Fraunhofer ISI

FRAUNHOFER-INSTITUT FÜR SYSTEM- UND INNOVATIONSFORSCHUNG

Matthias Pfaff

Material flows in the industrial system

Model-based analysis of material consumption in Germany and the effects of efficiency measures

FRAUNHOFER VERLAG

Fraunhofer-Institut für
System- und Innovationsforschung ISI

Matthias Pfaff

Material Flows in the Industrial System

Model-based Analysis of Material Consumption in Germany and the Effects of Efficiency Measures

FRAUNHOFER VERLAG

Kontaktadresse:
Fraunhofer-Institut für System- und Innovationsforschung ISI
Breslauer Straße 48
76139 Karlsruhe
Telefon 0721 6809-0
Telefax 0721 6809-152
E-Mail info@isi.fraunhofer.de
URL www.isi.fraunhofer.de

Zugl.: Karslruhe, KIT, Diss., 2019

D 90

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.
ISSN: 1612-7455
ISBN: 978-3-8396-1588-1

Titelbild: © Autor

Druck: Mediendienstleistungen des
Fraunhofer-Informationszentrum Raum und Bau IRB, Stuttgart

Für den Druck des Buches wurde chlor- und säurefreies Papier verwendet.

© by **FRAUNHOFER VERLAG,** 2020
Fraunhofer-Informationszentrum Raum und Bau IRB
Postfach 800469, 70504 Stuttgart
Nobelstraße 12, 70569 Stuttgart
Telefon 0711 970-2500
Telefax 0711 970-2508
E-Mail verlag@fraunhofer.de
URL http://verlag.fraunhofer.de

Alle Rechte vorbehalten

Dieses Werk ist einschließlich aller seiner Teile urheberrechtlich geschützt. Jede Verwertung, die über die engen Grenzen des Urheberrechtsgesetzes hinausgeht, ist ohne schriftliche Zustimmung des Verlages unzulässig und strafbar. Dies gilt insbesondere für Vervielfältigungen, Übersetzungen, Mikroverfilmungen sowie die Speicherung in elektronischen Systemen.
Die Wiedergabe von Warenbezeichnungen und Handelsnamen in diesem Buch berechtigt nicht zu der Annahme, dass solche Bezeichnungen im Sinne der Warenzeichen- und Markenschutz-Gesetzgebung als frei zu betrachten wären und deshalb von jedermann benutzt werden dürften.
Soweit in diesem Werk direkt oder indirekt auf Gesetze, Vorschriften oder Richtlinien (z.B. DIN, VDI) Bezug genommen oder aus ihnen zitiert worden ist, kann der Verlag keine Gewähr für Richtigkeit, Vollständigkeit oder Aktualität übernehmen.

Material flows in the industrial system: Model-based analysis of material consumption in Germany and the effects of efficiency measures

Zur Erlangung des akademischen Grades eines
Doktors der Wirtschaftswissenschaften (Dr. rer. pol.)
von der Fakultät für Wirtschaftswissenschaften
des Karlsruher Instituts für Technologie (KIT)

genehmigte

DISSERTATION

von

Matthias Peter Johannes Pfaff, M.A.

Tag der mündlichen Prüfung:	30.10.2019
Referent:	Prof. Dr. Rainer Walz
Korreferent:	Prof. Dr. Frank Schultmann

Für meine Mutter

Danksagung

Die vorliegende Arbeit entstand im Rahmen meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Fraunhofer-Institut für System- und Innovationsforschung ISI in Karlsruhe. Eine Reihe von Menschen haben mich in dieser Zeit begleitet und auf unterschiedliche Weise unterstützt, wofür ich mich hiermit bedanken will.

Besonderer Dank gilt meinem Doktorvater, Prof. Dr. Rainer Walz, der auch die Abteilung Nachhaltigkeit und Infrastruktursysteme am Fraunhofer ISI leitet. Ohne seine inhaltlichen Impulse und das Schaffen von Freiräumen wäre die Arbeit in dieser Form nicht zu verwirklichen gewesen. Ich danke auch herzlich Dr. Katrin Ostertag, die mich als Geschäftsfeldleiterin vor übermäßiger Projektlast schützte und stets Verständnis zeigte, wenn die Dissertation viel Zeit und Ressourcen in Anspruch nahm.

Ebenso möchte ich mich bei den Mitgliedern der Prüfungskommission, Prof. Dr. Steffen Rebennack, Prof. Dr. Ingrid Ott und insbesondere bei Prof. Dr. Frank Schultmann für die Übernahme des Korreferats bedanken.

Ich danke meinen Kolleginnen und Kollegen am Fraunhofer ISI, deren Unterstützung von langen inhaltlichen Diskussionen bis zu notwendigen Erinnerungen an Kaffeepausen reicht. Insbesondere möchte ich Luisa Sievers, Johannes Hartwig, Simon Glöser-Chahoud und Marcel Soulier für den engen inhaltlichen Austausch und ihre stetige Hilfsbereitschaft danken. Nicht zuletzt habe ich von der Unterstützung studentischer Mitarbeiterinnen und Mitarbeiter profitiert. Mein Dank gilt daher auch Lothar Chrubasik, Lena Höhne, Paul Heinzmann und Eva Wendeberg.

Vor allem danke ich aber meiner Familie und meinen Freunden, die immer für mich da waren und mich bekräftigten, meine Ziele zu verfolgen.

Karlsruhe, im Dezember 2019

Abstract

Over the past century, global material use has increased by a factor of eight and is now mainly fueled by non-renewable sources. If current trends continue, 180 billion tons of raw materials will be extracted from the environment every year by 2050. This extraction is accompanied by a number of environmental and social issues, including the declining availability of raw materials for future generations.

In order to address these issues, it is necessary to know which activities in society are the main drivers of material use and what steps could be taken towards a dematerialization of the economy. At the same time, raw materials are essential inputs for the world's economies and likely continue to be in the foreseeable future. Any reduction of material use must therefore be assessed with respect to its impact on the overall economy and its workforce.

In this thesis, a retrospective multi-regional input-output analysis first determines the entirety of raw material needed to satisfy Germany's consumption and investment needs, as well as the underlying drivers of this material demand over time. Building upon this, a macroeconomic simulation model with detailed environmental extensions is developed in order to estimate the potential consequences of material efficiency measures in the future, both from a physical and an economic perspective. Two prospective simulations are performed. The first assesses the impacts of a set of broad material efficiency technologies on Germany's overall material demand as well as on its economy. The second simulation, for which the model is additionally coupled with a substance flow model, illustrates stock and flow dynamics resulting from different efficiency measures in different parts of the German copper cycle.

The retrospective analysis shows that Germany's material demand has remained relatively stable since the turn of the millennium, though some observations indicate that it may start to rise in the future. The first prospective simulation indicates that overall material demand reductions are possible without creating a large macroeconomic burden. However, certain adjustment pressures may emerge for some sectors. In addition, resulting macroeconomic developments may cause re-increases in material demand. The second simulation reveals the importance of considering material stocks alongside material flows and shows that while some measures have a considerable potential to decrease the demand for primary material, they sometimes entail trade-offs. This precludes simple conclusions on their viability. In sum, this thesis contributes to a better understanding of the drivers of present and future raw material consumption and potential means of reducing it.

Kurzfassung

Im letzten Jahrhundert hat der globale Materialverbrauch um den Faktor acht zugenommen und speist sich heute hauptsächlich aus nicht-erneuerbaren Quellen. Bei anhaltenden aktuellen Trends werden bis 2050 jährlich 180 Milliarden Tonnen Rohstoffe gefördert. Diese Förderung birgt ökologische und soziale Probleme, unter anderem die reduzierte Verfügbarkeit dieser Rohstoffe für zukünftige Generationen.

Um diesen Problemen zu begegnen, müssen die gesellschaftlichen Treiber für die Rohstoffnachfrage und mögliche Schritte zur Dematerialisierung identifiziert werden. Gleichzeitig sind Rohstoffe essenzielle Inputs der Weltwirtschaft und werden dies auf absehbare Zeit bleiben. Reduktionen in der Rohstoffnachfrage müssen daher auch hinsichtlich ihrer Wirkungen auf die Wirtschaft und der damit verbundenen Beschäftigung untersucht werden.

In dieser Dissertation wird eine retrospektive multiregionale Input-Output-Analyse durchgeführt, um die gesamte Rohstoffbasis der deutschen Endnachfrage zu ermitteln. Darauf aufbauend wird ein makroökonomisches Simulationsmodell mit detaillierten Umwelterweiterungen entwickelt, um die Auswirkungen zukünftiger Materialeffizienzmaßnahmen aus physischer und ökonomischer Perspektive abzuschätzen. Zwei prospektive Simulationen werden damit durchgeführt. Die erste analysiert die Wirkungen eines breit definierten Sets von Effizienztechnologien auf Deutschlands Gesamtmaterialverbrauch und auf die deutsche Wirtschaft. Die zweite Simulation, für die das Modell zudem mit einem Stoffflussmodell gekoppelt wird, stellt die Dynamik zwischen Bestands- und Flussgrößen dar, die sich aus Effizienzmaßnahmen in unterschiedlichen Bereichen des deutschen Kupferkreislaufs ergibt.

Die retrospektive Analyse zeigt, dass der deutsche Materialverbrauch seit dem Jahrtausendwechsel relativ stabil war, wohingegen Hinweise auf eine mögliche zukünftige Steigerung gefunden werden. Die erste prospektive Simulation zeigt, dass Rohstoffnachfragereduktionen möglich sind, ohne größere makroökonomische Zerwürfnisse zu erzeugen. Es entstehen jedoch Anpassungsbedarfe für manche Wirtschaftsbereiche. Zudem könnten resultierende makroökonomische Entwicklungen zu Zunahmen der Rohstoffnachfrage führen. Die zweite Simulation zeigt die Wichtigkeit auf, Materialbestände neben Materialflüssen zu betrachten. Während manche Maßnahmen ein beträchtliches Potenzial zur Reduktion der Rohstoffnachfrage aufweisen, beinhalten sie teilweise Zielkonflikte, die einfache Schlussfolgerungen bezüglich ihrer Realisierbarkeit ausschließen. Die vorliegende Dissertation leistet somit einen Beitrag zu einem besseren Verständnis der Treiber des heutigen und zukünftigen Rohstoffverbrauchs und möglicher Maßnahmen, diesen zu reduzieren.

Contents

List of Figures

List of Tables

List of Abbreviations

CGE	Computable General Equilibrium
CN	Combined Nomenclature
CPA	Statistical Classification of Products by Activity
CPC	Central Product Classification
DMC	Domestic Material Consumption
DMI	Direct Material Input
DTA	Domestic Technology Assumption
EEIO	Environmentally Extended Input-Output
EoL	End-of-Life
EW-MFA	Economy-wide Material Flow Analysis
FTE	Full-Time Equivalent
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GVA	Gross Value Added
HS	Harmonized Commodity Description and Coding System
IA	Impact Assessment
IAM	Integrated Assessment Model
ICA	International Copper Association
IDA	Index Decomposition Analysis
ISI	Institute for Systems and Innovation Research
ISIC	International Standard Industrial Classification of All Economic Activities

IO	Input-Output
KRA	Kumulierter Rohstoffaufwand
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MFA	Material Flow Analysis
MRIO	Multi-Regional Input-Output
NACE	Statistical classification of economic activities in the European Community
OECD	Organisation for Economic Co-operation and Development
O&M	Operation and Maintenance
PGM	Platinum Group Metal
PIOT	Physical Input-Output Tables
PRODCOM	Production Communautaire
PSS	Product Service Systems
R&D	Research and Development
RMC	Raw Material Consumption
RME	Raw Material Equivalents
RMI	Raw Material Input
SD	System Dynamics
SDA	Structural Decomposition Analysis
SDG	Sustainable Development Goal
SEEA	System of Environmental-Economic Accounting
SERI	Sustainable Europe Research Institute
SFA	Substance Flow Analysis
SNA	System of National Accounts
TFP	Total Factor Productivity

TMC	Total Material Consumption
TMR	Total Material Requirement
EKC	Environmental Kuznets Curve
IRP	International Resource Panel
WIOD	World Input-Output Database

1 Introduction

1.1 Background

The global natural system is subject to unprecedented changes caused by human activity. Over the past three centuries, the world's population has increased tenfold and continuously expanded its impact on the planet's ecosystems (Crutzen and Stoermer, 2000). This includes an ever accelerating spread of human settlements, extraction of non-renewable resources and harmful emissions into the environment. Among the greatest challenges today resulting from human activity is anthropogenic climate change, which is caused by the emission of Greenhouse Gases (GHGs) from various sources, including the combustion of fossil fuels, agriculture and land-use change. Other changes, such as the growth in raw material extraction and the associated environmental impacts, are similarly profound. These developments have led to the proposition to name the current geological epoch after the human species, nameley the "Anthropocene" (Crutzen and Stoermer, 2000). Today multiple starting points for the Anthropocene are suggested, but the original article by Crutzen and Stoermer (2000) proposes the late 18th Century as this marks the beginning of industrialization, which first enabled a noticeable global impact of human activities. While the industrial era gave rise to the technological means of humanity's growing impact on the planet, the pace of this impact was initially rather slow. This changed with the "Great Acceleration" (Hibbard et al., 2006) starting in the middle of the 20th Century after the Second World War, which is characterized by exponential increases in virtually all indicators of anthropogenic expansion and reach into the world's ecosystems (Steffen et al., 2005, 2007, 2015).

