accounted for based on average additional material and energy requirements, based on (NETL, 2010).

In households, built environment, service sectors, cement and steel production feasible and probable energy saving measures are implemented. An detailed overview of these measures is given in supporting information. Technology development in the steel sector was based on EPA (2012). Technological improvements in the cement production sector were taken from EPA (2010) and Worrel et al. (2000). Passenger road transport was assumed to be based mostly on battery-electric or plugin-hybrid cars with vehicle efficiencies based on Girod et al. (2012) and Vliet et al. (2011). Domestic and commercial energy consumption was based on

information from EPA (2000), Daioglou (2012), Isaac and Van Vuuren (2009) and DECC (2013). These general technology developments are quite substantial in their emission reductions and cover around 30 of the 129 sectors distinguished in EXIOBASE. In this scenario, the cement production sector reduces CO₂ emissions by 3%, whereas the iron and steel production sector uses 6% less coal and about 50% less natural gas. Water transport and aviation technologies do not change other than the improved efficiency that was part of the BAU scenario already.

Towards-2-Degrees Scenario

After implementing all main feasible and probable technological solutions for climate change emission mitigation as reflected by the TS scenario, behavioural changes by consumers remain an option for a further emission reduction. Two types of behavioural changes have been investigated:

1. A shift from the consumption of high carbon-intensive products (goods and services) like air travel to low carbon-intensive products, like music performance and theatre.
2. Reduced production and consumption, implying reduced economic growth.

In this 2DS, on top of the TS, we initially tried to adapt only the final demand structure to achieve the 2-degrees emission reduction goal. Demand shifts had to be so extreme that we chose to investigate more realistic changes in final consumption. Since these would lead to a scenario falling short of the 2-degrees target, additionally a reduced economic growth was assumed. Obviously such measures are far away from plausibility in terms of psychology and policy instrumentation, but it gives insights what the effects could be.

4.2.3 Scenario model

Manipulating the supply-use tables has been carried out using a set of Octave scripts (Eaton et al., 2011). The basis of the script consists of about 30 smaller functions that carry out a specific task on the supply-use framework. For example checking the balance of the table, calculating efficiency, removing or inserting rows etc. These small functions have all been tested in an automated testing procedure. The smaller functions were used to set-up the scripts that implemented one of the scenario assumptions. The main script was a sequence of all these scenario scripts plus some intermediate result logging. The complete scenario model is

available in a software repository. See supporting information for a detailed description of the contents of the software repository.

A basic feature of the scripts and hence the model is the absence of dynamic mechanisms other than the exogenously defined changes discussed as part of the scenarios. These would include market mechanisms which would change relative prices; the scenarios are in constant prices (year 2000) for all products. The conversion between monetary flows and physical flows therefore is straightforward. In the scenarios, new technologies are added in monetary terms, directly corresponding with their underlying physical composition and emission factors, at the given prices. These underlying physical specifications are not part of the SUT framework itself but are modelled separately and feed into the SUT framework. There is no hybrid analysis in the sense of combining monetary and physical flow units as all physical flows have been converted into monetary flows. Scenarios are translated into “change factors”. An example of such a factor could be that the CO₂ emission per unit of output of an industry sector will become a factor 0.45 of the original CO₂ emission per unit output. Another example could be that the input of a certain product into an industry sector becomes 1.2 times the original input while everything else remains the same. These “change factors” are multiplied with one or more of the relevant intermediate use, final use or supply flows. When the commodity inputs or outputs of industry activities are changed, it creates an unbalance in the supply-use tables because the supply of commodities will not automatically match the use of those commodities. Depending on the scenario this changed use of products may result in changed income and expenditure and/or changed commodity supply. After each scenario step the supply-use tables are re-balanced using a GRAS algorithm (Junus & Oosterhaven, 2003).

For final analysis of the scenarios the SUTs were transformed into a product by product input-output table based on the industry technology assumption, see for instance Eurostat (2008) for details.

4.3 Results and Discussion

4.3.1 BAU and Techno scenarios

The GHG emission in the BAU scenario amount to 75 Gt CO₂ /yr. in 2050 which is over six times as high as the 11 Gt CO₂/yr. in 2050, corresponding to a 2-degrees target (Vuuren et al., 2011). The 75Gt CO₂, already is a substantial decoupling from GDP growth, but not yet absolute decoupling. A linear extrapolation of CO₂ emissions on the basis of GDP growth alone would imply 129 Gt CO₂/yr. emissions in 2050. Because the BAU scenario is used as a reference on which CO₂ emission mitigation assumptions are superimposed, the estimated CO₂ emissions in the BAU scenario are a key starting point. High BAU CO₂ emissions in 2050 would make reaching a 2 degrees target more difficult. Our estimate is on the high end compared to the BAU scenarios by the OECD (2012a), which were calculated as 61 Gt CO₂/yr. in 2050 with the IMAGE/ENV Linkages model. The scenarios specified in our study uses the same economic growth and population forecasts as specified in the OECD Environmental Outlook, so apparently factors like assumed autonomous energy-efficiency improvements cause this difference. An IPCC survey of BAU estimates of CO₂ emissions in 2050 range from under 40 to over 100 Gt CO₂/yr. (Moss et al., 2010, Meinshausen et al., 2011), implying our BAU scenario is in the middle range. Our total CO₂ emission estimate aligns with the IPCC RCP8.5 scenario (Riahi et al., 2011), which also is based on business as usual assumptions, see Table 4.1. The distribution of the emissions over the regions is however different. In our BAU scenario, fewer emissions will come from the RoW than in the IPCC RCP8.5 scenario.

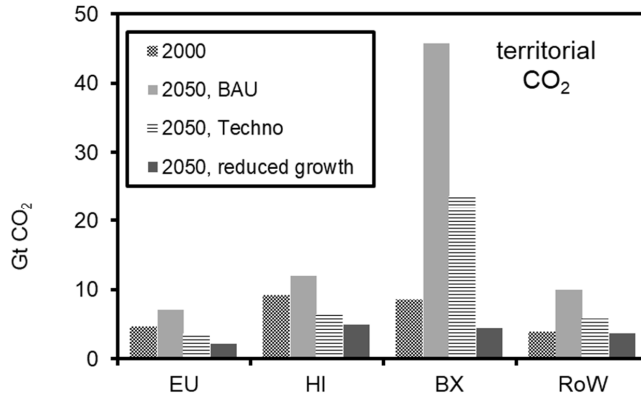


Figure 4.3: Territorial CO₂ emissions in the different scenarios in the four regions compared with our “towards two degrees” scenario where GDP growth is assumed to be reduced.

The main results for the Techno Scenario are given in Figure 4.3. It shows that the broad implementation of emission reducing measures, including 80% emission reduction by CCS on the remaining coal and gas use next to 80% emission reduction by applying CCS on bioenergy, will lead to an absolute reduction of the emissions of the developed countries (EU and HI) by nearly 30% relative to 2000. However the sum of such measures is not enough to reduce emissions in the two developing world regions (BX and RoW) below the 2000 level. For the whole world CO₂ emissions increase from 26 to 39 Gt, more than three times the 2-degrees target of 11 Gt in 2050. Special attention should be paid to the role of the BX region (including China, India, Indonesia and Brazil), responsible for more than half of all emissions in 2050. The emission reduction measures in the Techno Scenario reduce CO₂ emissions by about 50% compared to BAU in each region. Because the emission estimates in BAU 2050 for the BX countries are high compared to IPCC RCP scenarios the contribution of BX in 2050 under the Techno Scenario is high as well. The total emissions in our Techno scenario in 2050 are very much similar to the IPCC RCP4.5 emission scenario (Clarke et al., 2007) for 2050 but the distribution between the BX and the RoW regions is quite different, see Table 4.1.

Table 4.1: Emissions of CO₂ from fossil fuels and industry in Gt CO₂, compared to RCP8.5, RCP4.5 and RCP2.6 scenarios (RCP database, 2009).

Region	Actual year 2000	BAU scenario 2050	Techno scenario 2050	2DS 2050 reduced growth	RCP8.5 2050	RCP4.5 2050	RCP2.6 2050
EU	4.6	7.0	3.6	2.1	4.8	3.1	0.6
HI	9.1	12.0	6.3	4.9	15.9	6.3	1.6
BX	8.6	45.8	23.7	4.4	34.6	18.0	4.7
RoW	3.9	10.0	5.7	3.6	17.9	13.1	4.3
Total	26.2	74.8	39.3	15.0	73.2	40.5	11.1

The emissions from aggregate sectors for the BAU and Techno scenario are shown in Figure 4.4. Most sectors and private and public consumers are able to reduce their CO₂ emissions substantially in the Techno scenario compared to the BAU scenario. Agriculture shows a small increase in CO₂ emissions because of the extra demand for bioenergy. The electricity supply sector reduces CO₂ emissions from 24.5 to 2.4 Gt CO₂. Bioenergy in combination with CSS (BECCS) contributes 0.3 Gt CO₂ to this emission reduction. The electricity supply sector has the largest share of total CO₂ emissions (33%) in the BAU scenario. In the TS it is reduced to 6%. Having reduced the emissions from the electricity supply sector, the share of emissions from other sectors now become dominant although emission reduction measures were implemented in these sectors as well. Two aggregate sectors, manufacturing and transport, have a high share in the TS and show little improvement compared to BAU. This is the case even though in the manufacturing sector cement and basic steel production are assumed to have implemented CO₂ emission reduction technologies and in the transport sector land transport is assumed to be mostly based on electricity.

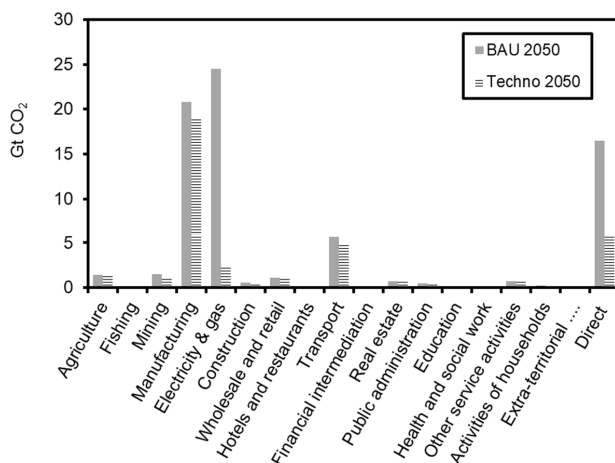
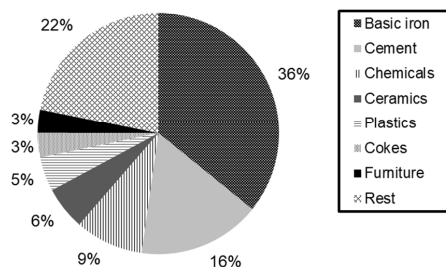


Figure 4.4: A breakdown of the Techno Scenario GHG emissions into emissions per NACE level 1 industry category plus direct emissions from households (label "Direct").

For more insight in the origins of emissions, the manufacturing sector and transport sector have been further split up into the highest sector level detail available to see which industries contribute most to the emission in the TS, see Figure 4.5. In the manufacturing industries it is cement production and basic iron manufacturing (blast furnace works). Given that these two sectors already include the feasible and probable technological technologies for GHG emission reduction until 2050 this means that further technologies would have to be developed and implemented substantially in the coming 35 years in order to further reduce emissions from these sectors. A plausible technology for cement manufacturing could be CCS for cement ovens (Schneider et al., 2011). In iron and steel production, some CCS might be possible, especially when combining first steps in reduction with coal gasification (Gielen, 2003). In the transport sector, emissions are dominated by air transport and sea transport. No specific GHG emission reduction technologies were assumed to be implemented in these sectors except general efficiency improvements. Further innovation in these sectors is necessary to bring down GHG emissions, as by shifting to low emission hydrogen or other low emission energy carriers. Such speculative options have not been assumed in the Techno Scenario.

Techno 2050, main CO₂ emitters, manufacturing sector



Techno 2050, main CO₂ emitters, transport services sector

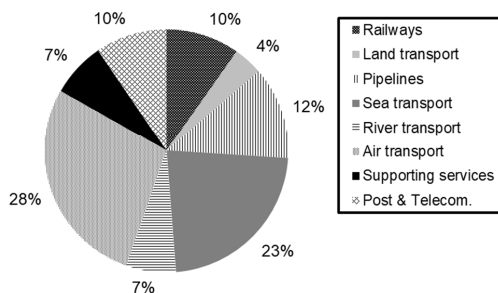


Figure 4.5: Main contributors to CO₂ emissions in the manufacturing sectors and transport services sectors in the Techno Scenario.

