Creating global scenarios of environmental impacts with structural economic models

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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 CO_2 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 CO_2 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) CO_2 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 nonhomothetic[1] 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 additional[1] GHG emission reduction measures were undertaken. In this scenario, the simple scenario model estimated an emission of 75 Gt CO_2/yr. in 2050. The IPCC BAU scenarios, as condensed in the representative concentration pathway RCP8.5, gives an emission of 73 Gt CO_2/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 CO_2/yr. in 2050. The estimated emissions are in this case comparable to RCP4.5 which assumes about 41 Gt CO_2/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 CO_2/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), estimated[1] CO_2 emissions from 2000 to 2014 (CDIAC, 2017) and results from the scenario model (See Chapter 4) are show in Figure 6.1. Notice that only CO_2 emissions from fossil fuels and industry are given. CO_2 emissions from land-use change are not included and CH_4 and N_2O are also not considered.

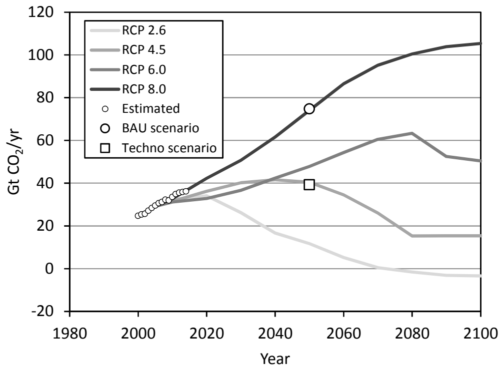

Figure 6.1: Representative concentration pathways (RCP) (Van Vuuren et al., 2011), estimated CO_2 emissions (CDIAC, 2017) and global CO_2 emissions from the BAU and Techno scenario.

As discussed in Chapter 4 and shown in Figure 6.1 there is a difference of about 28 Gt CO_2/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 CO_2 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 CO_2 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 ± 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 annually in 2050. In the Techno Scenario, 2.4 Gt CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 technology[1] 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 scale[1]. However the implementation of the technology, despite its acute importance[2], 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.

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