The development of raw material use is one manifestation of this long term trend. Over the past century, global material use has increased by a factor of eight. While there has been a slowdown of the growth rate in developed countries, it still increased by a factor of almost four since the middle of the 20th Century (Schaffartzik et al., 2014a). This development is accompanied by a shifting away from the agelong dominance of renewable biomass as the primary material input of human activity to non-renewable materials comprising of minerals, metal ores and fossil fuels, which together make up the majority of global material use today (Krausmann et al., 2009; Schaffartzik et al., 2014b, 2016). Current global material extraction amounts to over 70 billion tons per year (Giljum et al., 2014; Schandl et al., 2017) and may reach 180 billion tons in 2050 (Hatfield-Dodds et al., 2017). Industrialized countries, such as Germany, still play a major role in global material use. When taking used and unused (e.g. excavation material) extraction into account, Germany's domestic consumption of goods and services currently induces about 6% of global material extraction, which is slightly more than the 5% share of Germany's Gross Domestic Product (GDP) in the world total (United Nations, 2017).

Raw material extraction is often accompanied by environmental issues, including land-use changes, local emissions of toxic substances and global GHG emissions (Ayres, 1997; Giegrich et al., 2012; Norgate and Haque, 2010; Nuss and Eckelman, 2014). These environmental issues are reinforced by decreasing ore grades, which result in increased specific energy demands and environmental pressures (Calvo et al., 2016; Frenzel et al., 2017; van der Voet et al., 2018). In addition, many extraction activities create social problems, such as the exploitation of the local workforce, or the financing of political conflicts (Gandenberger et al., 2012; Manhart, 2007). The continued extraction of finite resources also raises issues of intergenerational equity, as these resources may not be available anymore to future generations.

In light of these problems, a number of countries and supranational organizations, including Germany and the European Union, have developed strategies to reduce raw material use, mostly in the form of material efficiency programs (Bundesregierung, 2016; BMUB, 2016; BMWi, 2010; European Commission, 2011, 2015; EEA, 2016). In order to put these strategies into practice, it is necessary to know which activities in society are the main drivers of material use. Since material use is not purely a physical phenomenon but inextricably linked to social, or in a narrower sense, economic activity, such an understanding must be developed in relation to the wider socio-economic system.

Notwithstanding the issues associated with material extraction, raw materials are essential inputs for the world's economies and likely continue to be in the foreseeable future (cf. Graedel et al., 2013). In fact, the material efficiency strategies mentioned above largely advocate the reduction of material use while not hampering economic growth. This is also reflected in the UN's Sustainable Development Goals (SDGs), which, among other things, promote economic growth alongside sustainable consumption and production (United Nations, 2015). Any reduction of material use must therefore be assessed with respect to its impact on the overall economy. It is thus important to be able to analyze the macroeconomic consequences of material efficiency measures.

Material efficiency is usually targeted at the reduction of the use of primary material since the extraction and refinement stages of raw material provision are associated with the largest environmental and social impacts (Nuss and Eckelman, 2014; Rankin, 2012). The amount of primary material extracted not only depends on overall demand, but also on the availability of secondary material as a substitute. The availability of secondary material is in turn determined by the amount of material contained in anthropogenic stocks that is no longer needed in its respective function and can therefore be recycled. In order to be able to understand the distribution of primary and secondary material in total material provision, it is therefore necessary to account for the buildup and eventual scrapping of material stocks.

1.2 Problem definition and objective

Next to other industrialized countries, Germany plays a considerable role in global material use. The first objective of this thesis is therefore a survey of Germany's material use over time and its structural determinants. Germany's direct and indirect material use in the time frame from 2000 to 2010 is documented in the environmental-economic accounts (Umweltökonomische Gesamtrechnung – UGR) of the German Statistical Office (Destatis, 2011, 2018). Recently, the German Environment Agency also published an extensive report on raw material use in Germany from 1994 to 2013 (Lutter et al., 2016b) and is currently preparing an update. Several other sources have compiled material flow accounts for Germany for different years, mostly in the context of commissioned studies (cf. Dittrich et al., 2013; Giegrich et al., 2012; Lansche et al., 2007; Schütz and Bringezu, 2008). The methodological approaches used to compile these material flow accounts appear to be similar across all of these studies, though they are only sufficiently explained in a number of cases. In addition, different data bases are used, of which only some are publicly available (Buyny et al., 2009; Kaumanns and Lauber, 2016). Furthermore, these studies do not identify the structural determinants of Germany's material use over time. However, in order to develop strategies to reduce material use, it is essential to know its drivers. The academic literature on economy-wide material flows generally relies more on publicly available data and uses standardized methodologies, which fosters reproducibility. However, most studies are conducted on the global or regional (e.g. EU) level without an explicit focus on Germany. Therefore, to the best of the author's knowledge, no detailed analyses exist of the structural determinants of aggregate material use in Germany over time. This gap is addressed by the first research question:

1. What is the temporal pattern of aggregate material use in Germany and which factors have contributed to this development?

Measures to reduce material use have to be compatible with economic well-being. Therefore, it is essential to be able to assess the potential effects of material efficiency measures on the overall economy. In order to do this, prospective analysis tools are required that can portray the reaction of economic systems to policy interventions such as the implementation of material efficiency technologies. The portrayal of macroeconomic effects resulting from material efficiency measures also allows for an assessment of the efficacy of these measures. While they have an expected savings potential, macroeconomic dynamics (and the corresponding physical effects) may lead to diverging results. If a material efficiency measure at the same time constitutes a stimulus to the economy, it may not only decrease specific material demands but also cause increases in the form of rebound effects. In an integrated model setup, such dynamics can be portrayed. Relevant integrated simulation models available today only have very aggregated representations of material flows (e.g. Meyer et al., 2007, 2012), while material flow models generally lack a link to the economic system (Gravgård Pedersen and de Haan, 2006). This gap is addressed by the development of a macroeconomic simulation model for Germany with high sectoral resolution, and the development of an integrated material module, which places detailed material flows in a macroeconomic context. With this model setup, the second research question can be addressed:

2. What are the macroeconomic consequences of material efficiency measures in Germany and how effective are they in reducing overall material demand?

A large share of raw materials used as inputs for economic activity are "throughput" in the sense that they are transformed chemically into waste or emissions within one year or less (Schaffartzik et al., 2016). This includes fossil fuels and many industrial minerals (e.g. fertilizer components). Other minerals and especially metals, in contrast, accumulate in anthropogenic stocks. After these stocks reach the ends of their lifetimes, the materials can at least be partially recovered as secondary material. The demand for primary material thus not only depends on overall material demand, but also on the availability of secondary material as a substitute for primary material. In order to be able to portray the availability of secondary material, the measurement of yearly flows must be complemented by a dynamic accounting of material *stocks* in society (cf. Wiedenhofer et al., 2019). Material stocks are commonly portrayed in material flow models, though the majority of these models are descriptive and thus only portray existing material cycles. A few studies have performed prospective simulations of hypothetical material flows (e.g. Müller, 2006; Pauliuk et al., 2017). However, these studies are generally not embedded in a macroeconomic context, thus the mutual influence of physical and economic dynamics is not (fully) portrayed. Macroeconomic simulation tools, on the other hand, normally do not contain representations of material stocks and only consider yearly flows. This gap is addressed through the coupling of the macroeconomic simulation model with a substance flow model. With this model setup, future effects of material efficiency measures on material flows and stocks, embedded in the overall economy, can be analyzed. This leads to the third research question:

3. What are the effects of different material efficiency measures on the availability of secondary material and the corresponding demand for primary material?

This thesis thus aims to provide insights into the three general topics of past material consumption in Germany, macroeconomic effects and changed material flows resulting from broad material efficiency scenarios, and material stock and flow dynamics in response to different efficiency measures.

1.3 Methodological approach and structure

The first research question is addressed through an analysis of past material flows in Germany. The methodology employed is an environmentally-extended Multi-Regional

Input-Output (MRIO) analysis based on the EXIOBASE database, which is among the most detailed MRIO databases available today. The drivers of Germany's material use are analyzed with the help of additive Structural Decomposition Analysis (SDA), which identifies the individual contributing factors to German material use. These factors include the material intensities of economic sectors, the structure of the German as well as the global economy, and the level and structure of aggregate demand in Germany.

In order to answer the second research question, a dynamic macroeconomic simulation model, ISI-Macro, is developed. ISI-Macro's high sectoral resolution of 72 production sectors makes it possible to analyze structural shifts in the economy resulting from material efficiency measures. It is extended with a material module, of which one part is based on detailed environmental information from EXIOBASE and is capable of portraying close to 230 categories of used and unused material extraction (including biomass) as well as a number of other environmental categories.

Due to the specifics of material cycles, the answering of the third research question will be focused on copper stocks and flows in Germany, which is the most widely used non-ferrous metal beside aluminum and is projected to experience considerable demand increases in the future (Elshkaki et al., 2016). For this, ISI-Macro is coupled with an adapted regionalized version of a substance flow model for copper. The other part of the material module of ISI-Macro thus serves as the connection between the macroeconomic simulation model and the substance flow model. Both models are implemented in a System Dynamics (SD) environment, which allows for a seamless integration.

The thesis is structured as follows. In Chapter 2, the conceptual background to material flow accounting in the industrial system is introduced. Following a brief background in the first part, the second part outlines the most relevant material flow approaches which stem from a physical perspective of the industrial system. Approaches measuring material flows based on the interaction of economic sectors are outlined in the third part. The fourth part starts with a general introduction to SD as a modeling methodology and then briefly outlines applications of SD to material flows and macroeconomics. The fifth part closes with chapter conclusions.

Chapter 3 outlines the rationale for Impact Assessment (IA) of policy interventions such as material efficiency strategies. The general rationale for IA is briefly outlined in the first part of the chapter. The second part presents theoretical considerations on IA in the context of material efficiency and identifies the unique features of material efficiency that are important to consider when performing an IA. For each of these features, appropriate ways of portraying them in a modeling setup are discussed in the third part. The chapter closes in the fourth part with conclusions.

The methodological approach and the data used are described in Chapter 4. The first part describes the German version of the substance flow model for copper, which is coupled to the macroeconomic simulation model, ISI-Macro. A description of ISI-Macro is presented in the second part. In the third part, the newly developed material module of ISI-Macro is described in detail, consisting of an aggregate material sub-module and a copper sub-module. The description of the aggregate material sub-module also serves as a general description of MRIO analysis. The fourth part closes with chapter conclusions.

Chapter 5 addresses the first research question with an empirical analysis. The first part presents the results of the retrospective MRIO analysis of material use in Germany. Different economy-wide material flow indicators for the time frame from 1995 to 2011 are presented and discussed in relation to results from other retrospective analyses. For the consumption based indicator Raw Material Consumption (RMC), an SDA is performed in the second part, which reveals the drivers of material consumption in Germany. The third part of the chapter presents conclusions on the results and the employed methodology.

In Chapter 6, the second and third research question are addressed with prospective simulations conducted with ISI-Macro. The first part of the chapter addresses the second research question and analyzes economy-wide effects of the implementation of a broad set of proposed material efficiency technologies for Germany. After a brief overview and scenario definition, the simulation results on the physical and on the economic level are presented. The first part of the chapter then closes with a critical discussion of the simulation results. The second part of the chapter addresses the third research question. It first outlines scenario assumptions on measures to reduce copper use in Germany and describes adaptations to the coupled model for the simulation of material stock and flow dynamics. Simulation results are then presented for a number of indicators, followed by a discussion of the results. The third part of the chapter closes with conclusions on the results of both prospective simulation studies.