4.3.2 Towards a two-degrees scenario

Taking the TS as starting point a further option to reduce GHG emissions is the final demand shift from high carbon-intensive to low carbon-intensive products, including services. Quite extreme shifts were investigated. The expenditure (including investments) on the most carbon intensive products in the EU responsible for the 20% of total carbon emissions of the EU was halved, redistributing this expenditure to all other lower carbon-intensive products bought by final consumers. This involves 50% expenditure reduction on eight high emission product groups, see Table 4.2. The products and data given are exemplary for the procedure only, indicating what such a shift might mean for emissions.

Table 4.2: The eight product groups whose production is responsible for about 20% of CO₂ emissions in the EU in TS.

Product groups	Contribution to consumption based CO₂ emissions (% of total EU consumption based CO₂ emission)
Ceramic goods	0.4
Electricity by coal	0.6
Sea and coastal water transportation services	5.1
Other petroleum products	0.4
Bricks, tiles and construction products, in baked clay	0.5
Basic iron and steel and ferro-alloys	7.4
Cement, lime and plaster	2.8
Air transport services	5.3

Only a modest reduction can be achieved by this measure, less than 10% emission reduction – from the 39.3 Gt in the TS hence still some 35Gt CO₂ emissions/yr. would remain. Table 4.2 shows further that the CO₂ emissions from aviation form one of the most important categories that should be reduced. It is however very unrealistic that the 50% expenditure reduction assumed in our scenario could be realized. The income elasticity for demand for air transport is high: above 2 in developing countries, and somewhat lower in developed countries (Smyth & Pearce, 2008). Rising GDP and income will hence lead to a relatively higher rise in demand for air transport. Extreme – probably unrealistic – rises of the price of air transport would be required to make the 50% demand reduction in our scenario reality. Hence, we separately investigated much less would the economy have to grow in order to remain within the 2 degrees target, in comparison to the OECD projections in our original BAU scenario. In this lower growth scenario option we made the straightforward assumption that GDP growth is only a result of population growth and efficiency improvements. So there is no autonomous GDP growth as has been assumed based on OECD projections in the original BAU and Techno Scenarios. Because the efficiency improvements in the BX and RoW region are assumed to be about the same but population growth in the RoW region is larger than in the BX region the GDP growth in the RoW region is larger (a factor 2.8 compared to 2000) than the economic growth in the BX region (a factor 1.8).

This scenario has severe disadvantages, since inequality in GDP per capita between the four regions persists, and lower growth is not aspired, in neither region. This reduced growth scenario is just introduced as a thought experiment to examine how much reduced growth actually is necessary to stay within the two degrees emission limits. The regional GDP-levels for this reduced growth scenario are given in Table 4.3.

Compared to the original Techno Scenario, GDP growth is halved on a world scale but the growth reduction is unequal in the different regions of the world. For instance, the BX region will just realize 18% of the GDP calculated in the original Techno Scenario. The CO₂ emission level based on reduced economic growth and assumed implementation of all feasible and probable technological solutions from the original TS scenario comes quite close to the 2-degrees CO₂ emission target for 2050, see Table 4.1. However particularly the assumed growth reduction is high. It is implausible such a growth reduction will be realized by policy or free choice.

Table 4.3: GDP, GDP growth (in trillion Euros), growth factor, and fraction of GDP relative to TS in the towards 2 degrees scenario (2DS).

Region	GDP 2000 Trillion Euro	GDP 2050 TS Trillion Euro	2050 2DS Trillion Euro	Growth factor relative to 2000	Fraction of GDP relative to GDP forecasted in BAU and TS.
EU	8.4	19.3	11.2	1.33	0.58
HI	18.1	36.6	27.5	1.52	0.75
BX	3.8	37.2	6.8	1.76	0.18
RoW	3.6	16.2	10.2	2.79	0.65
Total	34	109.3	55.7	1.64	0.52

Though technologies and expenditures have been specified in detail, they should not be seen as predictions but only as technical options, required to give specificity in the scenarios. We have taken electric cars as the dominant drive mode but it might as well be hydrogen or ammonia as a fuel, linked to an electric engine, or to other propulsion systems. It is the nature of the change that counts: a full shift in drive mode is required, away from de-central carbon emissions. The technologies resulting will be efficient in some way, as costs are a main selection mechanism. So our efficient electric cars are exemplary, not predictive for a specific technology. Any transport drive system should be (near) zero direct emission, as otherwise

CO₂ emissions from transport would remain too high. The other option, CCS on decentralized mobile emitters although conceptually possible seems hardly feasible. Also biomass fuel for transport would be undesirable as it has already been used for electricity generation in our scenarios.

One of the important limitations of the use of a static model is that it does not capture dynamic effects. Dynamic effects of climate policies, including market and income effects, technology development, learning curves, etc., surely will have consequences for emissions. The static model might therefore have too high emission estimates. But we force our model to reproduce the reasonable assumptions on GDP growth from the OECD which dictates the income effects. On the other hand dynamic models might be overoptimistic in terms of technologies, relative to our IO model. The IO model captures economy-wide chain effects at a detailed level, which are usually not captured in integrated assessment models or CGE models. These models somehow have to deal with mechanisms not well established for long term developments, including the adoption of emission reducing technologies. It is not certain that our assumptions are so negative compared to those, as we assume very substantial generic efficiency improvements, very substantial introduction of emission reducing technologies and technology shifts, and on top a full connection of all fossil and non-fossil energy sources to CCS.

The Techno Scenario is in the middle domain of the scenarios linked to a substantial warming by 2100. The 2-Degrees Scenario relates to the RCP2.6 scenario, where there are limited scenarios studies available. Getting towards a 2-degrees target may involve not so plausible socio-economic scenarios. Getting there in terms of the IO-scenario presented here involves ultimately a drastic assumption: limiting economic growth by about 50%. This is much higher than other studies have so far reported. Knopf et al. (2009) and Edenhofer et al. (2009) have for example reported a GDP decrease between 2.5% and 5%, due to climate policy measures. Such minor reductions relate more to cost of climate policy than to an active reduction of economic growth as a means for emission reduction.

One of the essential assumptions underlying the different 2-degree scenario outcomes is the elaboration of the shift from the primary to the secondary and tertiary sectors. We assume that at a global level such a shift is not possible, due to the still limited development stage of the developing countries in 2050. Several integrated assessment models implicitly assume a development in industrial energy intensity similar to historic trends in developed countries through energy intensity curves. Without suggesting a preference for any type of modelling, this study shows that the difference in outcomes of climate policy cost predictions, emerging from such implicit modelling assumptions, may be very large.

4.3.3 Base year, aggregation and uncertainty

The SUTs used in this study were derived from EXIOBASE which are a snapshot of the structural economy in 2000. Other multi-regional input-output models covering more recent years (even as recent as 2011) are available, for instance GTAP (Hertwich & Peters, 2009), WIOD (Dietzenbacher et al., 2013) and Eora (Lenzen et al., 2013). Taking a more recent SUT for the start of our analysis would probably improve the analysis of the emission reductions achieved with feasible and probable technological measures until the year 2050 because there is one decade less of projections to be made. However WIOD, GTAP and Eora do not allow the same manipulations at the level of detail we could do with EXIOBASE. The WIOD and GTAP models have a much less detailed industry sector/product classification while Eora has a mixed industry classification that in most countries is much more aggregated than in EXIOBASE. For our approach is quite essential that we have a common and as much detailed description of technology in all regions in our SUTs because the technology description is the handle by which we manipulate the SUTs. The higher the industry sector resolution the more accurate we can do so. Even at the 129 sector detail, we found that some of the sectors are still too aggregate to be able to easily implement the 2050 changes in the sector. Using the second version of EXIOBASE discerning 163 industry sectors and covering the year 2007 would be helpful in this respect. It is the combination of having detailed supply-use tables for each country/region and having a very large number of extensions compared to EORA, WIOD and GTAP (Tukker & Dietzenbacher, 2009) that makes EXIOBASE lagging more in time than the other MRIO systems.

The level of aggregation in input-output tables has influence on calculated emissions embodied in trade (Su et al., 2010; Su & Ang, 2010, Lenzen, 2011). Also the choice for using a multi-regional model versus uni-directional or domestic technology assumption to calculate emissions embodied in trade has influence on the calculated emissions. In our approach multidirectional trade is used to calculate emissions embodied in trade which is generally better than any other method (Andrew et al., 2009). Choosing for the highest sector resolution is the preferred approach when calculating emissions embodied in trade (Su et al, 2010) and is essential for implementing the technical changes. Our choice for modelling at an aggregated four region level has been a pragmatic choice. These four regions were chosen to reflect the focus of this study (i.e. the EU) and describing its trade relations in a proper way. Given these four regions, two approaches could have been followed 1) first aggregating the tables and then implementing the scenarios 2) keeping the country detail and only aggregate the final results. This study follows option 1 because not enough data were available to specify the scenarios at the level of detail of the individual countries and manipulating the SUTs would be much more cumbersome as the size of the system would be 100 times larger. The research by Su & Ang (2010) indicate that level of spatial aggregation within China affects the calculated emissions embodied in its export. Going from 1 region to 8 regions the emissions embodied in China's export dropped 15%. Because we do not focus on emission embodied in trade alone but on global emissions the effect on calculated consumption based emission will be smaller than this 15% and does not affect our conclusions.

4.4 Conclusions and outlook

The main conclusion is that reaching a 2-degrees target is not possible with deep changes in technology alone. Deep changes in consumption patterns will only have limited effects too. Only technological solutions combined with behavioural changes and a 50% reduction in economic growth may bring us close to the 2-degrees goal. This scenario is politically not attractive, but can only be avoided by additional, innovative technical and behavioural change. Such technical and behavioural innovations would take time for their substantial introduction, probably having their effects after 2050 only. Furthermore, the current focus on emission reduction in the electricity supply sector will mean that by 2050 other sectors become the major contributors to CO₂ emissions particularly steel and cement production, and

air and sea transport services. Advanced measures to reduce CO₂ emissions from these sectors should start to be developed now already, since otherwise they have a high contribution to global CO₂ emissions in 2050. Our study makes further clear that policy efforts in the EU would by 2050 not have a substantial influence on global emissions anymore. The share of EU emissions in effective scenario are down to 7%, due to economic growth in the developing countries.

The technology development in the next few decades needed to achieve the goal of maximizing temperature rise to 2°C, will require substantial public action in research and also development of high risk technologies. Also infrastructure development is a core public responsibility. If there are situations where emission reduction options are difficult to achieve due to a particular technology lock-in, specific measures have to be taken to resolve the problem. Missing and distorted markets are to be replaced or repaired. How exactly this is to be done, with which set of instruments does not follow from this scenario analysis. This analysis shows however that there is a dramatic task ahead for global and regional climate policy, with high demands on very broadly working climate policy instruments.

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Chapter 5

Metal supply constraints for a low-carbon economy?¹

Abstract

Low-carbon energy systems are more metal-intensive than traditional energy systems. Concerns have been expressed that this may hamper the transition to a low-carbon economy. We estimate the required extraction of Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb until 2050 under several technology-specific low-carbon scenarios. Annual metal demand for the electricity and road transportation systems may rise dramatically for indium, neodymium, dysprosium, and lithium, by factors of more than three orders of magnitude. However, in the base year 2000 the dominant uses were often in other sectors. Since growth in these other, previously dominant sectors has been less pronounced, the overall growth in society's metal needs is much less dramatic than in the electricity and transportation sectors. Total annual demand for the researched metals would rise by a factor of 3 to 4.5, corresponding to compound growth rates of between 2% and 3%. Such growth rates are similar or lower compared with historical growth rate levels over the last few decades. Prolonged higher levels have existed for copper, for example, with production rising by 8% per year from 1992 to 2006. Yet this state of affairs does not give cause for complacency. The richest resources may have been used, production is showing a tendency towards becoming very large-scale, and development times have increased, all leading to greater risks of disruption. It is therefore crucial, when developing specific technologies, that the resource-specific constraints are analysed and options for substitution are developed where risks are high.

5.1 Introduction

Low-carbon energy systems are considerably more metal-intensive than traditional energy systems, and authors have warned that this may hamper the transition to a low-carbon economy (Alonso et al., 2012). Especially assessments focusing on the implementation of low-carbon technologies in the energy and transportation sectors show a dramatic increase in

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the metal demands of those sectors (Kleijn et al., 2011; Roelich et al., 2014). For some metals it has been reported that the rapid increase in demand is not problematic. Availability of lithium, currently an essential element for electric vehicle batteries, is not expected to be a bottleneck for the rapid and widespread adoption of electric vehicles (Gruber et al., 2011). On the basis of a dynamic material flow model for the base metals aluminium, copper, chromium, nickel, lead, and iron, Elshkaki & Graedel (2013) found that supply is not limiting the introduction of renewable electricity generation technologies. On the other hand, they found that constraints in the supply of silver, tellurium, indium, and germanium could limit the introduction of some photovoltaics (PV) technologies (Elshkaki & Graedel, 2013). Most of these studies, however, did not take into account that the additional demand for low-carbon technologies should be considered in the context of a general increase in primary production of these metals for the entire economic system, also in relation to the build-up of infrastructure in newly developing countries.