Chapter 7 summarizes and concludes this thesis. The first part presents a summary of the empirical analyses. The second part closes with a methodological reflection, conclusions on the findings of this thesis and an outlook on possible future research avenues in the area of economy-wide material flows.

2 Material flows in the industrial system

In this chapter, the conceptual and methodological basis for analyzing the connected physical-economic system of industrial production will be described and approaches originating from different perspectives will be outlined. Section 2.1 starts with a brief rationale for analyzing material flows in relation to the wider economic system. Section 2.2 outlines the most relevant approaches describing the influence of industrial production on material demand which originate from a physical perspective. The most relevant approaches originating from an economic perspective are then outlined in Section 2.3. In Section 2.4, System Dynamics is introduced as a general modeling methodology and its applications to material flow and economic analysis are outlined. Lastly, the conclusions from this chapter are presented in Section 2.5.

2.1 Background

The physical and the economic dimensions of the industrial system are not independent of each other; the use of materials is driven by economic activity while the economy depends on material inputs (Daniels and Moore, 2001; Duchin, 1992; Kytzia et al., 2004). In other words, there is a "coupling between the physical and the monetary layer of industrial systems" (Pauliuk et al., 2015, p.104). Therefore, a detailed understanding of the interplay between material flows and economic dynamics is necessary in order to be able to inform policies related to raw material use. This is particularly true on the level of individual economic sectors, which have differing material requirements but are interconnected and thus exchange materials along their respective supply chains.

This and the following chapter intend to elucidate the bidirectional relationship between the physical and the economic layer of the industrial system. One side of this relationship is the influence of industrial production on material demand. A relatively large body of work exists on this topic in the form of what Daniels and Moore (2001) call "physical economy approaches", which are based on the conception of economic activity being inherently a physical process. Therefore, this view emphasizes the importance of being able to track physical flows through the economy (Ayres and Kneese, 1969; Georgescu-Roegen, 1971; Leontief, 1970). The approaches which are able to do that can in turn be broadly divided into those originating from a physical perspective and those originating from an economic perspective of the industrial system. While the former look at physical aspects of the industrial system without necessarily considering the economic dimension, the latter start with a description of the economic (monetary) dimension and add physical information to it. Despite these different origins, there is a considerable degree of complementarity and overlap between these approaches.

The other side of the relationship between the physical and the economic layer of the industrial system is the influence of human-induced changes in material flows and associated economic actions on industrial production and the overall economy. More specifically, this side of the relationship implies that measures to change material flows, such as the implementation of efficiency technologies, can have noticeable impacts on industrial production and the wider economy. The study of these effects therefore belongs into the domain of economic Impact Assessment, which will be the subject of Chapter 3.

2.2 Physical accounting of materials in the industrial system

There are a number of approaches which analyze the stocks and flows of materials within the industrial system from a physical perspective. The main difference between these approaches is their respective purpose. Some approaches are designed to measure the entirety of material flows within a predefined system, whereas others only trace a specific substance through various processes, and still others assess the material requirements of a product as part of a broader environmental assessment. The purpose of economy-wide material flow accounting in this thesis is twofold. On the one hand, the overall use of materials is to be determined based on the activity of different industrial sectors and in response to technical measures to increase resource efficiency. On the other hand, an individual substance – the widely used metal copper – is to be traced through the industrial system in order to assess the availability of secondary material and subsequently draw conclusions on primary demand. Copper is among the metals with relatively high environmental impacts (cf. Nuss and Eckelman, 2014), which is at the same time projected to experience considerable demand increases in the future due to its good electrical conductivity (Elshkaki et al., 2016), especially with increasing shares of renewable electricity generation and associated infrastructure needs (Elshkaki and Graedel, 2013; Kleijn et al., 2011).

Both of these objectives theoretically have several rationales behind them (cf. Table 2.1). In the case of an individual substance, the availability of secondary material has implications on the demand for primary material, which has a strategic dimension (e.g. a specific technological functionality) but can also be viewed from an environmental (e.g. toxins released during the extraction of a specific substance), social (social problems associated with the provision of the substance, e.g. so-called conflict metals), or intergenerational perspective (the future availability of that substance). Likewise, the overall use of (primary) materials can be assessed with respect to these

Table 2.1: Rationales behind the assessment of material flows

	Object of study	
Rationale	Individual substance	Sum of materials
Strategic/economic	Technological application	Material basis of society
	Specific toxicity (e.g. lead)	Material intensity
Environmental	High environmental footprint	Overall negative environmental impacts of material extraction
Social	Negative social impacts (e.g. conflict metals)	Distribution of materials and associated incomes
Intergenerational	Availability in future for specific function	Overall future availability

dimensions, though from a more general perspective, e.g. with respect to the overall (future) availability of materials or the overall environmental burden of material use. In the following, the most important approaches analyzing material flows are briefly described.

2.2.1 Material and Substance Flow Analysis

Material Flow Analysis (MFA)[1] is broadly defined as the "systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material" (Brunner and Rechberger, 2004, p.3). More specifically, "MFA refers to the analysis of the throughput of process chains comprising extraction or harvest, chemical transformation, manufacturing, consumption, recycling and disposal of materials" (Bringezu and Moriguchi, 2002, p.79). The term 'material' can refer to chemical substances, "natural or technical compounds or 'bulk' materials (for example, coal, wood)" (Bringezu and Moriguchi, 2002, p.79). Brunner and Rechberger (2004) expand the definition of 'material' to also include more broadly defined *goods* which possess economic value while at the same time emphasizing the aim of keeping the number of analyzed substances low so as to maintain *transparency* and *manageability*. Useful overviews of different MFA studies are provided by Chen and Graedel (2012) and Müller et al. (2014).

The focus of MFA lies on the systemic dimension, i.e. the system of interest is first defined spatially and temporally (Daniels and Moore, 2001). Subsequently, all

[1]Fischer-Kowalski et al. (2011, pp.870) use the acronym MFA for the related concept of Material Flow Accounting, which they call a more "descriptive" term than the "theoretically demanding" Material Flow Analysis, which as the name indicates, goes beyond accounting to also entail an analytical component. The authors point out that no well-defined distinction between the two uses exists. However, they locate Economy-wide Material Flow Accounting in category IIc of the characterization by Bringezu and Moriguchi (2002), which is outlined below in this section.

flows of the relevant materials within this system are captured in physical units. The spatial dimension can be defined on a geographical scale, for example in the form of national borders, or more narrowly on the scale of industrial processes (Bringezu and Moriguchi, 2002). The temporal dimension is then usually chosen so as to create a reasonable frame of analysis. An MFA could thus be carried out, for example, for the material flows within a country per year or within an industrial process per hour.

In order to cover the full scope of MFA, Bringezu and Moriguchi (2002) suggest a classification in which they distinguish between analyses of type I and type II. The former are based on a technical or engineering perspective and focus on specific environmental impacts. The object of primary interest are substances (Ia), materials (Ib) or products (Ic) and the impacts of their flows through a spatially defined system. Type II analyses, on the other hand, are focused on the analysis of socio-economic relationships and associated broader environmental concerns. Their objects of primary interest are firms (IIa), sectors (IIb) or entire regions (IIc) and the environmental implications of material flows through them. Table 2.2 illustrates the distinction between these two types and summarizes the different sub-types.

Table 2.2: Types of MFAs, adapted from Bringezu and Moriguchi (2002, p.81)

	Type of analysis		
Object of primary interest	Ia	Ib	Ic
	Specific environmental problems related to certain impacts per unit flow of:		
	Substances	Materials	Products
	e.g. Cd, Cl, Pb, Zn, Hg, N, P, C, CO_2, CFC	e.g. wooden products, energy carriers, excavation material, biomass, plastics	e.g. diapers, batteries, cars
	within certain firms, sectors, regions.		
	IIa	IIb	IIc
	Problems of environmental concern related to the throughput of:		
	Firms	Sectors	Regions
	e.g. single plants, medium and large companies	e.g. construction sectors, chemical industry, construction	e.g. total or main throughput, mass flow balance, total material requirement
	associated with substances, materials, products.		

Within this categorization, types IIb and IIc are of the main interest for the present thesis since material efficiency measures have different impacts on the affected economic sectors (see Section 3.2ff.), and the regional (in this case national) level is the level of analysis. In this type of MFA, “the main interest lies in the overall characterization of the metabolic performance of the studied entities, in order to understand the volume, structure and quality of the throughput and to assess the status and trend with regard to sustainability” (Bringezu and Moriguchi, 2002, p.84). An MFA conducted on the national level is also referred to as Economy-wide Material Flow Analysis (EW-MFA).

However, there are a number of problems associated with the broader field of MFA, specifically with EW-MFA and its integration in the wider economic system. On the one hand, the measurement of material flows *within* economies is not as well developed as the measurement of trade flows of materials *between* economies, which is, for example, possible with the help of the UN Comtrade database (United Nations, 2017; see also Section 2.3.5). The primary reasons for this are that material flows are mostly not recorded in relation to the wider economic system, leading to a lack of data sets using suitable product or sector classifications, while theoretically suitable data sets, such as the Production Communautaire (PRODCOM)[2] database, often contain sizable gaps (Tukker et al., 2006a). In sum, as Gravgård Pedersen and de Haan (2006, p.28) note, "in economy-wide material flow accounting, the economic system itself remains basically a black box." This is also the case for Substance Flow Analysis (SFA) and Life Cycle Assessment (LCA), which are described in the following sections. The interaction between environment and economy is only addressed systematically in the economic approaches presented in Sections 2.3.2 and 2.3.3.

Substance Flow Analysis can, broadly speaking, be considered a subset of MFA as it focuses on "one specific substance or a limited group of substances" (van der Voet, 2002, p.91; see also Haes et al., 1997 and van der Voet, 1996). Different rationales for focusing on individual substances in the context of waste management are pointed out by Brunner and Ma (2009), including the tracing of toxins and the conservation of substances important for economic processes. The latter is also the motivation for SFAs of copper carried out by, e.g., Graedel et al. (2002) and Glöser et al. (2013).

As Brunner and Rechberger (2004) point out, some authors use the terms SFA and MFA interchangeably as they do not distinguish between goods, materials and substances. It can be seen how the borders between the two concepts are somewhat fluid if "materials" can include everything from chemical substances to generic *goods* and SFA can entail not only a single substance but several substances. Graedel and Allenby (2003) therefore base their definitions of the different concepts on the object and scope of the analysis. According to this definition, SFA starts with a substance or a group of substances, while system boundaries can be set according to the question at hand. For instance, a single industrial metal such as copper can be traced through SFA on a global or on a regional level. SFA can thus be sorted into category Ia of the MFA classification scheme in Section 2.2.1 above (Bringezu and Moriguchi, 2002).

[2]In the latest version (2015), the PRODCOM table of sold volumes of goods within Germany has more than 50 % missing entries. PRODCOM is described in more detail in Section 2.3.5

2.2.2 Life Cycle Assessment

The International Organization for Standardization (ISO, 2006a, 2006b) defines LCA[3] in the following way: "LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e cradle-to-grave)." LCA thus constitutes a holistic assessment methodology covering not only material use but environmental impacts in general. An important characteristic of LCA is that the environmental impacts are linked to a system's *function* and not to its inherent characteristics. This allows for comparisons with alternatives which provide the same function. The basis for quantification of environmental impacts is thus the *functional unit*, which is usually a product or service (Bringezu, 1997; Daniels and Moore, 2001; Haes, 2002; Olivier et al., 2016). In contrast to MFA as defined above, LCA embraces "the nature of the impact rather than political boundaries" (Hellweg and Mila i Canals, 2014, p.1112), and strives for *completeness* in its assessment of environmental impacts, i.e. tries to cover as many substances and compounds as possible (Brunner and Rechberger, 2004). Haes et al. (1997) summarize the relationship between MFA, SFA and LCA on an abstract level as portrayed in Figure 2.1, which shows a certain degree of overlap between MFA/SFA and LCA but depicts them as mostly distinct approaches.

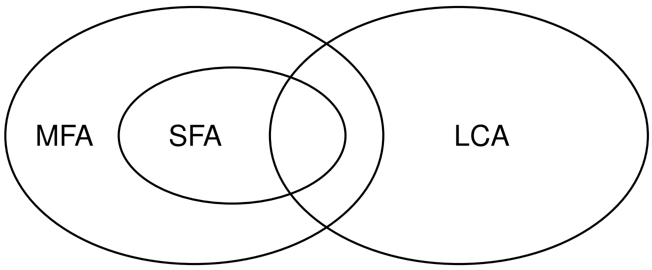


Figure 2.1: Commonalities between analytical tools, based on Haes et al. (1997, p.33)

Within the classification scheme of Bringezu and Moriguchi (2002) described in Section 2.2.1 above, LCA can thus be assigned to type Ic, which places the focus of the analysis on the environmental impacts of products. However, unlike SFA, it is unusual to describe LCA as a subset of MFA. This has mainly to do with LCA's orientation on the functional aspect of products and services of which the accounting of material flows is only a part. In this sense, "MFA can be regarded as a method to establish the inventory for an LCA" (Brunner and Rechberger, 2004, p.141). This is especially the case if LCA is applied to a system as opposed to a single good, and the aforementioned tension between transparency/manageability (MFA) and completeness

[3] Similar to Material Flow Analysis, Life Cycle Assessment is a comprehensive concept entailing an analytical dimension, of which Life Cycle Inventories (LCIs) are an integral component.

(LCA) can be adequately resolved. However, few LCA studies have been carried out above the product level, e.g. for entire systems, which is an emerging field, though an increasing number of studies are conducted at the process or even firm level and the methodology is being expanded to also be applied at the societal and regional level (Brunner and Rechberger, 2004; Daniels and Moore, 2001; Hellweg and Mila i Canals, 2014).

LCA can thus be allocated to the family of so-called bottom-up models, which merge detailed technological information to describe a larger system. This allows for a relatively accurate portrayal of technological change. Top-down models, in contrast, apply aggregate assumptions on technologies to make predictions of the behavior of systems and actors. They are often based on macroscopic cores which have no detailed representation of technologies (Rivers and Jaccard, 2006; Wilson and Swisher, 1993). While MFA may also be conducted through bottom-up modeling, top-down approaches are more suitable for analyses with a national or supranational scope and a variety of products involved (Pauliuk et al., 2013).

2.2.3 Aggregate material use indicators

One aim of EW-MFA is the calculation of aggregate material flows within a country in one year. For reporting and comparative purposes, various aggregate material use indicators have been defined. Two broad types can be distinguished: absolute material use indicators, which measure the total weight of materials used or processed within a predefined geographical space and time frame (e.g. within a country in one year), and composite indicators, which compare economic performance with material use. A wide variety of absolute material use indicators has been defined based on different conceptual approaches to material accounting. These conceptual differences are illustrated in the classification scheme in Figure 2.2, which is also the classification system used by the German Statistical Office for environmental-economic accounts (Destatis, 2017b). The indicators can thus be distinguished along three main dimensions (cf. Kosmol et al., 2012):

1. **input** vs. **consumption** based indicators: the former encompass all raw material inputs of an economy regardless of the intended final use, whereas the latter adopt a domestic consumption perspective and thus exclude the raw materials that go into exports. The implication of this differentiation is that the input based indicators count the material content of imports as well as exports and therefore cannot be used additively on a global scale. On the contrary, consumption based indicators can theoretically be added to a global material consumption indicator.

2. **direct** vs. **indirect** raw material content of imported goods: in the former case, imports are added to domestic material extraction with their respective weights, without accounting for embodied materials. The latter indicator type accounts

for these indirect material contents by incorporating all the extraction needed for the production of goods. Indirect indicators thus provide a more holistic picture of imported material use, which is also relevant for re-exports of imported goods and exports of processed goods, since these also contain embodied materials. If embodied material is included, these trade flows are counted in Raw Material Equivalents (RME). Indirect material use is indicated through the use of the "raw" (or the "total")-prefix as opposed to the "direct"-prefix. An exception is Domestic Material Consumption (DMC), which uses the prefix "domestic" instead of "direct", though it also refers to the direct material content only.

3. **unused** vs. **used** extraction[4]: the former accounts for all domestic and foreign material that needs to be moved during the extraction process of a given material but is not further processed and essentially remains at the place of extraction, or is lost or returned to the source. The latter does not take this into account as it may be considered to only constitute a relocation of material and not an actual consumption. In addition, data on unused material is generally of a lower quality than data on used flows and the relationship of unused material to environmental pressures is less clear. However, proponents of the inclusion of unused extraction argue that land-use changes take place and local pollution may occur. The inclusion of unused extraction is indicated with the prefix "total". Constituting another exception to the described nomenclature, the input-based indicator also taking unused extraction into account is called "Total Material Requirement (TMR)" as opposed to "Total Material Input".

The differences between the above indicators can be more easily discerned in Figure 2.2. In addition, the German Environment Agency provides a standalone glossary on resource conservation, which contains definitions of these and further material use indicators (Kosmol et al., 2012). It also describes the related concept of cumulative raw material demand (German: Kumulierter Rohstoffaufwand (KRA)[5]), which helps

[4]The United Nations' System of Environmental-Economic Accounting (SEEA) 2012 – Central Framework distinguishes in this context between three types of "natural resource residuals": losses during extraction, unused extraction (e.g. of mining overburden), and reinjections (United Nations, 2014). For simplicity, these are henceforth all summarized under the term "unused".

[5]Albrecht et al. (2012) define KRA as the sum of all direct and indirect biotic and abiotic raw materials used for the direct provision of a given product:

$$\text{KRA} = \sum_{r=1}^{s} R_{en,r} + \sum_{t=1}^{u} (R_{mat,t} - A_t)$$

where $R_{mat,t}$ = domestic and imported material resources required for the energetic provision of the respective product, $R_{mat,t}$ = domestic and imported material resources required for the material provision of the respective product, and A_t = domestic and imported excavation material (i.e. unused material). On the one hand, this definition illustrates the holistic approach of including all material and energetic resources that are necessary to provide the product to society. On the other hand, a distinction is made between used and unused material, though contrary to Kosmol illustrate the inclusion of all raw materials necessary for the provision of a given product.

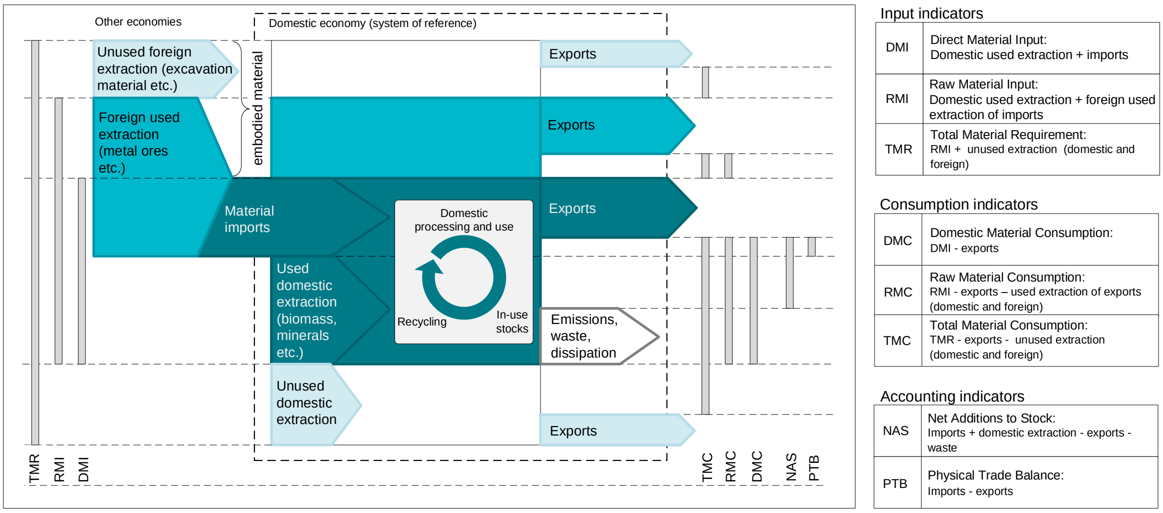


Figure 2.2: Aggregate material use indicators, based on Kosmol et al. (2012, p.42)

The other broad type of material use indicators are composite indicators, such as “raw material productivity”, which compares economic performance with material use and has been used in the German National Sustainable Development Strategy up until the year 2016 (Bundesregierung, 2002, 2012). Raw material productivity is measured simply by dividing GDP through Direct Material Input (DMI)[6], mainly because these are regularly reported statistics. This made it easy to construct time series of the indicator in order to record its development and assess whether relative or absolute decoupling between economic development and material use was observable. Relative decoupling is present if material use does not display the same growth rate as the overall economy (as expressed, e.g., through GDP), but still develops in the same direction. Absolute decoupling happens if material use develops completely independently of GDP, e.g. if material use keeps decreasing in a growing economy (see, for instance, BMWi, 2010; Bundesregierung, 2016; European Commission, 2008). The original resource related target of the Sustainable Development Strategy was a doubling of raw material productivity until 2020 from its 1994 level (Bundesregierung, 2002, 2012). The development and target of raw material productivity are shown in Figure 2.3a.

For the new German Sustainable Development Strategy, the more elaborate “total raw material productivity” was developed to account for embodied material require-

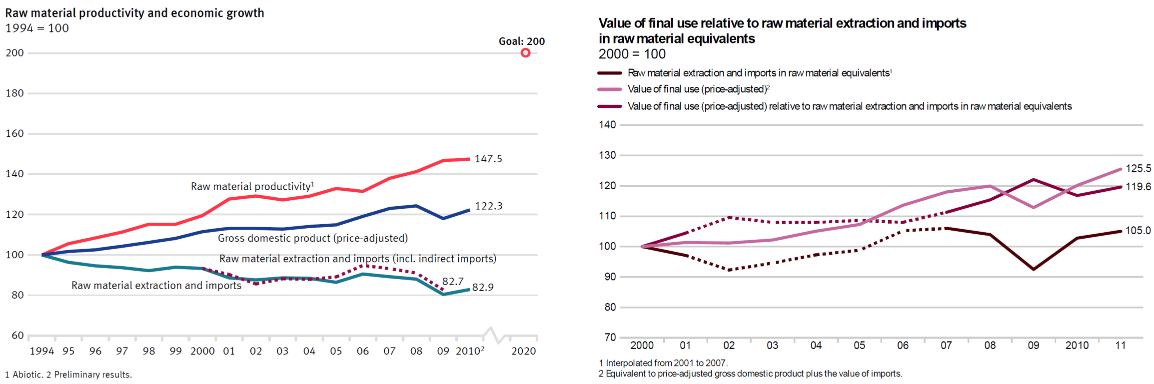
et al. (2012), Albrecht et al. (2012) only subtract unused material from the material resources and not from the energetic resources. The database the authors use to calculate KRA is described in Giegrich et al. (2012).

[6]Contrary to the standard definition, the measure for DMI used in the calculation of raw material productivity only includes abiotic raw materials.

ments in imported goods, thus substituting Raw Material Input (RMI)[7] for DMI. In addition, the monetary value of total imports is added to the numerator, since imports are taken to belong to final use not just in the form of materials but also in their monetary dimension (Bundesregierung, 2016):

$$\text{Total raw material productivity} = \frac{\text{GDP} + \text{imports}}{\text{RMI}}$$

The new indicator is more difficult to determine since RMI cannot be directly measured but has to be calculated, usually with some type of economic-environmental model (see Chapter 4). However, it provides a more holistic picture of raw material input into the German economy since it takes into account all material that is needed to produce the imported goods along their respective supply chains, not just the goods themselves. This is important as it precludes a supposed improvement of Germany's material footprint simply by externalizing industrial production and then importing the externally produced goods.



(a) Raw material productivity (b) Total raw material productivity

Figure 2.3: Development of raw material productivity indicators (Bundesregierung, 2012, p.64; Bundesregierung, 2016, p.124)

The change of the indicator was accompanied by an update in the related target. The new Sustainable Development Strategy calls for a continuation of the raw material productivity trend of 2000-2010 until the year 2030 (Bundesregierung, 2016), which roughly equals an annual increase of 1.5 % (see Figure 2.3b).

Müller et al. (2016) discuss the widespread use of these indicators critically with respect to the often unclear rationale behind using them. Connected to the discussion outlined at the beginning of this section, some questions may be better answered than others with these indicators. For instance, if the objective is to identify the materials

[7] The measure of RMI used in the calculation of total raw material productivity does include biotic raw materials and is therefore in line with the standard definition.

which contribute most to environmental problems, van der Voet et al. (2004) advocate the combination of MFA with other environmental information from LCA, as simple aggregate material use indicators alone do not convey much useful information in this respect.