This paper investigates potential bottlenecks in the supply of a wide range of metals, assuming the gradual introduction of far-reaching climate policies leading to full global implementation by 2050. We use a novel combination of methodologies, covering both the power generation and automotive sectors in detail and the broader economy more generally.

The novel aspect of our method is that specific data on the metal requirements for low-carbon energy and energy technologies are analysed in combination with long-term socio-economic scenarios implemented in a global multi-regional Input-Output model, which captures the global metal requirements and global greenhouse gas emissions of the global economy. This allows us to create a consistent scenario of metal demand and greenhouse gas (GHG) emissions. For instance, if mining of a particular metal increases, there will be an increase in the amount of machinery needed for the mining sector, and also in the associated electricity production (and hence GHG emissions) for making that machinery.

A key consideration in developing this methodology is that the future supply and demand of metals cannot really be predicted. There is uncertainty about how energy technologies will develop and what their metal requirements will be. Different scenarios with different assumptions concerning the penetration of low-carbon energy technologies can be envisaged

(IPCC, 2014; IEA, 2008; OECD, 2012a, 2012b). It is unknown if new options for substitution between metals and with other materials will become available. Recent examples of this are the current shift in plumbing from copper to polymers and aluminium (TEPPFA, 2013; Hix & Seydel, 2016), and the way some automobile and wind turbine producers avoided using neodymium when its prices spiked in 2011 (ENERCON, 2011; Tukker, 2014; Widmer et al., 2015). How the supply of metals may develop is also unknown. The main supply constraint is that a metal must be mined economically. The actual long-term supply of metals is highly dependent on new (mining) technology, cumulative availability curves, and expected and actual prices (Tilton & Lagos, 2007; Yaksic & Tilton, 2009; Gordon et al., 2007). Expected prices determine investment in mines, for given funding options and within political constraints.

The metals that we were able to analyse with the global multi-regional scenario model were Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb. In the case of other metals, data on their extraction, reserves and use were insufficient to make a full analysis, as we did for the eleven selected metals.

5.2 Materials and Methods

Long-term scenarios for supply and demand of metals are difficult to make. This is particularly true for minor metals such as In, Nd, Dy, and Li. New high-tech technologies can lead to disruptive demand change in just a few years, while it can take 10 years or more to adjust production and open new mines (Tukker, 2014). In this paper we try to deal with this unpredictability by analysing whether various contrasting scenarios for metal demand fall within a ‘viable operating space’ with regard to supply. We define this viable operating space as a situation where, in view of knowledge about economic reserves and past supply growth rate, the supply can in principle meet the demand in the scenarios. If expected demand for a metal falls outside this operating space, this strongly suggests a risk of steep price rises. In that case, consideration should be given to developing material substitutes or alternative technologies, or opening up new mining options.

The proposed concept of viable operating space for metal supply and demand is based on the following information: (a) estimated annual demand for metals in 2050 in a given scenario; (b) annual supply of metals in 2000; (c) historical growth rates of this metal supply; (d) estimated cumulative metal demand until 2050 in a given scenario; (e) estimated economic reserves in 2000, and (f) historical growth rates of these reserves. The assumption is that supply problems are likely to occur if demand growth for a metal will be much higher in the future than in the past, and/or if the cumulative requirements until 2050 are significantly higher than the economic reserves in 2000, including the observed historical growth rates of these reserves. These extrapolated supply quantities and reserve volumes thus act as upper boundaries of the viable operating space (see Figure 5.1 for a conceptual graphical explanation). This allows us to compare these boundaries with scenarios for the rise required by the expected demand for metals in 2050 in relation to supply in 2000, and to compare the current economic reserves with the expected cumulative metal demand until 2050. With this information, we can make an overall assessment of potential bottlenecks in the supply of metal resources due to effective climate policy, or in positive terms: define the viable operating space.

It should be noted, however, that although our concept can give a clear indication of future supply problems, it also has limitations. A significant increase in demand could lead to substantial price rises, which in turn would increase economic reserves: reserves that had been too costly to mine can be extracted profitably at these higher prices. We did not take this into account. But conversely, our approach also takes no account of potential absolute limits to metal availability. While most of the recent metal supply crises were related to disruptive demand changes (e.g. Tukker, 2014; Erecon, 2015; Sprecher et al., 2015), which are factors covered by our concept, in the longer term such absolute scarcity problems could also play a significant role. We therefore regard the boundaries derived from our concept as ‘upper boundaries’. Whereas the actual supply rate (amount mined) of metals is quite well known in 2000, there is less information about the economic reserves of metals in 2000. Published estimates of economic reserves can vary considerably and change rapidly, as shown by Gruber et al. (2011) for lithium. All the economic reserve data have been derived from the USGS (Kelly & Matos, 2009).

Different supply scenarios can be envisaged on the basis of cumulative supply curves and real prices, but such an analysis was not carried out in this study for two reasons. First, cumulative supply curves are uncertain or unknown for the metals considered in this study. Second, cumulative supply curves are only valid for currently known mining technology; the cumulative supply curve shifts if cost-reducing technology changes take place (Yaksic & Tilton, 2009).

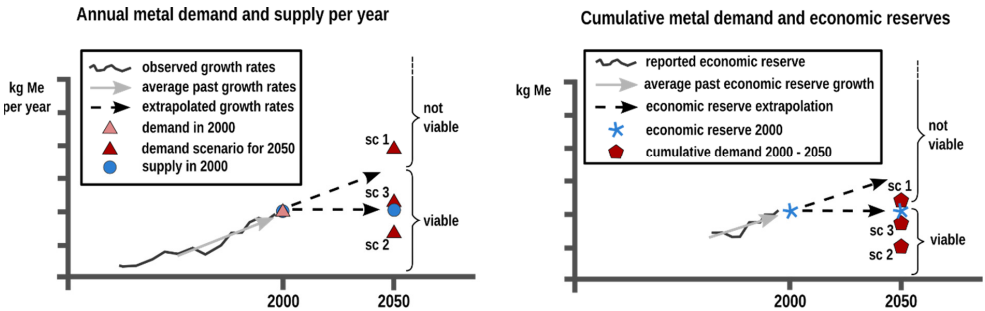


Figure 5.1: Conceptual illustration of the viable operating space for metal demand in 2050 based on historical data. Scenarios requiring much higher growth rates of annual supply and demand than in the past (left) are outside the viable operating space. Scenarios requiring higher cumulative use until 2050 than economic reserves available in 2000 (right) are also outside the viable operating space. These two figures can be produced for each of the metals analysed in this study. Please note that scenarios 1, 2, and 3 shown in the graphs are only examples and do not relate to the actual scenarios in the text.

As stated above, the demand for the eleven metals in 2050 in the four scenarios was estimated by combining two methodologies. Global metal requirements for low-carbon electricity and road transportation systems were calculated from appropriately scaled Life Cycle Assessment (LCA) inventories. Estimates for metal consumption in the rest of the economy are based on a global multi-regional extended Input-Output (IO) model, combined with expected GDP growth and extrapolation of general historical efficiency improvements and specific changes in energy intensive activities (steel production, cement production, built environment, domestic appliances). The metal requirements are based on three scenarios superimposed on a business-as-usual scenario, making a total of four scenarios. They are:

- 1) **Business-as-usual (BAU) scenario**, on an 5-6 degrees path in 2100. We based our BAU scenario on historical developments, including efficiency improvements, extrapolated until 2050 (de Koning et al., 2014, 2016). The GDP development in the BAU scenario, like all the other scenarios below, follows projections by the OECD (OECD, 2012b). It appears that the GHG emissions in the BAU scenario constructed in this way are on a trajectory towards an 5-6 degrees of global warming in 2100, similar to the RCP8.5 BAU scenario (IPCC, 2014; de Koning et al., 2014).
- 2) **Technological Scenario (TS)**, on a 2 – 3-degrees path. The second scenario is a Techno Scenario (TS), which integrates all probable and possible technical CO₂ emission reduction measures currently envisaged. It is a techno-optimistic scenario and includes, for instance, carbon capture and storage (CCS) on all the remaining fossil fuel power plants, widespread introduction of electric vehicles and complete electrification of household heating. The TS brings us onto a trajectory of about 2-3 degrees of global warming in 2100, similar to the RCP4.5 scenario (IPCC, 2014). GDP growth in the TS also follows projections made by the OECD (OECD, 2012b).
- 3) **Blue Map electricity supply (BMES) scenario** of IEA, on a 2 – 3-degrees path. The third scenario is similar to the TS scenario except that the global electricity supply mix in 2050 is taken from the IEA Blue Map scenario (IEA, 2008), with 23% nuclear, 26% fossil with CCS, and 44% renewables. The IEA Blue Map scenario suggests that by 2050 global energy CO₂ emissions would be halved compared with 2005 emissions, which would put average global temperature increase on a trajectory of 2 – 3 °C above pre-industrial temperatures. The CO₂ emissions cut would have to be realized at the same time as the world economy grows by 3.3% per year until 2050 and the global population grows to 9.2 billion in 2050 (IEA, 2008).
- 4) **Rare Earth Metals (REM) scenario**, also on a 2 – 3-degrees path. The REM scenario is similar to the BMES scenario but assumes additionally that all newly manufactured electric cars are equipped with neodymium magnets. Only the neodymium in the rare earth magnets is considered and not the dysprosium, which is currently an essential element in conventional rare earth magnets (Sprecher et al., 2014); the dysprosium content of rare earth magnets will likely decrease because neodymium magnets can be manufactured with 80% lower dysprosium content while retaining or even improving the favourable characteristics of conventional rare earth magnets (Chen et al., 2015).

In the REM scenario the average electric car contains 690g of neodymium, while in the TS and BMES scenarios the average electric car contains only 10g of neodymium.

As can be seen from the scenario descriptions, these low-carbon futures require significant technological change in the electricity and (road) transportation sectors. We therefore calculated metal requirements for these sectors using detailed Life Cycle Inventory (LCI) data, combined with global annual capital goods production in these sectors, for instance for PV cells, wind energy, nuclear power plants, and electric cars (IEA, 2008; Keppler & Cometto, 2012; EPRI, 2004). Annual electricity production volumes and number of produced vehicles in each scenario are given in Tables A and C of the supporting information. Life Cycle Inventory data showing the amount of metals needed for the electricity production technologies (Da Silva et al., 2013; van der Giesen, 2008; Laleman et al., 2013; Moss et al., 2011; Pihl et al., 2012; Wilburn, 2011) and amount of metals in the transportation vehicles (Burnham, 2012; Hawkins et al., 2012) are given in Tables B and D of the supporting information.

For activities *other* than electricity production and (road) transportation, we used EXIOBASE, a detailed global multi-regional environmentally extended Input-Output (IO) model (Tukker et al., 2013; Wood et al., 2014, 2015; de Koning et al., 2014, 2016). Onto this global IO model we imposed expected GDP growth from 2000 to 2050 (OECD, 2012b). We further assumed continuation of the trends in general efficiency improvement as observed from 1999 to 2009 using information from the World Input-Output Database (WIOD). The construction of the WIOD is described in Timmer (2012). Efficiency trends for all regions considered in our model were obtained by examining the amount of each input needed to produce a certain output by one of the 35 sectors available in the constant price series of the WIOD database. We assumed that the observed annual change (observed over a decade) in inputs required to achieve a certain output will continue until 2050. The final demand from these other sectors, in combination with the Leontief inverse of the 2050 table, resulted in an estimate of the primary demand for metals from these other sectors.

The IO scenario model¹ has previously been used to assess the effect of introducing renewable technologies on GHG emissions (de Koning et al., 2014, 2016). The scenario model covers the global economy, divided into four regions: the European Union, other developed countries, fast-developing countries, and the rest of the world. Each of these regions is on its own economic development path and connected by trade with the other regions. Each economic region is divided into 129 products/services and 129 industry sectors. The primary result of the scenario model is a set of supply-use tables that describe the structural global economic relationships. Converting the supply-use tables into an IO model gives us an estimate of the total demand for products in 2050 according to the four different scenarios, and therefore also an estimate of their total demand per metal in 2050.

The micro-level LCA information is combined with the information from the global IO model. The amount of metal used by specific climate change mitigation technologies is added to the rising demand for metals due to economic growth in general and the build-up of infrastructure in developing countries. A detailed description of the technologies used in the different scenarios and their associated metal use is given in the supporting information.