2.3 Economic accounting of materials in the industrial system

The majority of economic approaches used for the account of material flows in the industrial system are based on Input-Output (IO) analysis. IO analysis portrays the interconnectedness of economic sectors through supply and use relationships and is therefore well suited to track the complex flows of products. The structure of IO tables allows for the portrayal not only of direct but also of indirect exchange between sectors in order to cover entire supply chains. This enables the calculation of cumulative sectoral production, based on a given composition of aggregate demand.

Due to limited data availability, the commonly available tables are highly aggregated (e.g in comparison with product-level LCIs) and therefore often contain groups of products within individual sectors, such as the non-ferrous metals sector (e.g. Destatis, 2016c). For ease of integration with national accounts, common IO tables are denoted in monetary units. However, the monetary value per physical weight can vary widely for different products and at different stages of the supply chain (Weisz and Duchin, 2006).

This and the relatively high aggregation of common IO tables makes them by themselves an imperfect tool for a detailed analysis of physical material or substance flows with the potential for large errors in the estimation of sectoral and overall material demands. For this reason, approaches that utilize the intersectoral logic of IO tables but allow for a better representation of physical flows have been developed. These range from the physical analog to monetary IO tables over the disaggregation of existing (physical) tables to the introduction of physical extensions to monetary tables. The most important of these approaches will be described in the following sub-sections.

2.3.1 Input-Output Analysis

IO analysis is an analytical framework with which the interdependence of industries in an economy can be analyzed. It is a part of the System of National Accounts (SNA), which brings together the supply and use sides of the economy (Kuhn, 2010). IO analysis was originally developed by Wassily Leontief in the late 1930s (see, for example, Leontief, 1936), and has since then become a widely used tool for structural economic analysis (Kuhn, 2010; Miller and Blair, 2009). Leontief himself once described IO analysis as “a practical extension of the classical theory of general interdependence which views the whole economy of a region, a country and even of the entire world as a single system and sets out to describe and to interpret its operation in terms of directly observable basic structural relationships" (Leontief, 1987, p.860). The most common type of IO model is the static open quantity model, which will be described in the following. This model is considered *open* because final demand, which serves as the driver of all economic activity described by the model, is assumed to be exogenous. This means that other parts of the model have no influence on the level or composition of final demand; it can be assumed to rather depend on consumption preferences or investment decisions. As will be seen below, "closure" of an IO model can be achieved by making final demand endogenous, i.e. making it dependent on other parts of the model. The standard model is considered a *quantity* model because its focus lies on the quantities of goods traded as opposed to, e.g. prices. Nevertheless, the quantity model is a mixed unit model in the sense that the quantity relationships are described in monetary terms. These monetary flows can be understood as the number of units exchanged at a hypothetical unit price of 1 (Leontief, 1986; Seetzen, 1979). If the interest lies in price changes resulting from shifts in value added, a price model can be used. Other types of IO models as well as a more detailed description of IO theory and the construction of IO tables can be found, for example, in Eurostat (2008a); Fleissner et al. (1993); Miller and Blair (2009); Suh (2006).

At the core of Input-Output analysis are symmetric IO tables, which are derived from supply and use tables. The former show the supply of products by product type and supplying industry, whereas the latter show the use of products by product type and type of use (Eurostat, 2008a). Supply and use tables are mostly rectangular, since the number of goods is usually higher than the number of producing industries portrayed in these tables (ten Raa and Rueda-Cantuche, 2007). Two broad types of IO tables can be constructed from the supply and use tables: product by product or industry by industry tables, the former of which is used by the German Statistical Office (Destatis, 2016c). The difference between these types lies in whether the focus is on the production technology behind products or industries, or on the sales structure of industries or the products they sell. A more detailed explanation of this difference is provided by, e.g., Eurostat (2008a) and Miller and Blair (2009). Irrespective of which type of IO table is constructed from supply and use tables, a number of assumptions have to be made due to the differing amounts of industries and products. Thus, IO tables have to be seen as synthetic databases, which are considered useful for the analytical insights they can provide and not for a precise representation of the economic system. In their general form, IO tables describe in monetary units for a given year:

(I) the flow of intermediate goods between production sectors,

(II) the flow of final goods between production sectors and final demand (consumption, investment and exports),

(III) and the use of non-industrial inputs, or so-called primary inputs (such as labor and capital), surpluses and taxes less subsidies within production sectors.

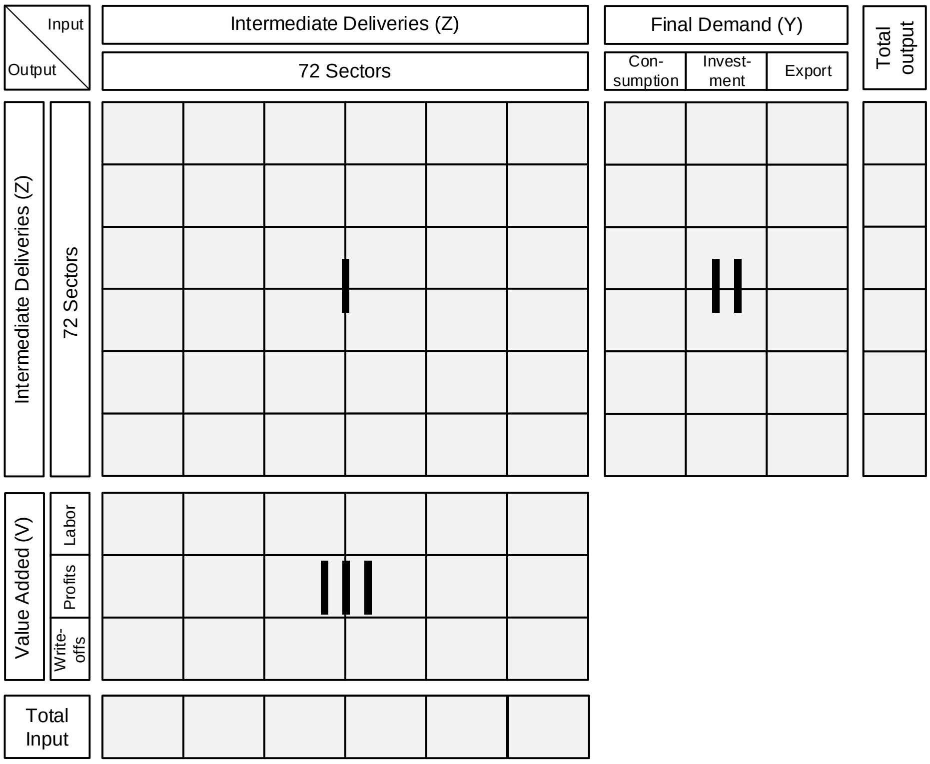


Figure 2.4: Structure of input-output tables

These three parts are represented by the three main quadrants of IO tables, which are illustrated in Figure 2.4. The first quadrant, the intermediate deliveries matrix $\boldsymbol{Z}$, is an $n \cdot n$ matrix, where n indicates the number of production sectors portrayed in the IO table. The production sectors' outputs of intermediate goods are shown in the rows and their inputs in the columns. The composition of a sector's inputs is sometimes called the sector's production "recipe" as it indicates which inputs are necessary to produce a given output. Currently, the IO tables issued by the German Statistical Office contain 72 production sectors (Destatis, 2016c).

The intermediate deliveries portrayed in the first quadrant serve the purpose of producing "final" goods, i.e. consumption and investment goods. The second quadrant, the final demand matrix $\boldsymbol{Y}$, thus shows the uses of each sector's final goods in each of the final demand categories, which include private and public consumption, building and equipment investment (which together equal gross fixed capital formation), exports, and changes in inventories and valuables (which is sometimes merely used as a balancing term). The final demand matrix thus has n rows, but m columns for the final demand categories. Intermediate deliveries and final demand sum up to total use (row sums). In domestic IO tables, extra rows for imports of intermediate and final goods are added below the first and the second quadrant, whereas in mixed tables, the imports are directly added to the respective entries for intermediate and final goods.

The third quadrant, the value added matrix $\boldsymbol{V}$ with n columns and l rows, shows each sector's primary inputs, surpluses, and taxes and subsidies. Next to intermediate inputs that are processed into final goods, other inputs are necessary for the sectors' production or are part of the regulatory framework as in the case of production taxes less subsidies, or simply reflect surpluses. The first row of the value added matrix contains the product taxes and subsidies of each sector. Together with the sum of intermediate deliveries in producers' prices, these sum up to intermediate deliveries in purchasers' prices. The remaining entries are compensation of employees (= wages and salaries), taxes on production less subsidies, capital depreciation (= consumption of fixed capital) and net operating surpluses (= net profits). Together, these four entries make up gross value added. The sum of intermediate inputs (column sums) plus gross value added make up total supply. The supply and use sides of the economy must be balanced and therefore total supply equals total use; both are also referred to as gross output $\boldsymbol{x}$ (Eurostat, 2008a; Horowitz and Planting, 2009).

IO models rely on a number of (partly restrictive) assumptions (Miller and Blair, 2009; Suh, 2004; Weisz and Duchin, 2006):

1. Linear-limitational production functions: this implies that all production factors (intermediate deliveries and primary inputs) are in a constant, proportional relationship to each other and to the output of a respective sector.
2. Each sector produces one homogeneous product that it sells to all sectors without differentiation.
3. Monetary and physical flows are proportional, implying that the monetary deliveries sold from one sector to all other sectors always have the same physical content per monetary value.

The latter two assumptions become less problematic with an increasing number of production sectors covered, as the number of secondary or co-products (with differing production recipes) within individual sectors decreases. The ideal IO table would thus cover as many production sectors as there are products. However, this is obviously impossible due to data limitations and lack of manageability.

The mixed unit (quantity x price) IO models described here are also restricted to analyses of quantities and cannot at the same time portray price changes. Price changes can only be virtually portrayed through changes in the mixed unit if quantities are held constant.

In their basic form, IO models consist of a set of linear equations that describe the distribution of products from each production sector throughout the economy. As described above, gross output of one sector is from the use-perspective the sum of intermediate deliveries and final demand (Miller and Blair, 2009, pp.16):

$$x_i = \sum_{j=1}^{n} z_{ij} + y_i \tag{2.1}$$

Where x_i = gross output of sector i, z_{ij} = intermediate input from sector i to sector j, and y_i = final demand in sector i. Based on the assumptions outlined above, intermediate input coefficients can be defined by relating intermediate inputs from all supplying sectors to the gross output of the receiving sectors, respectively:

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{2.2}$$

Equation 2.1 then becomes

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + y_i \tag{2.3}$$

where x_j = gross output of sector j, and a_{ij} = input coefficient from sector i to sector j. In matrix notation[8], Equation 2.3 can be denoted as

$$\begin{aligned} \boldsymbol{x} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} \\ &= (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \\ &= \boldsymbol{L}\boldsymbol{y} \end{aligned} \tag{2.4}$$

where $\boldsymbol{x}$ = vector of gross output, $\boldsymbol{y}$ = vector of final demand, $\boldsymbol{A}$ = input coefficient matrix, $\boldsymbol{I}$ = unit matrix and $\boldsymbol{L} = \boldsymbol{(I - A)^{-1}}$ = inverse coefficient matrix (often referred to as the Leontief-inverse).

Whereas the $\boldsymbol{A}$-Matrix only displays direct intermediate inputs, the Leontief-inverse displays the cumulative inputs along the entire supply chain and thus also includes indirect intermediate inputs. This can be illustrated by decomposing Equation 2.4 with the help of the Neumann series (Fleissner et al., 1993, pp.75):

$$\begin{aligned} \boldsymbol{x} &= (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \\ &= (\boldsymbol{I} + \boldsymbol{A} + \boldsymbol{A}^2 + \boldsymbol{A}^3 + \ldots + \boldsymbol{A}^r + \ldots)\boldsymbol{y} \end{aligned} \tag{2.5}$$

Equation 2.5 shows that the direct intermediate input requirements are followed by an asymptotically smaller row of indirect intermediate input requirements. This implies that the upstream inputs of a product are covered to the full extent and no cut-off point needs to be defined (as is the case in LCA).

As outlined at the beginning of this section, the high aggregation of standard-issue IO tables in conjunction with the assumptions on the homogeneity of products and the proportionality between monetary and physical flows makes them by themselves an imperfect tool for MFA. Relatively large deviations can be observed between monetary and physical flows. For instance, as will be seen in Section 4.3.2, the monetary

[8] The notation throughout the thesis follows the conventions of matrix algebra, where matrices are denoted as bold upper-case letters, vectors as bold lower-case letters and elements as simple lower-case letters.

deliveries of the aggregated non-ferrous metals sector in the German IO table differ substantially from the deliveries of copper in physical units (see also Figure 4.13).

2.3.2 Physical Input-Output Analysis

The basis of physical IO analysis form Physical Input-Output Tables (PIOT), which "describe the flows of material and energy within the economic system and between the economic system and the natural environment" in physical units (Eurostat, 2001, p.63). Physical Input-Output analysis in principle follows the same logic as monetary IO analysis. Thus, physical IO analysis "records all physical flows associated with the economic activities as defined in the SNA" and is thus in principle fully compatible with standard national economic accounts (Hoekstra and van den Bergh, 2006, p.375). A detailed and harmonized description of physical IO analysis is given in the SEEA 2012 – Central Framework (United Nations, 2014). The Central Framework also describes the base tables of PIOTs, which in their physical version contain additional entries accounting for the environment and natural inputs derived from it as well as the residuals given back to it. Analogous to their monetary version, the supply and use identity holds, implying a closed mass balance. For the construction of physical IO tables, the same assumptions are used as in the construction of monetary IO tables (Gravgård Pedersen and de Haan, 2006; Miller and Blair, 2009).

Physical IO tables are subject to the same restrictions as monetary IO tables. Most importantly, the assumption holds that each sector produces one homogeneous product. In the context of MFA, this implies that individual materials have to be represented by individual sectors. However, this quickly leads to excessive data requirements if a consistent (i.e. fully balanced) PIOT is to be constructed. One way to address this is the construction of hybrid IO systems in which physical data is presented alongside monetary data. This is possible because of the common classifications and definitions in physical and monetary IO analysis. A hybrid IO table thus allows for an illustration of environmental effects of economic activity (or, conversely, the economic implications of environmental action). In this case it is also possible to only include a limited set of variables, for instance the materials of interest for a specific research question. It is then not necessary to construct an exhaustive PIOT (United Nations, 2014). Such a hybrid presentation of monetary and physical data is conceptually very close to Environmentally Extended Input-Output (EEIO) analysis, which is described in the following section.

2.3.3 Environmentally Extended Input-Output Analysis

Environmentally Extended Input-Output analysis is essentially, as the name suggests, an extension of standard (normally monetary) IO analysis to include environment-related information for each sector, such as material/resource use, emissions and land use. The approach is based on Wassily Leontief's early observation that "pollution is a by-product of regular economic activities" (Leontief, 1970, p.262). The environment-related information is attached to the monetary IO table in the form of environmental coefficients which represent the amount of environmental effect per unit of gross output of each sector. Underlying this is the assumption that the environmental effects caused by the production of a sector are proportional to the output of that sector and are constant over time[9] (Tukker and Jansen, 2006). Formally, to arrive at the absolute environmental burden $\boldsymbol{M}$, the environmental coefficient matrix $\boldsymbol{E}$ is multiplied with the gross output matrix $\boldsymbol{X}$, which is calculated by multiplying the Leontief-inverse with the diagonalized final demand vector $\boldsymbol{y}$:

$$\begin{aligned} \boldsymbol{M} &= \boldsymbol{E}\boldsymbol{X} \\ &= \boldsymbol{E}(\boldsymbol{I} - \boldsymbol{A})^{-1}\hat{\boldsymbol{y}} \end{aligned} \tag{2.6}$$

Therefore, EEIO analysis allocates environmental impacts of a "production-consumption system" to the different final demand categories, "on the basis of the extent that a final expenditure category 'demands' input of one of the preceding production processes in the technology matrix, and the emission per euro production of that process" (Tukker et al., 2006b, p.22). A comprehensive treatment of materials in an EEIO table requires the definition of material use coefficients at the lowest stage of the supply chain. In the case of metals, this would be metal ores extracted from the environment. Consequently, sectors processing the ores have to be present in the IO table. This makes it possible to distinguish between different metals, which are then delivered to sectors on a higher level of the supply chain and so forth.

The advantage of EEIO analysis is the ease of integration with existing IO tables, which themselves can be part of larger analysis tools, such as macroeconomic models. As Tukker et al. (2006b, p.9) note, "EEIO tables and models are based on a comprehensive accounting framework covering all economic activities. EEIO tables bring together economic and environmental data in a consistent, related sectoral framework." At the same time, the matrix of environmental coefficients can be expanded or truncated depending on the research question. However, despite the flexibility regarding the size of the environmental coefficient matrix, similar to physical IO analysis, the quality of EEIO analysis depends largely on the resolution of the IO table.

Overall, the use of IO-based approaches in the assessment of material flows has several advantages. First, the whole economy is covered systemically; second, a high compatibility is established with economy-wide MFA data as well as the UN's System of Environmental-Economic Accounting; and third, it allows for easy integration into standard systems of national accounting (Schaffartzik et al., 2014a).

[9]Of course, in dynamic analyses, intermediate input coefficients and environmental coefficients can be changed if the necessary information is available.

2.3.4 Extensions to existing approaches

In order to combine the respective strengths of the physical and the economic approaches described above, so-called hybrid approaches have been developed (see Suh and Kagawa, 2005 for an introduction, and Duchin, 1992; Konijn et al., 1997 for early work in this area). Conceptual contributions in this area have been made by Joshi (2000); Lenzen (2002); Bailey et al. (2004a,b); Suh (2004). In the sense that some of the above described approaches utilize information drawn from other approaches, e.g. physical extensions of monetary IO tables, they may also be called “hybrid”. However, the term has mostly been used to describe a combination of top-down approaches, such as IO analysis, with bottom-up approaches capturing material flows, e.g. product level LCA (Lutter et al., 2016a). They therefore often analyze the material use of specific processes or sectors (e.g. Acquaye et al., 2011; Joshi, 2000; Nakamura and Nakajima, 2005; Onat et al., 2014; Rodríguez-Alloza et al., 2015; Suh, 2004; Suh et al., 2004; Takase et al., 2005; Treloar et al., 2000; Watanabe et al., 2016; Wiedmann et al., 2011). However, fewer hybrid studies have been conducted at the economy-wide or regional level (e.g. Lindner and Guan, 2014; Liu et al., 2012; Schoer et al., 2012). As will be seen in Chapter 4, a hybrid approach can be useful for a detailed portrayal of physical aspects of the industrial system in an economic model.

2.3.5 Product and sector classification systems

Even though the physical and the economic approaches to describing the industrial system have developed somewhat independently, they can be connected through widely used and standardized product and sector classification systems. The European product and sector classification system can be broadly divided into economic activities and products (which consist of goods and services). Economic activities are classified by the Statistical classification of economic activities in the European Community (NACE)[10]. It was originally developed in 1970 and is since 2008 used in its second major revision, NACE Rev. 2. A large number of economic statistics are reported in the NACE classification, e.g. data on production, employment, national accounts. NACE is a four-digit hierarchical classification system, which is structured in the following way (Eurostat, 2008b):

1. First level: headings identified by an alphabetical code (sections, N=21)[11]
2. Second level: headings identified by a two-digit numerical code (divisions, N=88)
3. Third level: headings identified by a three-digit numerical code (groups, N=272)
4. Fourth level: headings identified by a four-digit numerical code (classes, N=615)

[10] The term NACE is derived from the French “Nomenclature statistique des Activités économiques dans la Communauté Européenne” (Eurostat, 2008b).

[11] The first level (sections) mainly serves to provide a rough categorization and is therefore often left out in statistics.

Products are classified according to the Statistical Classification of Products by Activity (CPA). CPA product categories are related to the activities defined in the NACE economic activity classification, where each CPA product is assigned to a single NACE activity, regardless of whether it is a transportable or a non-transportable good or service. Therefore, the CPA structure is parallel to that of NACE at all levels and thus corresponds to the four hierarchical levels from *sections* to *classes*. However, there are additional *categories* and *subcategories* which each add one digit to the four-digit NACE classification, resulting in six levels (Eurostat, 2013). The German production sector classification system (currently WZ 2008) follows the conventions of NACE with different levels of aggregation, depending on the type of data for which it is used. Products are thus categorized through CPA codes (Destatis, 2008).

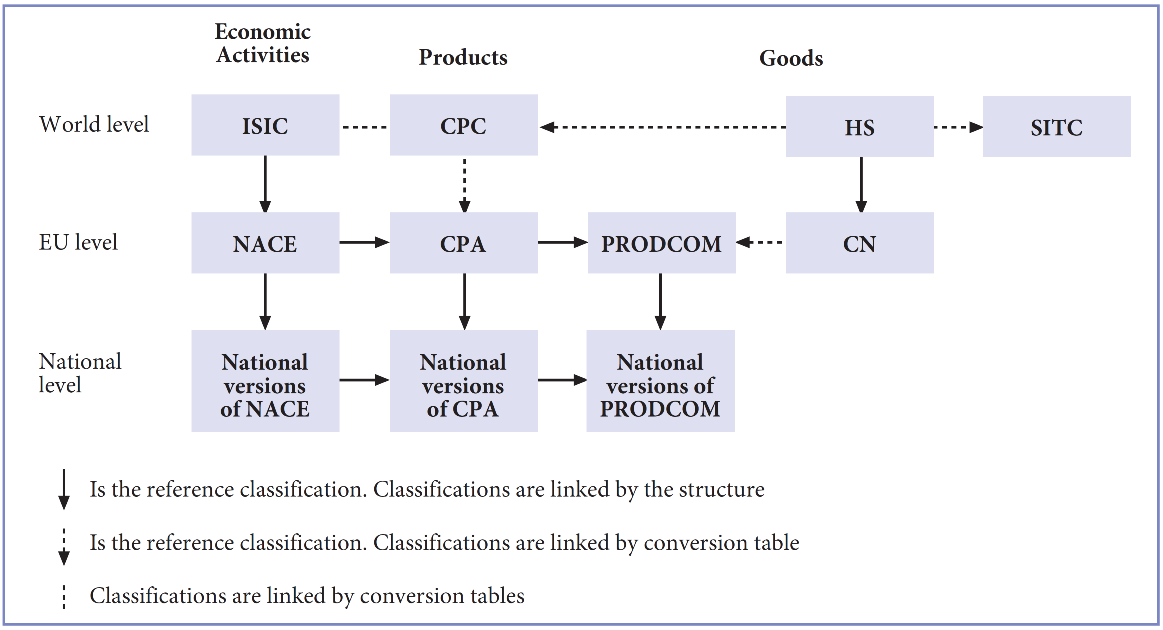


Figure 2.5: The international system of economic classifications (Eurostat, 2008b, p.13)

In order to meet the requirement of a more detailed differentiation for customs purposes and trade statistics, the Combined Nomenclature (CN) was developed. It extends the CPA product classification to eight digits (mainly for goods which are actually traded) and is updated on a yearly basis. At the European level, it constitutes the most detailed product classification (Eurostat, 2015b). As Fig. 2.5 indicates, the PRODCOM classification system connects the CN and CPA systems conceptually. However, PRODCOM originates from a survey of manufactured goods where most PRODCOM codes correspond to one or more CN codes, but some (mostly those referring to industrial services) do not (Eurostat, 2015b). The correspondence between the different levels of the NACE, CPA and CN classifications is illustrated in Fig. 2.6.

In order to be able to measure international trade and compare national economic systems, an international system of economic classifications has been developed under the auspices of the United Nations Statistical Division. The above described European classification system is part of this integrated international system of statistical classifications. Fig. 2.5 shows this system, which can be split up into different geographical levels as well as different classification categories.

$$\underbrace{\overbrace{\overbrace{[1\ 2\ 3\ 4]}^{\text{NACE}}\ [5\ 6]}^{\text{CPA}}\ [7\ 8]}_{\text{CN}}$$

Figure 2.6: Structure of the European economic classifications, based on Eurostat (2008b)

As can be seen in Fig. 2.5, the economic activity classification NACE is derived from the International Standard Industrial Classification of All Economic Activities (ISIC). Thus, ISIC and NACE share the exact same structure at the highest levels, while NACE is more detailed at lower levels. The national versions of NACE are yet more detailed. The product classification CPA can be linked to the broader Central Product Classification (CPC) through conversion tables. The European trade classification CN corresponds with the international Harmonized Commodity Description and Coding System (HS), which is sometimes shortened to “Harmonized System”, and consists of six-digit product codes. It therefore possesses an identical structure to the CN classification for the first six digits, and may be expanded to eight digits for a higher resolution (Eurostat, 2008b). As will be seen later, the correspondence between the HS and CN systems can be used to attribute highly disaggregated goods reported in international trade statistics to economic sectors of European national accounts.