The scenario model that we have developed is different from previously published hybrid IO approaches in the field of energy technology scenarios. One such hybrid approach with a long history is the combination of MARKAL models with IO (Klaassen et al., 1999). An example of recent work is Daly et al. (2015), who estimated upstream CO₂ emissions across energy technologies for the UK. MARKAL-IO models typically focus on a single region and emissions of major air pollutants, not on the material requirements of energy technologies against a backdrop of global material requirements, like the scenario model used in this study. MARKAL models endogenously select the lowest cost energy technology, while the costs are uncertain and influence the outcome of the models (Bosetti et al., 2015). In the scenario model used in this study, energy technology scenarios are exogenously determined on the

¹ Octave source code implementing the scenarios, all starting data and resulting supply-use tables are freely downloadable from: <https://www.universiteitleiden.nl/en/research/research-projects/science/cml-cecilia2050---optimal-eu-climate-policy>

basis of technical and socio-economic considerations, and both their GHG emissions and material use are taken into account, integrated in a global multi-regional IO model.

Another class of hybrid IO models is integrated LCA-IO models. Typically these models are used to investigate the environmental and economic impacts of introducing a specific (new) technology in a particular country. For instance, the influence of using alternative fuel options for public transportation (Ercan & Tatari, 2015) or the introduction of a sugarcane-based biofuel industry in Australia (Malik et al., 2014). In these studies the new technology is combined with an IO model that describes a static economic background. The scenario model in this study uses LCA data to change a wide range of sectors, from electricity production, transportation, and cement to households. The IO model does not act as a static background but is changed to reflect the structure of the economy in 2050 as it develops according to different scenarios.

Two types of models that do indeed overlap with the scenario model used in this research are macro-econometric models and computable equilibrium models (CGE). However, these models do not have the sectors/product resolution and the GHG and material information required to enable an assessment as carried out in this study.

A limitation of our combined LCA-IO scenario model is the absence of built-in economic mechanisms and lack of price information, which are central elements in macro-econometric and CGE models. Structural changes in the economy, such as shifts from primary sectors to service sectors or shifts in trade patterns, have to be added exogenously to the IO scenario model. A further limitation of our combined LCA-IO scenario model is its lack of a recycling sector that allows for the estimation of metal recycling flows. This means that our scenario model structurally overestimates annual primary demand for metals in 2050.

5.3 Results

The 2050 demand per metal and per scenario is calculated with the combined LCA-IO model, as a ratio to the annual metal demand and supply in 2000, see Figure 5.2. As indicated, in all scenarios we used a global real GDP growth (in constant prices) based on OECD (2012) of

2.4% per year, leading to a factor 3.2 higher GDP in 2050 compared with 2000. The results in Figure 5.2 show a general growth in metal demand by a factor of 3 to 4, and hence imply a slight overall increase in the metal intensity of the economy.

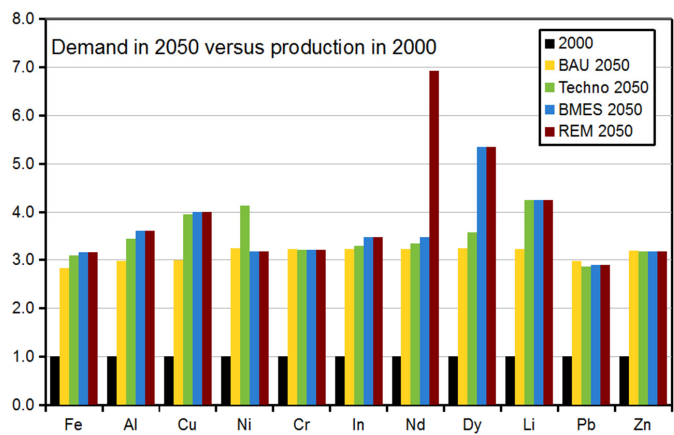


Figure 5.2: Annual supply of metals in 2000 versus demand for metals in 2050 in the BAU, Techno, BMES and REM scenarios in 2050. Indexed values; annual supply of the metal in 2000 = 1.

The actual metals demand in 2000 and the estimates for metals demand in 2050 form the basis for an estimate of the cumulative amount of metals consumed from 2000 until 2050. We use the simplest assumption on annual rise of consumption of metals from 2000 until 2050: a linear increase in demand for metals. The linear trend assumption gives a higher total use over this period than a compound growth rate because the compound growth rate is convex to the linear trend. The resulting estimate for cumulative metal demand is compared with the known economic reserves in 2000 (Kelly & Matos, 2009). Cumulative metal demand until 2050 for the four scenarios divided by the known economic reserves in 2000 is shown in Figure 5.3.

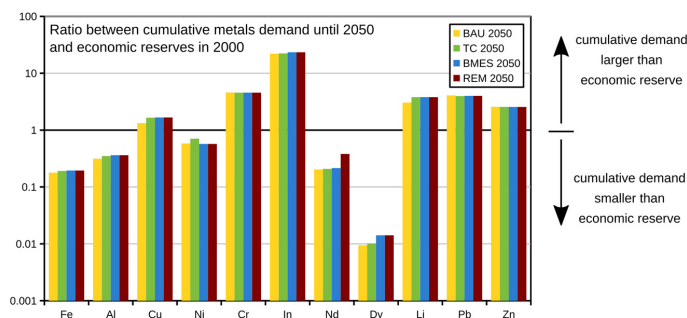


Figure 5.3: The ratio between cumulative metals demand from 2000 until 2050 and the known economic reserves in 2000. Economic reserves in 2000 are set at '1'. The y-axis has a logarithmic scale.

The values presented in Figure 5.2 and Figure 5.3 can be recalculated to produce a compound rate by which the annual production rate or economic reserve expansion of metals would have to increase. Table 5.1 does so for the required growth in metal production, compared with two historical ranges of production changes; using two different time periods gives some additional insight into the possibilities for adjusting supply to demand. Table 5.2 does so for the required expansion of reserves, compared with the actual expansion of reserves in the past.

Table 5.1: The annual metal production growth rate required to satisfy demand for metals in 2050.

Category	Scenarios of annual growth rate of production (%)				Observed annual growth rate of mining production (%)	
	BAU 2050	TS 2050	BMES 2050	REM 2050	1980 - 2006	1992 - 2006
Fe	2.1	2.3	2.3	2.3	2.8*	5.0*
Al	2.2	2.5	2.6	2.6	3.1	4.0
Cu	2.2	2.8	2.8	2.8	4.5	8.0
Ni	2.4	2.9	2.3	2.3	2.7	3.2
Cr	2.4	2.4	2.4	2.4	2.3	3.8
In	2.4	2.4	2.5	2.5	10.0	10.8
Nd	2.4	2.4	2.5	4.0	6.4 [#]	7.5 [#]
Dy	2.4	2.6	3.4	3.4	6.4 [#]	7.5 [#]
Li	2.4	2.9	2.9	2.9	5.7	6.9
Pb	2.2	2.1	2.2	2.2	0.1	0.8
Zn	2.3	2.3	2.3	2.3	2.1	2.5

* Fe ore mining production data, [#] Rare earths mining production data.

Table 5.2: The annual expansion rate required to satisfy cumulative metal demand until 2050.

Category	Annual rate of economic reserve expansion (%)				Observed historical rate of economic reserve expansion (%)
	BAU 2050	TS 2050	BMES 2050	REM 2050	1992 - 2006
Fe	s.	s.	s.	s.	1.4
Al	s.	s.	s.	s.	0.6
Cu	0.6	1.0	1.0	1.0	3.0
Ni	s.	s.	s.	s.	2.0
Cr	3.1	3.1	3.1	3.1	-3.8
In	6.4	6.4	6.5	6.5	n.a.
Nd	s.	s.	s.	s.	n.a.
Dy	s.	s.	s.	s.	n.a.
Li	2.3	2.7	2.7	2.7	4.6
Pb	2.9	2.8	2.8	2.8	0.4
Zn	1.9	1.9	1.9	1.9	3.3

Note: s. means sufficient because the economic reserves in 2000 are already large enough to satisfy cumulative demand until 2050. No historical data could be found on the development of economic reserves of the metals In, Nd, and Dy.

5.4 Discussion

The BAU scenario requires a growth in production of the studied metals of 2.1 to 2.4 % per year, which in all cases, except for lead, is less than the historical supply growth between 1980 or 1992 and 2006. This is partly because future global economic growth is estimated at 2.4% (OECD, 2012b), considerably lower than over the last 25 years. For most metals we see a BAU demand growth in line with economic growth, and very little decoupling of material use from economic growth. This runs counter to policy intentions of, for instance, large economic blocks like the EU, whose ambition is to put strong resource-efficiency policies in place (EC, 2014). For major metals such as Fe, Al, and Cu, the BAU scenario shows a slight decoupling, due to the fact that our model is based on the assumption that the efficiency gains shown by economic sectors in the past can be extrapolated into the future (see Methods section).

As expected, metal demand is higher in the various low-carbon scenarios. However, apart from some exceptions, this additional demand is quite small. In the Techno scenario, the introduction of low-carbon technologies leads to a demand growth in aluminium, copper, indium, neodymium, dysprosium, and lithium slightly above the base level of economic growth (2.4% per year, or a factor of 3.2). The largest demand growth is for lithium, with a factor 4.3 increase in 50 years, or 2.9% per year. Changing the electricity supply mix in the direction of more renewables, as in the BMES scenario, increases the demand for metals compared with the BAU scenario, but not by very much. In the BMES scenario, dysprosium demand becomes larger by a factor of 5.3 than the demand in 2000, while in the BAU scenario this is a factor of 3.2. The REM scenario shows that full electrification of private cars in 2050, using solely neodymium magnet based technology (about 690g of Nd per car), raises Nd demand by a factor of 6.9 compared with 2000 (Figure 5.2), while in the BAU scenario this is a factor of 3.2. The REM scenario would require a 4% annual supply growth of Nd.

The annual increase in metals demand is to a large extent determined by the use of these metals in many applications in an expanding global economy, rather than their specific use in renewable energy technologies, electric cars, and construction. It is only for copper, lithium, and indium in general, and neodymium in the REM scenario, that demand is raised substantially above the expansion rate of the global economy by the change in electricity generation technology and the massive introduction of electric cars. An example is the specific use of lithium in car batteries. While its use in car batteries increases 2.0×10^3 times, the overall demand growth for lithium is only a modest factor of 4.3 (2.4 % p.a.). This is because lithium is now primarily used in ceramics, glass, other types of batteries, and greases, rather than for electric car batteries (DOE, 2010).

Looking at the annual expansion of metal production required for the BMES scenario, the largest annual increase is found for dysprosium at 3.4% per year. In the REM scenario, the largest annual increase is found for neodymium at 4.0% per year.

Figure 5.3 shows that the high estimate of cumulative demand for iron, aluminium, nickel, dysprosium, and neodymium until 2050 can be met by the currently known economic reserves of metals. However, this does not mean that no further development of mines is necessary.

Particularly the production rate of dysprosium and neodymium has to be increased. But as Table 5.1 shows, historical data on the growth rate of mining production indicates that this is well within the range of normal technical capabilities. In the period 1980 – 2006, the mining production of the metals under consideration showed a minimum of 2% annual increase, often exceeding 4% per year. The only exception is mining production of lead, which saw increases of well below 1%, probably because the use of lead was restricted in various applications due to toxicity concerns (Tukker et al., 2006). We refer further to Table 5.1 and the supporting information.

For copper, chromium, indium, lithium, zinc, and lead, the current economic reserves as known in 2000 are not sufficient to meet the cumulative demand for these metals until 2050. Additional mines of similar quality have to be developed, metal prices have to increase, or improvements in mining and refining technology have to be made in order to expand the economic reserves and satisfy cumulative demand. These economic reserves would have to increase by a factor of 1.6 for copper and 23 for indium by 2050, barring substitution.

This annual expansion rate of the economic reserves of copper, chromium, and lithium is modest: between 1.0% and 3.1%. As shown in the supporting information, such expansions of economic reserves have been achieved in the past decades (from 1992-2006), in a period of declining metal prices. Only for indium is a higher expansion of economic reserves of close to 7% per year required. Indium is a special case, however. It is only produced as a by-product of zinc refining. Very few zinc refineries extract indium in their process at present, whereas they might do so if the price of indium were to increase, leading to a much higher supply of indium (USGS, 2012; Polinares, 2012). Elshkaki & Graedel (2013) also identify indium as problematic. These authors state that while indium reserves are more than sufficient to meet demand until 2050, the problem lies in increasing the supply rate; however, they do not make the connection with zinc refining.

The high growth rate of neodymium in the REM scenario may be a bottleneck. In that scenario, all electric cars are going to use neodymium magnets, causing demand for that metal to surge to levels that require annual expansion rates far above 3%. But alternative technologies are available for that specific case, such as non-permanent electric magnets

based on copper, as now already used in Tesla cars and some wind turbines. The answer to this problem is therefore simple: if neodymium supply problems occur, the BMES scenario may become reality, with private electric cars using non-permanent magnets based on copper. It should further be noted that a 4% supply expansion of neodymium is still well within the historically realized supply expansion of 6-7% per year up to 2006 (see Table 5.1).