2.4 System Dynamics as a modeling methodology

System Dynamics is a methodology for the modeling of complex dynamic systems. It is based on systems theory and portrays functional cause-and-effect relationships between model variables. SD as a modeling methodology was originally developed by Jay W. Forrester at the Massachusetts Institute of Technology (MIT) in the 1950s, who studied methods grounded in control theory and transferred them from the technical sphere to social systems (Forrester, 1961). This allows for the description of these systems through a set of differential equations, which can be solved with numerical solution procedures. The System Dynamics Society defines SD in the following way:

> "System dynamics is a computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems — literally any dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular causality." (System Dynamics Society, 2017)

A mathematical description of the basic principles of SD can be found in Section A.1 in the Appendix. The remainder of this section outlines applications of SD to material flow and economic analysis.

2.4.1 Application to material flow analysis

System Dynamics is a useful tool for modeling material systems over time since it is capable of portraying material flows as well as material accumulation in the form of material stocks (see for example Bornhöft et al., 2013; Glöser et al., 2016). Chen and Graedel (2012) and Müller et al. (2014) provide useful overviews of different material flow modeling studies in general, with some applications in System Dynamics. As a dynamic modeling methodology employing time delays, SD can also portray other time dependent developments, such as aging processes. Figure 2.7 shows a simplified metal cycle with the different steps in the supply chain. Starting from the refinement of concentrates, the refined metal gets processed into semi-finished goods and then into finished or end-use goods[12]. At the end of their lifetimes, the finished goods get scrapped and either go into recycling or are "lost" in the sense that they exit the cycle as portrayed in Figure 2.7, e.g. because they end up on landfills. Different stocks along the supply chain can be portrayed, and different types of semi-finished and finished goods can be differentiated. This in turn allows for a detailed representation of stock vintages, which has implications for the development of downstream stocks. For example, finished goods with short lifetimes lead more quickly to outflows of the finished goods stock into the waste stock, and so on. The distribution of products with different lifetimes can thus lead to complex dynamics regarding waste flows and the availability of secondary material. Examples of material or substance flow analyses carried out in a System Dynamics environment can be found in Glöser et al. (2013); Sprecher et al. (2015); Soulier et al. (2018a,b).

The simplest way of portraying aging processes in SD is through delay functions, which suppose specific lifetimes of products. The outflow (scrapping) of a specific product stock is thus simply a delayed function of the inflow (production) of that stock (see Section A.1 in the Appendix for an explanation of the relationship between stock and flow variables in SD). Due to variations in lifetimes and related data uncertainties, it appears reasonable to use lifetime distributions (probability density functions of lifetimes). Depending on the degree of knowledge about the product lifetimes, different distributions can be used. However, generally a normal distribution around the historic

[12] The terms "finished" and "end-use" are used interchangeably henceforth.

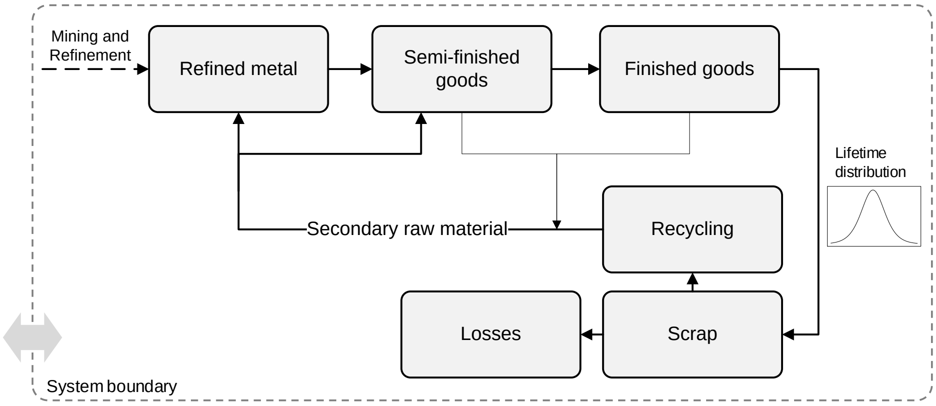


Figure 2.7: Simple illustration of a metal cycle, based on Graedel et al. (2011, p.359)

mean appears to be a reasonable approximation since the value of the mean has a larger influence on the modeled aging processes than the form of the distribution (Glöser et al., 2013).

Effects specific to individual vintages and changing product characteristics, such as material compositions and use patterns, can be portrayed with the help of aging chains. These aging chains consist of individual stocks for each time step. At the end of each step, the products can either enter the next stock, i.e. the next vintage, or get scrapped. Thus, the entirety of smartphones, for example, may be represented by a chain of stocks consisting of new smartphones, 1 year old smartphones, 2 year old smartphones, and so on.

2.4.2 Application to macroeconomic analysis

System Dynamics has also been used in macroeconomic modeling settings. According to Radzicki (2011), the very first paper published in the field of System Dynamics (Forrester, 1956) can in essence be understood as a critique of traditional economic modeling. The relationship between SD and economics has ever since been characterized by a certain tension. SD modelers emphasize the merits of their methodological approach compared to traditional economic modeling techniques, such as the capability to identify dynamic system behavior as opposed to finding tight data fits based on static assumptions. Traditional economists, on the other hand, attack System Dynamics mainly for not adhering to standard theory and placing too little value on good fits (Radzicki, 2011).

Despite these differences, System Dynamics has been applied in a number of economic modeling exercises, ranging from aggregated long term macroeconomic simulations over theoretical studies to macroeconomic Impact Assessment. The most well-known example of long term macroeconomic simulations are Forrester's foundational world and national models (Forrester, 1971, 1982) and the famous study commissioned by the Club of Rome, "The Limits to Growth", which analyzes long term economic and population growth in the context of finite resources (Meadows et al., 1972). A theoretical overview of SD as a macroeconomic modeling tool is provided by Rothengatter and Schaffer (2006). Yamaguchi (2014) analyzes the special topic of the role of money in macroeconomic dynamics. Finally, a more applied use of SD is represented by macroeconomic IA studies, such as in Schade (2004); Krail (2009); Bassi et al. (2012). Some studies have tried to find some middle ground between theory and empirical application and thereby partially resolved some of the aforementioned tension between System Dynamics and traditional economics (Forrester, 1982; Sommer, 1981, 1984; Sterman, 1986; Schade, 2005).

The majority of macroeconomic models implemented in System Dynamics provide aggregated portrayals of the economy and focus on analyzing system behavior, often over relatively long time horizons (e.g. Forrester, 1971, 1982; Meadows et al., 1972; Sterman, 1986). As outlined above, the dynamics arising from complex feedback structures are considered more important in these models than the exact development of individual variables. Often, macroeconomic SD models also include detailed depictions of money demand and supply, leaning towards a Keynesian view of the economy (Forrester, 1982; Wheat, 2016; Yamaguchi and Yamaguchi, 2016). However, more detailed sector models have also been implemented in System Dynamics, mainly for the purpose of IA (Schade, 2004, 2005; Krail, 2009; Bassi et al., 2012). These models do not emphasize the overall system development so much as the interaction of the individual system components, especially the dynamics arising from the feedback structure between these components. A similar approach is chosen for the macroeconomic model developed in this thesis, which will be described in detail in Section 4.2.

2.5 Conclusions

This chapter was motivated by the conception of an interlinkage between the physical and the economic layers of the industrial system. On one side of this interlinkage is the influence of economic processes on physical material flows. This influence can be described by approaches stemming from the physical sciences, often summarized under the umbrella term MFA, and approaches stemming from the economic sciences, mainly based on some type of IO analysis. In the former case, the influence of economic processes on physical flows is mostly taken as given and not considered explicitly. Such a depiction of physical flows can therefore be very detailed but it generally lacks a structural connection to the (socio-)economic processes that gave rise to these flows in the first place. In the latter case, economic activity is explicitly portrayed as the underlying driver of physical flows. However, the depiction of physical flows relies on the quality of the underlying depiction of economic flows and of their connection to the physical sphere. Thus, while each of these approaches has its respective advantages, holistic analyses of material flows in the industrial system call for combinations and/or extensions of them.

The other side of the interlinkage is the influence of changes in material flows, for example through material efficiency measures, on the economic dimension of the industrial system. The effects of such changes are typically assessed with some type of economic Impact Assessment. The rationale for IA, some theoretical considerations and specific features of material flows in the context of IA are the subject of the following chapter.

The present chapter also introduced SD as a modeling methodology particularly suitable for the simulation of material stocks and flows, as well as macroeconomic dynamics. Specifically aging processes and hence stock accumulations are easy to implement in SD environments. In combination with the capability of portraying feedback effects, this makes SD a suitable approach to model complex dynamic systems.

3 Economic Impact Assessment in the context of material efficiency

The previous chapter elucidated one side of the relationship between the physical and the economic layer of the industrial system. This chapter describes the other side, namely the mechanisms behind the influence of human-induced changes in material flows on industrial production, and ways to conceptualize them in the context of Impact Assessment (IA). The aim of this chapter is thus to provide the conceptual and methodological basis of economic IA of the implementation of material efficiency technologies. Section 3.1 starts with a brief introduction to economic IA and outlines different Impact Assessment methodologies. In Section 3.2, theoretical considerations on IA in the context of material efficiency are outlined. The elements of the deployment of material efficiency technologies that are important for IA are explored in detail in Section 3.3, before Section 3.4 closes with some concluding remarks.

3.1 Background

In light of an ever increasing complexity of socio-economic-environmental systems, the future effects of specific policies are difficult to predict (de Ridder et al., 2007). Policy making is therefore increasingly accompanied by some form of Impact Assessment. Especially in the realm of sustainability policies such as material efficiency, where multiple and sometimes contrasting objectives are involved (e.g. ecological benefit vs. economic cost), IA forms an integral part of rational policy design and evaluation (George and Kirkpatrick, 2007; Jacob et al., 2007). As stated in the introduction, material efficiency strategies in Germany and the European Union as well as the UN's SDGs explicitly state the importance of the compatibility between material efficiency and economic well-being. In order to test material efficiency strategies for this compatibility, it is thus important to be able to assess their potential impacts on the economic sphere.

IA is an *ex-ante* form of the broader field of policy assessment, which is supposed to inform about the potential *future* effects of policies (Adelle and Weiland, 2012). In the European Union, IA has been used as a decision support tool since 2002, mainly oriented along the lines of its sustainable development strategy (European Commission, 2001, 2002). Comprehensive guidelines were published in 2009 (European Commission, 2009).

In contrast to the other side of the relationship between the physical and the economic layer of the industrial system (as discussed in the previous section), the influence of changes in material flows on the economy has not been analyzed in great detail so far. The majority of the existing studies conducted in this field use some type of generalized IA methodology that has been adapted to the special case of material efficiency. The economic impacts of energy efficiency measures have been researched in greater detail empirically (e.g. Alexandri et al., 2016; Barker et al., 2015; Carnall et al., 2016; Ostertag and Dreher, 2002; Wei et al., 2010) but also theoretically (e.g. Breitschopf et al., 2013; Croucher, 2012; Mirasgedis et al., 2014). Since energy efficiency is similar to material efficiency in some respects, these studies provide some useful insights.

Due to the complexity of the topic, the majority of analyses with a quantitative orientation have been carried out with modeling approaches. Generally speaking, these approaches follow two different philosophies. On the one hand, there is a branch of analyses concentrating on the technological specifics of material efficiency innovations, the materials involved and an accurate portrayal of production structures within the economy, to which studies carried out by Nathani (2003), Walz (2011), Ostertag et al. (2013) and Cooper et al. (2016) belong. These analyses are generally based on a bottom-up approach by looking at individual technologies and sectors, though most of them contain top-down representations of the overall economy. However, since most of these analyses use rather simple and mostly static IO models, macroeconomic dynamics are usually not well represented.