5.5 Conclusions

Our work confirms the significant rise in metal requirements for a low-carbon transition in the (land) transportation and electricity sectors that has been reported by others (e.g. Kleijn et al., 2011; Gruber et al., 2011; Alonso et al., 2012; Roelich et al., 2014). Yet we also show that, because existing uses of metals in other sectors in society will not require a drastic transition, the overall annual supply increase needed to satisfy future metal demands in low-carbon scenarios is not extreme. Indeed, the various scenarios, including those with strong low-carbon ambitions such as the BMES and REM, require a modest supply growth compared with recent historical data on the realized growth in metal supply. This is in line with the conclusions of Elshkaki & Graedel (2013) and a detailed LCA study of Hertwich et al. (2015) on low-carbon technologies. They concluded that while copper and iron requirements of the power system would rise significantly, “only two years of current global copper and one year of iron production will suffice to build a low-carbon energy system capable of supplying the world’s electricity needs in 2050”. Because our method does not take account of recycling as a metal supply source, it might even overestimate the demand for primary metals. Iron is such a case. According Pauliuk et al. (2013), demand for primary steel peaks between 2020 and 2030, and increasing secondary production will satisfy a still increasing total steel demand.

In the context of our framework of a viable operating space, we see that the BAU and TS scenarios require less supply growth than the BMES and REM scenarios, but apart from Nd and Dy the differences are relatively small. We see that for all scenarios the required supply expansions fall well within the historical supply growth rates. From the perspective of required growth of economic reserves, the 7% annual expansion of indium stands out, but this problem is similar in all scenarios and can probably be solved by increasing by-production from Zinc mines. At this point we would therefore conclude that all the scenarios in principle

face similar challenges in metal supply in the future, rather than some being more viable and others less so, given our viable operating space framework. These conclusions are obviously limited to Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb, the metals we studied. The situation could be different for other metals (e.g. silver, tellurium, and germanium for specific PV technologies, as suggested by Elshkaki & Graedel (2013)).

There are reasons not to be complacent, however. The analysis shows that production of virtually all metals relevant for the low-carbon transition will have to increase significantly. Since it may take a decade or more to open mines, especially large, deep open-cast mines, investments in new mining operations have to take place well in advance of increases in production. At present, however, it is politically uncertain whether a low-carbon society will develop and, if so, which scenario will materialize. This makes the return on investment uncertain and investors may not invest in new mines in time. Demand-supply imbalances and price hikes may then occur, particularly if government policies are unexpectedly and widely adopted, causing a much faster transition to low-carbon technologies and electric vehicles than the 100% implementation by 2050 that we assumed in our BMES and REM scenarios. Building new mines and expanding existing ones has negative local environmental consequences, which can also be a delay factor, especially if these reserves are located in fragile environments. Moreover, in the case of several metals it is necessary to exploit new deposits, which may have lower metal ore concentrations than are currently available. Extracting metals from ore bodies with lower metal concentrations means that more energy, water, and auxiliary materials are needed to extract the metal, with possibly higher environmental impacts and larger political risks (Prior et al., 2012).

The main message of this research is that availability of Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb is unlikely to be a bottleneck for the transition to a low-carbon energy system. However, the combination of lack of certainty about return on investment, long lead times in expanding mining production, and concerns about impacts of mining that delay expansion of mining capacity may well create imbalances in demand and supply (Tukker, 2014; Sprecher et al., 2015).

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Chapter 6

Discussion, conclusions, and outlook

6.1 Introduction

This thesis investigated the potential of structural economic models to be used as a scenario model for economic development and associated environmental interventions. Next to an introduction and conclusions, it contains 4 chapters. Chapter 2 evaluated different model types used in climate scenario analysis. Chapter 3 contained an investigation of the effect of aggregation of supply-use tables on material footprints. In Chapter 4 and 5, a structural scenario model was presented that was used to evaluate the effects of the introduction of a wide range of low-carbon technologies on CO₂ emissions and resource use until 2050. In combination, these chapters tried to answer the research questions posed in chapter 1:

1. How can an EIO framework be turned into a long term global quantitative scenario model that allows us to investigate environmental interventions and their effect on natural environment and economy?
2. What are the strengths and weaknesses of such an EIO based scenario tool compared to other quantitative scenario modelling approaches that use for instance econometric modelling, integrated assessment modelling, and computable general equilibrium modelling?
3. What is the appropriate spatial and economic sector resolution for a successful implementation of scenarios in the developed scenario model?
4. How can this quantitative scenario model be used to investigate:
 - a. If the introduction of renewable energy technologies can reduce GHG emissions in 2050 to a level in line with the 2 °C limit?
 - b. If the introduction of these renewable energy technologies might be constrained by the supply of metals until 2050?

5. How can, also given experiences in case applications, the EIO based scenario model developed in this thesis, be expanded to overcome certain weaknesses it has compared to other quantitative scenario models?

Section 6.2 answers the research questions 1 - 3 with regard to the form and position of IO based models. Section 6.3 answers the research question 4 with regard to the case studies and gives some further reflections on outcomes. Section 6.4 does suggestions for further research.

6.2 Research questions with regard to IO based scenario model

6.2.1 Research question 1: Creating a long term global quantitative scenario model

This research showed that we can use the EIO framework for a global quantitative scenario model that allows us to investigate environmental interventions and their effect on natural environment and economy. Our modelling approach works, in short as follows:

- 1) Supply-use tables are seen as the production recipes of products.
- 2) The production has to increase to provide products for a growing population.
- 3) Production recipes change over time, due to a general trend of in the efficiency of production. Future production efficiency improvements are estimated by extrapolating improvements from the past.
- 4) 2 & 3 lead to a growth in GDP.
- 5) The supply-use tables are further scaled to match OECD GDP forecasts for 2050.
- 6) On top of that the production recipes are changed due to the implementation of low carbon technologies or the production of some sectors is increased at the expense of other while maintaining the same output.
- 7) Energy use for combustion and hence CO₂ emissions from intermediate users and final users are kept synchronised with the size of the energy inputs of the sectors and households as influenced by requested sector output, general efficiency changes and specific low carbon technologies.
- 8) CO₂ emissions can further be cut back by the use of carbon capture and storage.
- 9) The resulting balanced supply-use table containing a would-be world is subsequently transformed into an input-output table for further analysis.

6.2.2 Research question 2: Strengths and weaknesses compared to other models

The EIO based scenario tool, in comparison with macro-econometric models, computable general equilibrium (CGE) models, and integrated assessment models (IAMs) is simple. Yet this simplicity is a strength for long-term static comparative studies. CGE models, macro-econometric models and IAMs all rely on parametrization of behavioural mechanisms that have been derived from present experience, but which might not be representative for long-term future situations. A strength of the EIO based scenario tool is its consistent and comprehensive description of 129 economic activities in a country.

A weakness of the EIO based scenario model is its simple description of the economy. Behavioural mechanisms like nonhomothetic¹ utility functions for consumer demand, factor mobility, and price mechanisms are not included. It is hence not possible to analyse effects of economic policy measure such as subsidies or taxation. For the same reason it is not possible to make an assessment of the direct costs and benefits of climate policies and it certainly cannot assess damages to the economy due to climate change. Another weakness of the current EIO based scenario model is the poor description of waste and recycling flows and stocks are completely absent.

The EIO based scenario model does not include a model (models) of environmental processes, and feedback of environmental change to economic sectors. However because of the comprehensive description of the economy and environmental interventions the EIO based scenario model might offer a good starting point to make a link to environmental process models. Environmental system models that ultimately includes a feedback on economic production. Of particular interest is the full feedback of increasing global mean temperature on agricultural and forestry sectors.

¹ The utility function in the structural scenario model can be called homothetic. This means that the income elasticities of demand of goods equals to one. As income grows the preference for goods does not change. Like the structural model scenario model, many CGE models assume homothetic utility functions (Burfisher, 2011)

6.2.3 Research question 3: Appropriate spatial and economic sector resolution

In Chapter 3 the error introduced by spatial and sectoral aggregation in supply use tables was investigated. Results of this investigation show that when there is a need for aggregated indicators (for instance on the average EU level) performing the calculations at the highest level of detail and aggregating the final results is the best approach. But working at the highest level of detail can be unpractical or impossible. For instance necessary data are not always available at that level of detail or calculations take too much time. In these cases aggregation might be necessary. Such a case was the structural scenario model presented in Chapter 4 and 5.

Chapter 3 gives guidance for the type of aggregation that can be introduced. Spatial aggregation is preferred above sector aggregation. Spatial aggregation is likely to distort footprint calculations less than sector aggregation. The rationale is that the production recipes in different countries does not differ as strongly as production recipes in between sectors. Of course this statement depends on the countries or the sectors that are being aggregated. An example might be illustrative here. A coal power plant in the Netherlands will operate very similarly to a coal power plant in Germany or Belgium. Spatial aggregation will not lead to large aggregation errors. An aggregation of different types of electricity production e.g. gas, coal and nuclear power plants might introduce larger aggregation errors because the production recipes are quite different. But spatial aggregation of countries where technology is very different is not advisable either.

In the structural scenario model described in Chapter 4 and 5 spatial aggregation was carried out, but sectoral and product detail was maintained. Spatial aggregation was done on the basis of economic development status. As such the structural scenario model balanced the theoretical best approach and practicalities in the best way possible.

6.3 Research question 4 with regard to empirical cases

In Chapter 4, the structural scenario model indicates that it will be very difficult to reduce GHG emissions in 2050 to a level in line with the 2 °C limit, given projected population and

economic growth. Less consumption growth, especially in high income countries should be actively explored as a policy option if the “well below” 2 °C target is to be met.

In Chapter 5, the structural scenario model indicates that the introduction of substantial amounts of low carbon energy technologies is likely not constrained by the supply of metals until 2050. Possible resource constraint problems are not a reason not to start introducing low carbon energy technologies. We will now reflect in more detail on each of these cases

6.3.1 A structural model for climate change scenario analysis

In Chapter 4, several scenarios were presented that depicted possible worlds in 2050. The GHG emissions in each scenario were estimated using a structural scenario model as discussed in Section 6.2.

One of the scenarios was a business as usual (BAU) scenario where no additional¹ GHG emission reduction measures were undertaken. In this scenario, the simple scenario model estimated an emission of 75 Gt CO₂/yr. in 2050. The IPCC BAU scenarios, as condensed in the representative concentration pathway RCP8.5, gives an emission of 73 Gt CO₂/yr. in 2050 (RCP database, 2009). The similarity between the two numbers gives some support for the validity of the structural scenario model approach.

Using the same structural scenario model, the GHG emissions of another scenario was estimated. In this scenario, the so-called Techno scenario, all technology that can probably be used to reduce GHG emission in 2050 is assumed to be in operation. In this scenario, the structural scenario model estimated an emission of 39 Gt CO₂/yr. in 2050. The estimated emissions are in this case comparable to RCP4.5 which assumes about 41 Gt CO₂/yr. in 2050. Our Techno scenario is quite far away from an emission pathway that limits average global temperature increase to two degrees in 2100. Such a representative emission pathway (RCP2.6) assumes an emissions of about 11 Gt CO₂/yr. in 2050.

¹ This scenario is based on among others a continuation of the efficiency improvements in the industry sectors as observed in the period 1999 – 2009 when GHG emission reduction policies were already in place in many countries.

An overview of the RCPs (Van Vuuren et al., 2011), estimated¹ CO₂ emissions from 2000 to 2014 (CDIAC, 2017) and results from the scenario model (See Chapter 4) are shown in Figure 6.1. Notice that only CO₂ emissions from fossil fuels and industry are given. CO₂ emissions from land-use change are not included and CH₄ and N₂O are also not considered.

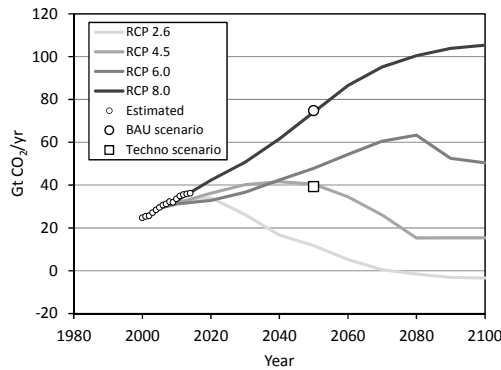


Figure 6.1: Representative concentration pathways (RCP) (Van Vuuren et al., 2011), estimated CO₂ emissions (CDIAC, 2017) and global CO₂ emissions from the BAU and Techno scenario.

As discussed in Chapter 4 and shown in Figure 6.1 there is a difference of about 28 Gt CO₂/yr emission in 2050 between the Techno scenario and the RCP 2.6. It is of importance to know the reasons for this large difference. Is the simple structural model overestimating CO₂ emissions given its input parameters or are different assumptions in the scenario reason for the observed differences? Differences in the scenario may be divided in differences in economic growth prospects, population development or the technology used for CO₂ emission reduction.

¹ Please notice that the term estimated is used and not observed. Carbon dioxide emissions from fossil fuel burning and cement manufacturing are estimated based on fossil fuel use and cement production. Uncertainty in the global emission estimates are assessed to be about $\pm 5\%$ (Le Quéré et al., 2012).

Population development in the simple structural scenario model follows United Nations projections (UN, 2013). Population is assumed to be about 9 billion persons in 2050 which is similar to the global demographics assumption underlying the IMAGE framework. Different assumptions in population development cannot be the reason for the observed CO₂ emission differences.

Economic growth prospects as input for the structural model discussed are based on OECD forecasts that assume 100 trillion Euro (2000 price level), a factor three growth since 2000, see Chapter 4. IPCC AR4 scenarios (Van Vuuren et al., 2011) assume GDP in 2050 is in the range of 100 - 150 trillion Euro (2000 price level)¹. Differences in economic growth can therefore not be the main reason for the differences in the estimated emissions in 2050.

The difference in the CO₂ emissions per year in the Techno Scenario and the IMAGE RCP2.6 scenario must therefore be found in either the underlying technology implementation assumptions and/or how this technology assumptions affect CO₂ emissions are modelled in both scenario models. Some of the technology implementation assumptions differences in the IMAGE RCP2.6 scenario and the Techno Scenario are discussed below.

Differences in the quantity of BECCS can explain a small part of the difference in the CO₂ emissions in the Techno Scenario and the IMAGE RCP2.6 scenario. In the IMAGE RCP 2.6, the requirement for BECCS ranges between 2 and 10 Gt CO₂ annually in 2050. In the Techno Scenario, 2.4 Gt CO₂ is captured and stored annually in 2050.

A small part of the gap is explained by differences in CCS efficiency. In the Techno Scenario, CCS is assumed to operate at an efficiency of 80%, see Section 4.4.2. In the IMAGE RCP 2.6 scenarios CCS efficiency is assumed to be 90%. Assuming 90% efficiency in the Techno Scenario an additional emission reduction of about 0.3 Gt CO₂ would be achieved. Additionally the Techno Scenario assumes that much more electricity is being consumed and produced. However given the substantial CCS on power plants it only explains 0.3 Gt CO₂ of the gap.

¹ Using an average exchange rate of 0.92 USD/Euro in 2000 (ECB).

The analysis above showed that the economic and population growth assumptions cannot explain the gap between Techno Scenario and RCP 2.6 scenarios. Further looking into differences in the technologies could also not explain the differences in estimated CO₂ emissions. This first superficial scenario model comparison shows that there is a need for further comparison between the structural scenario model and other climate change mitigation scenarios.

Different outcomes of different models should be assigned to different scenario inputs or different model assumptions. A situation where it is unclear what the causes are of differences between scenario model outcomes is highly unsatisfactory because it signals a lack of understanding of mechanisms in the models.

In this respect it is of eminent importance that the mechanisms incorporated in the scenario model are transparently documented, and all the inputs, intermediate results and outputs are available. If such information is not available and therefore a thorough inter model comparison is not possible, it hampers scientific progress. To enhance transparency and aid model comparison it would be helpful if (intermediate) results of CGE and E3ME models would be published as a set of supply-use tables with environmental extensions for each year that is simulated.

6.3.2 Resource constraints in climate change scenarios

Our investigation into possible metal resource limitations concluded that the build-up of a low carbon energy infrastructure is not severely hampered by restrictions in supply of eleven different metals, see Chapter 5. Both the amount of resources and the resource supply rate of metals until 2050 seems to be sufficient for the build-up of a low carbon infrastructure. This cautiously optimistic conclusion must be seen in the light of our low carbon infrastructure scenario and the limited number of metals taken into account. The outcome of this investigation does not mean that it takes little effort or that there will be no short term supply disruptions or that the resource exploration comes without additional environmental impacts, see Chapter 5.

Our cautiously optimistic resource outlook contrasts with the rather pessimistic outlook on the possibilities of reaching a CO₂ emission level in 2050 that align with a 2 °C climate target using the same scenarios and using the same scenario model. We may ask ourselves why this is the case. Are the assumptions on the level of low carbon technologies introduced in the energy system so limited that there is a limited GHG reduction and a limited additional amount of metals needed for the low carbon technologies?

As discussed in Section 6.3.1 the market penetration of low carbon technologies introduced until 2050 is rather optimistic. That these scenarios do not bring us on a 2°C climate target is not the result of a limited introduction of low carbon technologies and can for a small part be explained by our assumption of a limited contribution of BECCS (negative emissions).

The positive outlook on metal resource constraints is partly influenced by our assumptions on the ability to change technology¹ when (short-term) supply restrictions occur. In Chapter 5, several of such examples are presented. For instance replacement of copper piping by composite/plastic piping, switching of neodymium magnets for electromagnets, reducing the concentration of dysprosium in rare earth magnets while maintaining the favourable temperature resistance of the magnets. We assume that technology can change fast and that this technology can be implemented fast in cases where metals or metal products have to be substituted. This assumption is permitted because: 1) the technology implementation does not need far reaching societal changes and 2) there is a market mechanism in place (resource prices) that drives technology change. Factors that may limit the speed of change are to be found in legal restrictions such as building codes (Gann et al., 1998). For instance the use of fibre reinforced concrete is limited by building codes (Di Prisco et al., 2009).

In contrast the ability to change technology and the implementation of technology takes decades when it comes to renewable energy technologies. In principle low carbon energy technology is available. The renewable energy technology development trajectory that started

¹ Technology change is described very casually here. From an evolutionary economical point of view technology change can be divided into several phases: technology development, application development and market development. The important message here is that existence of operational technology does not mean that it has a sizeable market share. Flying cars may serve as an example.

in the early 1970's as a reaction to the oil crisis and environmental concerns (Meadows et al., 1972) has brought us to a point that the technology is ready for implementation and is indeed implemented on large scale¹. However the implementation of the technology, despite its acute importance², is not fast enough. Even if all Paris pledges are fulfilled the two degrees target will not be met (Rogelj et al., 2016). In contrast to the technology development for metal substitution there is 1) a need for far reaching societal changes 2) no market mechanism is in place to price carbon emissions. These two fundamental differences make that the implementation of technology that replaces the fossil fuel based technology much slower than the technology changes that alleviate or circumvent looming (short-term) resource constraints.

In the metal demand scenarios the secondary supply of metals was left out of consideration. In a society that has built-up its infrastructure, infrastructure that only has to be maintained and not expand anymore, secondary supply of metals can for a substantial part satisfy demand. Typically future demand for aluminium and iron might be supplied from secondary sources alleviating demand from virgin resources. If structural scenario models are going to be used for further future metal supply and demand scenarios, these secondary streams need to be reckoned with. Because secondary streams originate from demolition, recycling and waste treatment, these waste treatment activities and waste flows need to be incorporated in the supply-use tables.

The economic value of waste is often unknown or the actual physical flows are very poorly connected to the monetary flow in supply-use tables. Therefore supply-use tables as available at national statistical offices often do not give insight in waste supply, recycling and secondary supply of materials. Augmented supply-use tables exist that incorporate waste flows. Without being complete, examples of different approaches are the Japanese waste input-output model (Nakamura et al., 2002, 2007), the set of hybrid EXIOBASE supply-use tables (Tisserant et al., 2017) and the incorporation of post-consumer waste collection and recycling activities in the EIPRO study (Tukker et al., 2006). A methodological overview of

¹ It's interesting to notice that this trajectory took about half a century. A technology development trajectory often takes about 50 years' time (Hirooka, 2006).

² At the rate of emissions in 2014 the carbon budget for the 1.5 °C target would be used by about 2020 (IPCC, 2014). The budget for the 2 °C target would be used by about 2027.

waste treatment in physical input-output tables was given by Dietzenbacher (2005). However these studies are either not global or are hampered by lack of good data that allows for a good estimate of the physical waste flows. Therefore incorporation of waste activities and waste flows to supply-use tables still needs further attention.

6.4 Research question 5: Recommendations for further research

From the former sections one can deduce that there are a number of areas that are interesting for further investigation:

- 1) Spatial and sectoral detail of structural scenario models
- 2) Improved potential of analysing feedback effects in the economy
- 3) Options to combine the strengths of structural models with those of other models

6.4.1 Improved spatial and sectoral detail

In Chapter 2 it is argued that structural scenario models might be used for an analysis of the repercussions of a changing environment on the economy. We might ask ourselves if the current spatial and economic sector resolution is sufficient for such an analysis. To answer this question we first look at the reasons for selecting the current spatial and economic sector resolution.

Originally input-output tables were used as a framework for national accounting. The sector/product resolution was determined by 1) practical issues such as data availability and the effort it would take to do calculations and 2) the contribution of sectors to the economy. This led to input-output tables where only a few primary sectors and many tertiary sectors are distinguished in the majority of available input-output tables.

Since a few years input-output analysis has seen wide application in environmental studies. To be able to provide relevant and detailed information on environmental impacts associated with economic activities the sectoral resolution needed to increase for sectors where most of the environmental interventions take place. These sectors are often the primary and secondary sectors. Therefore a lot of effort was put into the disaggregation of primary sectors such as agricultural, mining, and secondary sectors such as electricity production sectors (Wood et al.,

2014, 2015). The result was EXIOBASE. It is a supply-use and input-output database that has a sector resolution which reflects the environmental importance of sectors.

If supply-use tables are going to be used for scenario models that investigate repercussions of a changed environment on the economy we again have to ask ourselves if the resolution is sufficient for such an analysis. While we have not fully investigated this question there are indications that again the resolution has to be increased. Effects of climate change are highly dependent on geographical location. Low lying area can be affected by increasing sea levels. Increases in temperatures are more pronounced towards the Poles. This indicates that the current large geographical areas such as the US, China, India, Australia and especially the Rest-of-World region needs to be disaggregated into smaller areas depending on expected climate change effects.

Further geographical disaggregation of IO databases is in this case important. Large countries such as China, India, and the USA should be subdivided into smaller regions because the structure of the economic system differs substantially in the regions and climate change impacts will be very different in the different regions (Zhang et al., 2014). Climate change impacts in the Gulf Coast states of the US are different in Washington state (Melillo et al., 2014).

6.4.2 Improved potential for analysing feedback effects on the economy

Our discussion on resource availability of eleven different metals and the build-up of a low-carbon society shows that while resources are not a bottleneck for the implementation of the renewable energy technology, the supply rate of most metals needs to increase substantially until 2050. Mining and refining of metals is associated with environmental impacts. Increasing the rate of supply of metals, perhaps by using lower grade ores, will need increasing additional energy, water, and land resources (Graedel & Van der Voet, 2010). The connection between the introduction of renewable energy technologies, metal supply and environmental impacts is not clear. Maybe limits on the use of metals for renewable technologies are not defined by resource limits but by environmental impact limits. The interlinkages between metal use, resource depletion, and environmental impacts within a world that tries to steer towards a low-carbon society therefore needs further attention.

As argued in Section 6.3.2 for a proper analysis of future metal demand and primary metal supply, secondary resource availability has to be taken into account. Current approaches to describing waste and stocks in supply-use tables are not yet comprehensive or of sufficient quality. This topic still need further attention in the future.

The attractiveness of the structural scenario models is that they cover the global economy, have a detailed description of the environmentally relevant sectors, cover a wide range of environmental interventions, and are simple to operate. They might therefore be used for a further investigation of the interlinkages as described above. Hybrid LCA-IO models in which mining activities, using different ore grades, are described in more detail in physical terms combined with IO model seems a natural way forward. The approach would not be much different from the hybrid LCA-IO model that was developed for Portugal to accommodate fast changing electricity production mixes against a slower changing general economy (Guevara & Domingos, 2017).

6.4.3 Combining the strengths of structural models with those of other models

The current generation of process based integrated assessment models contain a limited assessment of feedback effects of climate change on economic activities. With average global temperature increases beyond the 2 °C target, feedback effects of climate change on economic activities will increase. In how far that will affect economies and the capability of economies to implement climate mitigation strategies is unknown. The structural models, with their relatively detailed spatial description of the activities in an economy could be helpful here. Having spatially detailed economic models is essential because climate change impacts are highly dependent on geographical location as argued in Section 6.4.1. The structural models could be used for the description of the economic system in an integrated assessment model. This structural model combined with a simplified environmental systems model might make it possible to analysis of the impacts of climate change on economic activity, specifically agricultural and forestry activity.

On the short term, the structural scenario model must be updated to the latest available IO data and the scenario model should be validated and compared to other types of climate change scenario models.

6.5 References

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Summary

One of the important contributions of environmental sciences to policy making is to analyse how future economic development might impact our environment. The influence of the economy on the environment at present is larger than ever before. As a result the environment is changing and this changing environment can threaten the resource basis of our economy. A particular area where the effect of economy on the environment has already global economic repercussions is climate change. To limit the effects of climate change, global average temperature since pre-industrial measurements are to be kept well below 2 °C preferably even at 1.5 °C. The 2 °C limit and certainly the 1.5 °C target means that substantial GHG emission reductions should be realized already by 2050. How these emission reductions should be achieved is unclear. At least it is clear that the use of fossil fuels should be reduced.

It is important to know if indeed the introduction of the renewable energy technologies can achieve the deep GHG emission reduction that are required in 30 years' time against a backdrop of population growth and economic growth. Therefore we investigate in this thesis the effects of the introduction of renewable technologies on GHG emissions and resource use until 2050.

The principal global economy-environment model used in this investigation is based on a global multi-regional environmentally extended input-output (EIOA) framework. It is in principle a static model. A model that is mostly used to analyse inter-industry relationships and effects of (marginal) changes in the demand for products. It is not often used for long-term scenario analysis as is required in this research.

The first research question to be answered was therefore how an in principle static EIO framework can be turned into a long term global quantitative scenario model that allows us to investigate environmental interventions and their effect on environment and economy?

Current global scenario models used in climate change research are either very simple regression models, macro-economic models and integrated assessment models. The scenario model developed in this thesis uses another modelling approach. A second question to be investigated is how the EIOA framework based scenario tool compares to the other types of global scenario models used in climate change research. Especially what are the strengths and weaknesses of the different modelling approaches?

The number of sectors and countries distinguished in the EIOA framework determine how specific technology developments can be included in which regions in the scenario model. It was therefore investigated what the appropriate spatial and economic sector resolution has to be for a successful implementation of scenarios in the developed scenario model?

Having created a scenario model we used this model to investigate two cases. 1) If the introduction of renewable energy technologies can reduce GHG emissions in 2050 to a level in line with the 2 °C limit? And 2) if the introduction of these renewable energy technologies might be constrained by the supply of metals until 2050?

Finally given the experience gained using the EIOA framework based scenario tool in the case studies and comparing it with other types of global scenario models how can the EIOA framework based model be adapted to overcome certain weaknesses it has, compared with other quantitative scenario methods?

A long term global quantitative scenario model was developed based on global multiregional supply-use tables that distinguish 129 different commodities and sectors for the year 2000. The year 2000 is the base year for our scenario studies. Implementation of scenarios for the year 2050 in these supply-use tables is done in several consecutive steps:

- 1) Supply-use tables are seen as the production recipes of products.
- 2) The production has to increase to provide products for a growing population.
- 3) While the efficiency of the production improves especially in developing countries.
- 4) 2 & 3 lead to a growth in GDP

- 5) On top of that the production recipes are changed due to the implementation of low carbon technologies or the production of some sectors is increased at the expense of other while maintaining the same output.
- 6) Energy use for combustion and hence CO₂ emissions are kept in synchronized with the size of the energy inputs of the sectors as influenced by requested sector output, general efficiency changes and specific low carbon technologies.
- 7) CO₂ emissions can father be cut back by the use of carbon-capture and storage.
- 8) The resulting balanced supply-use table containing a would-be global world is subsequently transformed into an input-output table for further analysis.

Using this framework multiple scenarios that assume different use of low-carbon technologies in 2050 into the global economy can be made.

The developed global EIOA framework based scenario tool was used in the field of climate change scenario studies, a research field that typically uses computable general equilibrium (CGE) models, macro-econometric models or integrated assessment models (IAM). These models have a long development history and it is rightfully to ask what the contribution of the global EIOA framework based scenario tool can be in this mature research area. To be able to answer this question an evaluation was made of current global climate change scenario models. The models were evaluated in terms of their description of the economic system, environmental system, the solution mechanism used to calculate the GHG emissions for a particular scenario and how accessible the models (results) are to external researchers. The evaluation shows the strength and weaknesses of the global EIOA framework based scenario tool and where the application of the framework might be useful. A weakness of all models evaluated is the reliance on extrapolation of past trends. Sometimes this extrapolation is obvious as for instance in IOA based scenario tool where it is assumed that observed general efficiency changes can be extrapolated into the future. Sometimes it is less obvious when observed elasticities are assumed to remain constant over time. Another weakness of all modelling approaches is the very limited or absence of process descriptions where climate change can affect the economy. With the current prospect that the 1.5 °C limit will be breached it might be expected that such repercussive effects become more pronounced. There are no global scenario models that can take these effect reasonably into account. A strength of the EIO based scenario tool is its consistent and comprehensive description of 129 economic

activities in a country. A weakness and a strength of the EIO based scenario model is its simple description of the economy. It is not possible to analyse effects of economic policy measure such as subsidies or taxation but the model is easy to understand and to couple to other models. The linearity of the EIO based scenario model cannot be seen as a drawback of these types of models compared to CGE models. The widely used CGE models are in practice also often linearized. The IAMs are currently the only models with a detailed description of processes happening in the environment such as land use changes and biodiversity impacts.

When developing a global EIOA framework based scenario tool, the question of which sector resolution and spatial resolution has to be used in the model is important. Therefore the effect of aggregation on calculated material footprints was investigated. The investigation showed that spatial aggregation is preferred above sector aggregation. The rationale is that the production recipes in different countries does not differ as strongly as production recipes in between sectors. Of course this statement depends on the countries or the sectors that are being aggregated. An example might be illustrative here. A coal power plant in the Netherlands will operate very similarly to a coal power plant in Germany or Belgium. Spatial aggregation will not lead to large aggregation errors. An aggregation of different types of electricity production e.g. gas, coal and nuclear power plants might introduce larger aggregation errors because the production recipes are quite different. But spatial aggregation of countries where technology is very different is not advisable either. In the global EIOA framework based scenario tool spatial aggregation was carried out, but sectoral and product detail was maintained. Spatial aggregation was done on the basis of economic development status. As such the structural scenario model balanced the theoretical best approach and practicalities in the best way possible.

In a first case study, the scenario tool was used to investigate if the introduction of feasible renewable energy technologies can reduce GHG emissions in 2050 to a level in line with the 2 °C limit against a backdrop of population and economic growth. Three different scenarios were developed. From a business-as-usual (BAU) scenario to a scenario which complies to the 2 °C limit. The BAU scenario was in close agreement with other BAU scenarios that have been created with integrate assessment models and brings us on RCP8.5 which means that the

global temperature will rise by about 5-6 °C in 2100. The other two scenarios developed indicate that only with a reduced economic growth the 2 °C limit can be met.

A second case study carried out with the developed scenario model looked at the possibilities or impossibilities of supplying resources for the low carbon technologies until 2050. Possible resource bottlenecks for eleven different metals were investigated ranging from bulk metals such as iron and aluminium mostly used in general infrastructure to specific low carbon technology metals such as lithium and neodymium. While most studies try to forecast or even predict supply and demand of metals until 2050, our methodology started from the notion that development of supply and demand cannot be predicted but that it is better to determine a viable operating space where it is likely that supply and demand can be matched. It is also important to look at global demand. It might be that the implementation of renewable energy technologies leads to a tenfold increase of that metal in that specific application. However there is already a large application of the metal in other applications that is not expected to grow so much, the overall expected increase of that metal is not so dramatic.

In this case study, again the same low carbon scenarios were investigated plus two other scenarios that investigated the possibilities of equipping every electric car with neodymium magnets or having an electricity production mix with a higher use of renewable energy technologies. The result of this case study shows that the overall annual supply increase needed to satisfy future metal demands in low-carbon scenarios is not extreme and in line with or even lower than supply increases observed in the past. However demand-supply imbalances and price hikes may still occur, particularly if there is a faster transition to low-carbon technologies and electric vehicles than assumed in our scenarios. There is another reason why the result is not just a positive message. Extracting metals from ore bodies with lower metal concentrations means that more energy, water, and auxiliary materials are needed to extract the metal, with possibly higher environmental impacts.

To be able to further develop the EIO based scenario model first an important weakness of this model approach must be tackled. It has not been validated. Recently a time series of global multi-regional supply-use tables have become available that can be used for that.

Furthermore a side-by-side comparison of the global scenario models using the same scenario starting points should be carried out to fully inform us about the behaviour of the models.

Coupling the EIO based scenario model with environmental process models might be a promising direction of research because a full integration might give us the possibilities to analyse scenarios where repercussion from climate change on the economy might be taken into account.

When the EIO based scenario model is indeed going to be used to investigate possible repercussions of climate change on the economy, the sectoral and spatial differentiation question has to be revisited again and likely spatial disaggregation has to be increased. If the introduction of renewable energy technologies and associated resource use are to be analysed in more detail, the EIOA framework the description of waste and recycling flows and stocks should be improved. This likely call for further improvement of the creation of hybrid unit or physical input-output tables. Special attention has to be given to the occurrence of interlinkages between degrading resources, food and feed production, energy use, water use and environmental impacts. In an ever tightening safe operating space, it must be prevented that one of such an interlinkage spirals out of the safe operating space.

Samenvatting

Een van de belangrijke bijdragen van de milieuwetenschappen aan beleidsvorming is het analyseren van de invloed van toekomstige economische ontwikkelingen op het natuurlijk milieu. De invloed van ons huidig economisch handelen op het natuurlijk milieu is groter dan ooit tevoren. Als gevolg hiervan verandert het natuurlijk milieu en bedreigt zelfs de natuurlijke basis van onze economie. Klimaatverandering is één van de mondiale milieuproblemen waarbij negatieve effecten op onze economie reeds zichtbaar zijn. De gemiddelde temperatuurstijging moet ruim onder de 2 °C blijven, bij voorkeur zelfs onder de 1.5 °C om verdere negatieve effecten van klimaatverandering beperkt te houden. De 2 °C limiet en zeker de 1.5 °C doelstelling vereisen dat broeikasgasemissies sterk gereduceerd moeten zijn in 2050. Hoe deze emissiereductie moet plaatsvinden is onduidelijk. In ieder geval moet het gebruik van fossiele brandstoffen verminderen.

Hoe groot de bijdrage van hernieuwbare energiebronnen ter vervanging van fossiele energiebronnen kan zijn bij het verminderen van broeikasgasemissies tot 2050 is belangrijke informatie. Een bijdrage die bewerkstelligd moet worden terwijl de wereldbevolking en economie groeit. Daarom onderzoeken we in dit proefschrift de effecten van de introductie van hernieuwbare energiebronnen op de uitstoot van broeikasgassen en het gebruik van materialen nodig voor de hernieuwbare energietechnologieën tot 2050.

Het belangrijkste gekoppelde economie-milieumodel gebruikt in dit onderzoek is gebaseerd op economische aanbod- en gebruiktabellen verrijkt met gegevens over milieu interventies. Dit gekoppelde milieu-economie model is in principe statisch. Het wordt veelal gebruikt voor de analyse van economische relaties tussen sectoren en de economische effecten van een marginale verandering in de finale vraag naar producten. Dit model type wordt niet vaak gebruikt voor lange termijn scenario studies zoals vereist binnen dit onderzoek.

De eerste onderzoeksvraag die beantwoord dient te worden is de vraag hoe de in principe statische aanbod- en gebruiktabellen ingezet kunnen worden voor kwantitatieve mondiale scenariomodellen die ingezet kunnen worden voor de analyse van milieu interventies.

Eenvoudige regressie modellen, macro-economische modellen en geïntegreerde beoordelingsmodellen worden gebruikt als scenariomodel in de klimaatwetenschap. Het mondiale scenariomodel ontwikkeld in dit onderzoek is anders van opzet. Een tweede onderzoeksvraag die beantwoord dient te worden is de vraag hoe het model gebaseerd op aanbod- en gebruiktabellen zich verhoudt tot de andere meer gangbare typen mondiale scenariomodellen. Specifiek willen we onderzoeken wat de zwakke en sterke punten zijn van de verschillende modelbenaderingen.

Het aantal landen en sectoren onderscheiden in het scenariomodel gebaseerd op aanbod- en gebruiktabellen bepaald hoe specifiek technologische ontwikkelingen in bepaalde regio's gemodelleerd kan worden. Daarom is onderzocht hoeveel landen en sectoren onderscheiden moeten worden om de hernieuwbare energietechnologie scenario's goed te kunnen modelleren.

Na het maken van het scenariomodel is het model gebruikt voor het beantwoorden van twee praktische vragen 1) Resulteert de voorziene introductie van hernieuwbare energie technologieën tot aan 2050 in een broeikasgasemissiereductie die overeenkomt met de 2 C limiet? 2) Wordt de introductie van hernieuwbare energietechnologieën tot aan 2050 mogelijksterwijs gehinderd door een beperkte beschikbaarheid van primaire metalen?

De ervaringen met het gebruik van het mondiale scenariomodel gebaseerd op aanbods- en gebruiktabellen en de vergelijking van het model met andere typen scenariomodellen leidt tot aanbevelingen om zwakke punten te verbeteren.

Het lange termijn mondiale scenariomodel is gebaseerd op mondiale multiregionale aanbod- en gebruiktabellen voor het jaar 2000. In deze tabellen worden 129 producten en sectoren onderscheiden. Het jaar 2000 is het basis jaar van waaruit de scenario's worden opgebouwd.

Implementatie van scenario's voor het jaar 2050 vindt in verschillende opeenvolgende stappen plaats:

- 1) De aanbod- en gebruiktabellen worden gezien als de ingrediënten nodig voor het maken van een product.
- 2) De hoeveelheid geproduceerde producten moet groeien om aan de behoefte van de groeiende wereldbevolking te voldoen.
- 3) Terwijl de productie efficiëntie stijgt vooral in de zich sterk ontwikkelende landen.
- 4) De mechanismen gemodelleerd in 2 en 3 leiden tot economische groei.
- 5) Naast de groeiende productie en de stijgende productie efficiëntie wordt de hoeveelheid geproduceerde producten in sectoren verhoogd of verlaagd naar gelang de implementatie van koolstofarme energietechnologieën.
- 6) Gebruik van brandstoffen en gerelateerde CO₂ emissies zijn direct evenredig met de omvang van energiegebruik zoals beïnvloed door omvang van productie, efficiëntieverbetering en de specifieke implementatie van koolstofarme energietechnologieën.
- 7) CO₂ emissies kunnen nog verder verlaagd worden door de inzet van CO₂ afvang uit afvalgassen en opslag.
- 8) De resulterende gebalanceerde aanbod- en gebruiktabellen welke de hypothetische mondiale economie en zijn broeikasgasemissies beschrijven in 2050 worden vervolgens getransformeerd naar input-output tabellen voor verdere analyse.

Met bovenstaande procedure kunnen verschillende mondiale scenario's worden gemaakt waarin het effect de inzet van koolstofarme energietechnologieën in 2050 kunnen worden onderzocht.

Het ontwikkelde mondiale scenariomodel is gebruikt om het effect van emissiereductietechnologieën te onderzoeken. In klimaatscenario onderzoek wordt voor hetzelfde doel veelal gebruik gemaakt van algemene evenwichtsmodellen (CGE), macro-econometrische modellen of geïntegreerde beoordelingsmodellen (IAM). Deze modellen kennen een lange ontwikkelingsgeschiedenis en het is daarom noodzakelijk ons af te vragen wat een ander type scenariomodel nog kan bijdragen aan dit gevestigde wetenschapsgebied. Om deze vraag te beantwoorden zijn de verschillende modeltypen gebruikt in klimaatscenario studies geëvalueerd. De modellen zijn beoordeeld op beschrijving van economisch systeem,

milieusysteem, de manier waarop het model wordt doorerekend en de beschikbaarheid van het model. Deze evaluatie laat zien wat de zwakke en sterke punten zijn van het ontwikkelde scenariomodel en voor welke toepassing het model het meest geschikt is. De evaluatie van de modellen laat zien dat alle modeltypen vertrouwen op extrapolaties van historische trends. Deze extrapolatie is overduidelijk in het geval van het IOA gebaseerde scenariomodel waarin wordt aangenomen dat historische efficiëntieverbeteringen zich ook voordoen in de toekomst. Soms zijn deze extrapolaties minder zichtbaar. Zo wordt bijvoorbeeld aangenomen dat inkomenselasticiteit van de vraag naar goederen gelijk blijft. Een ander zwak punt van alle modeltypen is het ontbreken of zeer beperkt aanwezig zijn van een mechanistische beschrijving van de effecten van klimaatverandering op de economie. Met het huidige vooruitzicht dat de veilig geachte 1.5 °C grens wordt overschreden, mag verwacht worden dat een negatieve terugkoppeling van klimaatverandering op de economie meer zichtbaar wordt. Er zijn geen scenariomodellen die deze effecten redelijkerwijs modelleren. Een voordeel van het EIOA gebaseerde scenariomodel is de consistente en complete beschrijving van 129 verschillende economische activiteiten in een land. Een sterkte en tegelijkertijd een zwakte is de zeer eenvoudige beschrijving van het gedrag van de economie. Het is niet mogelijk om effecten te analyseren zoals subsidies of belastingen. Daarentegen is het gedrag van het model eenvoudig te verklaren en te koppelen met andere modellen. Het lineaire karakter van de EIO gebaseerde scenariomodellen kan niet als een zwak punt gezien worden ten opzichte van de CGE modellen. De algemene evenwichtsmodellen worden in de praktijk ook vaak lineair opgelost. De IAMs zijn op het ogenblik het enige modeltype die een gedetailleerde beschrijving geven van de mechanismen in het milieu zoals landgebruik verandering en effecten op biodiversiteit.

Sectorale en regionale differentie is belangrijk wanneer een mondiaal scenariomodel wordt ontwikkeld. Daarom is het effect van sectorale en ruimtelijke aggregatie op de berekende materiaal voetafdruk onderzocht. De resultaten laten zien dat ruimtelijke aggregatie te prefereren is boven sectorale aggregatie. De verklaring hiervoor is dat de ingrediënten nodig voor het maken van een product meer verschillen tussen sectoren dan tussen landen. Dit resultaat is wel afhankelijk van de regio's of sectoren die worden geaggregeerd. Een voorbeeld kan verhelderend zijn. Een kolengestookte elektriciteitscentrale in Nederland komt sterk overeen met eenzelfde centrale in Duitsland of België. Ruimtelijke aggregatie zal in dit

geval niet leiden tot aggregatie fouten. Een sectorale aggregatie van gasgestookte, kolengestookte en kerncentrales zou juist wel aanleiding geven tot aggregatie fouten omdat de ingrediënten voor het maken van elektriciteit in de verschillende sectoren sterk verschillen. Aggregatie van regio's waarin de technologie sterk verschillend is, is ook niet aan te raden. In het ontwikkelde scenariomodel is de maximaal mogelijke sector resolutie bewaard. Ruimtelijke samenvoeging heeft plaatsgevonden op basis van economische ontwikkelingsstatus. Op deze manier balanceerde het mondiale scenariomodel de theoretisch beste benadering en de praktische mogelijkheden op de beste manier.

In een eerste praktische toepassing van het scenariomodel is onderzocht in hoeverre een redelijkerwijs te verwachten inzet van hernieuwbare energietechnologie kan leiden tot het terugdringen van broeikasgasemissies in 2050 overeenkomend met de 2 °C doelstelling. Een emissiereductie die behaald dient te worden terwijl de wereldbevolking en economie blijven groeien. Drie verschillende scenario's zijn ontwikkeld; van een scenario zonder enig additioneel klimaatbeleid ("business as usual") tot een scenario waarin de 2 °C doelstelling wordt gehaald. Het business-as-usual (BAU) scenario komt sterk overeen met BAU scenario's ontwikkeld met behulp van geïntegreerde beoordelingsmodellen. In dit scenario komen de emissies overeen met RCP8.5 wat betekent dat de mondiale temperatuurstijging ongeveer 5-6 °C zal zijn in 2100. De twee andere scenario's duiden erop dat alleen met een minder sterke economische groei de 2 °C doelstelling behaald kan worden.

In een tweede praktische toepassing van het scenariomodel is onderzocht of de redelijkerwijs te verwachten inzet van hernieuwbare energietechnologie gelimiteerd kan worden door een tekort aan primaire metalen tot aan 2050. Mogelijke limieten zijn onderzocht voor elf verschillende metalen, variërend van ijzer en aluminium dat veel wordt toegepast in de bouw en infrastructuur tot aan metalen die veel worden toegepast in hernieuwbare energietechnologieën zoals lithium en neodymium. Veel voorgaande studies probeerden mogelijk toekomstige tekorten te bepalen of zelfs te voorspellen door toekomstige vraag en aanbod te modelleren. Centraal in mijn studie staat juist de onmogelijkheid van het voorspellen van de ontwikkeling van vraag en aanbod. In plaats daarvan wordt een ruimte gedefinieerd waarin het waarschijnlijk is dat het aanbod kan voldoen aan de vraag. Daarnaast is het belangrijk om te kijken naar de mondiale vraag vanuit elke sector en niet alleen naar de

vraag vanuit de te installeren hernieuwbare energietechnologieën. Het kan zo zijn dat de vraag vanuit een specifieke energie technologie door een grotere inzet van deze technologie tienmaal groter wordt. Als deze technologie uiteindelijk maar een klein aandeel heeft in de totale vraag zal de toename naar dit metaal niet zo dramatisch zijn.

In deze toepassing van het scenariomodel worden dezelfde scenario's gehanteerd als bij het onderzoek naar de inzet van hernieuwbare energie technologieën plus twee andere scenario's. De additionele scenario's zijn een elektrisch autopark dat volledig overgaat op het gebruik van neodymium magneten en een scenario waarbij zon en wind een veel groter aandeel hebben in de elektriciteitsopwekking.

De resultaten van deze scenariostudies laten zien dat het jaarlijks aanbod van metalen toereikend is om aan de jaarlijks toenemende vraag als gevolg van de introductie van hernieuwbare energie technologieën te voldoen. De stijgende vraag is zelfs overeenkomstig of lager dan stijgingen die zich in het recente verleden hebben voorgedaan. Niettemin kan er nog steeds spanning ontstaan tussen vraag en aanbod waardoor prijzen sterk kunnen stijgen, zeker indien er wordt gekozen voor een snellere introductie van koolstofarme energie technologieën en elektrische auto's dan aangenomen in de doorberekende scenario's. Er is een andere reden waarom de uitkomsten van deze studie niet alleen positief is. De winning van metalen uit ertsen met lagere metaalconcentraties betekent dat er meer energie, water en andere hulpmaterialen nodig zijn om het metaal te ontsluiten, mogelijkserwijs met hogere milieu interventies tot gevolg.

Validatie van het scenariomodel is een eerste vereiste voor verdere ontwikkeling. Recentelijk zijn tijdreeksen van aanbod- en gebruiktabellen beschikbaar gekomen die hiervoor gebruikt kunnen worden. Ten tweede zou een gedetailleerde vergelijking gemaakt moeten worden met andere mondiale scenariomodellen uitgaande van dezelfde uitgangspunten zodat er een goed beeld ontstaat van het gedrag van de modellen.

Het koppelen van het scenariomodel met een milieuprocesmodel zou een verdere interessante ontwikkelingsrichting kunnen zijn. Een volledige integratie zou de mogelijkheid kunnen

bieden om scenario's te analyseren waarbij de terugkoppeling van klimaatverandering op de economie in rekening genomen kan worden.

Indien het scenariomodel inderdaad gebruikt gaat worden om de mogelijk negatieve terugkoppeling van klimaatverandering op de economie te onderzoeken, moet de ruimtelijke en economische resolutie van het model opnieuw bepaald worden. Waarschijnlijk zullen meer regio's onderscheiden moeten worden omdat effecten van klimaatverandering zeer afhankelijk kunnen zijn van locatie. Een meer gedetailleerde analyse van het gebruik van materialen voor energietechnologieën betekent dat afval en recycling stromen en de voorraad materialen in gebouwen en infrastructuur beter moeten worden beschreven. Dit betekent dat het maken van hybride eenheid of fysieke aanbod- en gebruiktabellen verbeterd zou moeten worden.

Bij het maken van klimaatscenario's zou er speciaal aandacht besteed moeten worden aan de combinaties van afnemende kwaliteit van ertsen, voedsel en diervoeder productie, energie en water verbruik en samenhangende milieudruk. In een afnemende milieugebruiksruimte moet voorkomen worden dat deze combinaties leiden tot onbeheersbare milieuschade.

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Curriculum Vitae

Arjan de Koning received his pre-university (VWO) diploma from the Interconfessioneel Westland College in Naaldwijk in 1989. In 1996 he graduated cum laude in environmental hygienics from Wageningen Agricultural University. From 1996 to 2000 he worked as a researcher at the Energy Research Centre of the Netherlands (ECN). Topic of his research was the measurement and modelling of the interaction of trace amounts of radiocaesium (^{137}Cs) with soils and sediments. Since 2000 he is employed as a researcher at the Institute of Environmental Sciences at Leiden University, department of Industrial Ecology. His research ranges from environmental chemistry and life cycle impact assessment to input-output analysis.

His interests are focussed on providing data, methods and tools for environmental analysis. Next to his research he contributes to minor and master courses on topics such as multimedia modelling, historical industrial transformations, programming, life cycle analysis and input-output analysis.

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