On the other hand, there is a branch of analyses concentrating on the macroeconomic dynamics resulting from material efficiency measures, normally with little attention to the nature of these measures and the materials involved. Studies by Meyer et al. (2007, 2012) belong to this branch. Within this branch, the impacts of material efficiency are assessed in a similar way to other policy interventions. The standard tool for this task are Integrated Assessment Models (IAMs), which usually contain a flexible macroeconomic core with various extensions for the analysis of different policy fields (e.g. Ciscar and Dowling, 2014). Even though IAMs are powerful policy support tools, their universal use has been criticized for being too indiscriminate, specifically in fields which possess many peculiarities, such as material flows in the industrial system (Pauliuk et al., 2017). Some IAM groups have therefore opted for constructing various extensions to the base models, most prominently in the case of the models E3ME (Barker et al., 2014) and GEM-E3 (Capros et al., 2017). However, for specific analyses such as the stock and flow dynamics of metal cycles, the coupling of detailed bottom-up and more aggregate top-down approaches is more flexible and can more easily capture the specifics of the system in question. The specifics of material efficiency as an intervention in the industrial system will be described in the following sections.

3.2 Theoretical considerations on Impact Assessment of material efficiency

Material efficiency as conceived here is achieved through the implementation of technologies which make a more efficient use of material inputs in production processes possible or increase the amount of material that can feasibly be recovered from unused anthropogenic stocks. The implementation of material efficiency technologies can be broken down into three core elements. The first is the capital investment necessary for the installation of a material efficiency technology, which can be represented by a macroeconomic investment impulse. Once installed, the efficiency technology has to be operated an maintained, which results in changed demand for Operation and Maintenance (O&M) services within the sector installing the technologies or from other sectors providing these services. Finally, changes in material demand due to the installation of the efficiency technology result in changed material flows throughout the economy. In sum, this yields the following macroeconomic impulses:

1. a change in investment demand, which accrues to investment goods producing sectors
2. a change in O&M demand, which accrues to sectors that provide these services to those sectors implementing the efficiency innovations
3. a change in demand for intermediate deliveries from material producing sectors

The combination of positive and negative impulses precludes immediate ex-ante conclusions on the direct effects on macroeconomic aggregates. In any case, structural shifts are likely to happen, generally benefiting sectors producing investment goods and disadvantaging sectors supplying the raw materials which are saved through the efficiency innovations. Indirect effects may also accrue to entirely different sectors, such as household services, due to the interconnectedness of the economy. The magnitude of all these effects on the national level is also dependent on the respective import shares of the affected sectors.

Each of these direct effects is accompanied by indirect effects in upstream industries as well as induced effects on overall economic activity. The relationship between direct, indirect and induced effects can be described according to a terminology by Breitschopf et al. (2013), which was originally developed for the assessment of employment impacts of renewable energy technology deployment, but is generally applicable. This terminology will be used henceforth.

Direct effects accrue to all economic sectors directly involved in the installation and O&M of the technologies. The use of new technologies also affects sectors not involved in investment and O&M. In the case of material efficiency technologies, this includes the suppliers of raw materials. The effects include changes in production, value added and employment in the affected sectors.

Indirect effects accrue to upstream sectors of the directly affected sectors through their interconnectedness in the production system, as portrayed by the intermediate deliveries matrix in IO tables (see Section 2.3.1). This includes those sectors that are indirectly affected by the new installations and O&M as well as those indirectly affected by replaced technologies and their O&M. In addition, upstream industries of the sectors directly affected by the technological change, e.g. through reduced material demands, also experience indirect effects.

Induced effects result from changes in aggregate production, with associated changes in income and thus consumption, which eventually affects all sectors in the economy. In addition, the investments have an impact on overall productivity, which in turn changes the theoretical production potential of the economy. These developments may also have an influence on international competitiveness and trade, thus inducing further effects on the overall economy.

From a modeling perspective, these effects can be conceptually divided into *exogenous* inputs, which lead to *endogenous* mechanisms in the model. Direct effects are a direct result of the exogenous inputs, which in this case consist of the three impulses listed above, investments, O&M and changed material flows. Indirect effects on upstream industries and induced effects then endogenously unfold within the model.

A further distinction of the macroeconomic effects of technology deployment in general is made between *gross* and *net* effects. In essence, gross effects do not contain a counterfactual perspective: only those industries directly or indirectly involved in or affected by an intervention such as material efficiency are considered, while other industries, which would have developed differently in the absence of the considered intervention or would have been affected by alternative interventions, are not covered. These industries and the upstream industries are in a sense also subject to direct and indirect effects, but not covered in the gross perspective. They are generally associated with existing technologies that may get replaced by the new technologies. For instance, in the realm of renewable energy deployment, it is commonly assumed that new conventional energy technology investments may at least get partially replaced by renewable energy technology investments (see, e.g., Duscha et al., 2016). The gross perspective also excludes induced effects, since these also accrue to industries beyond those involved in material efficiency. In contrast, net effects contain counterfactual and induced developments. They therefore represent the final state of the economy after all adaptation mechanisms have taken effect (Breitschopf et al., 2013). The entire set of effects described above is illustrated in Figure 3.1.

Other potentially important factors are the status of capacity utilization, the funding of the investments and price changes in the sectors which implement the efficiency technologies or the sectors which supply raw materials, as well as their associated macroeconomic effects. In a situation in which production capacities are not fully utilized, an increase in demand (e.g. in the form of investment goods) can be met without negative effects on other parts of the economy. This is not the case if production capacities are fully utilized and resources have to be shifted from one purpose to another.

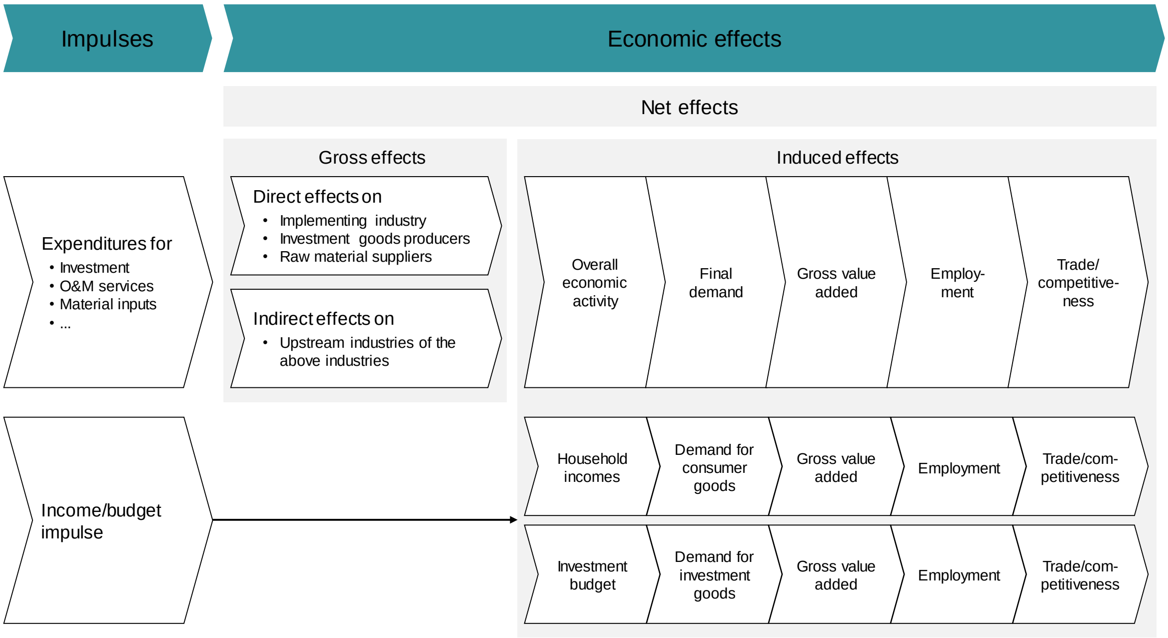


Figure 3.1: Illustration of impulses and economic effects, adapted from (Duscha et al., 2014, p.6)

A similar issue revolves around the funding of investments, which is already a contentious issue in macroeconomic modeling since it is inherently difficult to portray the financial sector in a comprehensive way. Mercure et al. (2016) and Pollitt and Mercure (2017) see the main issue of this debate in the extent to which investments in a new technology are assumed to 'crowd out' other investments that would have otherwise been made. Whereas (neo-classical) equilibrium theory assumes finite and fully utilized financial resources, non-equilibrium (e.g. Keynesian) theory assumes that financial resources can be freely created by banks and are therefore not inherently finite. In the former case, investment in new technologies is thus assumed to displace financial resources from other (actually optimal) uses by driving up the interest rate through increased demand for money. The demand-induced interest rate increase cannot be alleviated by expanding the money supply since the value of money decreases proportionally to the expansion, thus having no real effect on the economy. In the latter case this does not necessarily happen since new financial resources can be created if the demand for money increases and the planned investment is considered to be of acceptable risk and to provide adequate returns. This relationship can be complicated by the existence of knowledge spillovers from sectors which benefit from investments in efficiency technologies to other sectors. The crowded out sectors may indirectly benefit from spillovers, thus the crowding out effect is counteracted. A palpable example for this is investment in military Research and Development (Grubb et al., 2014).

The choice of underlying theory and the corresponding specification of the model can therefore have a considerable impact on modeling outcomes. In fact, in the related field of technologically induced CO_2 abatement, studies which use Computable General Equilibrium (CGE) models based on neo-classical theory generally arrive at less optimistic results, including negative ones, with respect to GDP and employment (e.g. Böhringer et al., 2013; Goulder and Schneider, 1999), though naturally there are also exceptions, depending on the type of policy intervention modeled (e.g. Fragkos et al., 2017). In contrast, studies which use models based on Keynesian principles generally predict more positive effects (e.g. Barker et al., 2015; Blazejczak et al., 2014; Duscha et al., 2016; Lehr et al., 2012).

Depending on the legislative and economic framework, price changes of raw materials and downstream products resulting from technology deployment can be positive or negative. Positive price changes can be expected if the implementation of the technology happens in response to, e.g., mandated efficiency standards accruing to all producers of a given product type. In this case, it is conceivable that the investment expenditures are directly passed on to consumers, who may then adapt their demand depending on their price elasticities of consumption. Alternatively, if prices cannot easily be passed on (for example because demand for a given product is highly elastic) firms must lower their dividend payments and/or investments. Each of these options would lead to a lower aggregate consumption or investment budget. A loss of competitiveness in the domestic market by the firms is in this scenario unlikely since the efficiency standards apply to all producers. However, international competitiveness might suffer if these standards are not adopted in other countries.

In the absence of economic/incentive based instruments, such as CO_2 taxes, technology mandates or mandatory efficiency standards, it is unlikely that measures are taken which increase the costs for producers. Firms would not invest in efficiency technologies if it did not pay off for them in the form of financial savings, and would thus have no rationale for raising prices. Therefore, if firms do invest in efficiency technologies in the absence of mandatory efficiency standards or policies changing fincancial incentives, it is likely that so-called “no-regret potentials” are present. They describe a situation in which previously unused efficiency potentials can be realized at no or negative net costs (Walz, 2011). While in pure neo-classical theory these no-regret potentials do not exist by definition, a more realistic view is offered by the wider literature, which identifies a number of reasons for their existence, such as the institutional settings of firms or behavioral obstacles (Ostertag, 2003; Bleischwitz, 2003; Bréchet and Jouvet, 2009; Walz and Schleich, 2009). Whether these savings then lead to negative price changes depends on the market situation. In perfect competition, the diffusion of the efficiency technology may force firms to eventually lower prices, though in the short to medium term they may remain unchanged. In a monopoly situation, the efficiency savings would remain with the firm and may be eventually paid out as dividends or get reinvested, all of which would leave prices unchanged (Berkhout et al., 2000; Pfaff and Sartorius, 2015; Saunders, 2013a). Effects on the prices of raw materials themselves based on changed material demands are unlikely to happen due to the (technological or geographical) specificity of material efficiency technologies with respect to the wider market. The efficiency technologies may only apply to a fraction of the uses of the target materials and thus not have a large potential to change overall prices. In addition – in the context of efficiency technology deployment – Germany plays a relatively unimportant role in global raw material markets and therefore may not induce large price developments. Prices may also not have a large effect on material demand in the form of material substitution, since the material-level substitutability[1] of many materials is limited. This is because industrial applications rely on very specific properties of the materials they employ, which can often only be approximated to limited degrees by substitutes. For instance, Graedel et al. (2013) discuss the substitutability of a set of raw materials for different uses in the context of the material basis of modern society. A number of high volume materials, including copper, lead and even iron, are characterized as presently having no good substitutes for their major uses. Materials used in technologically more advanced applications often have still lower degrees of substitutability, including titanium and other superalloy metals, as well as several platinum group metals and rare earth elements (Brunot et al., 2013; Graedel et al., 2013).

Material efficiency is therefore a field in which macroeconomic dynamics are more strongly determined by technology-induced effects in the economy than by behavioral responses to price developments. This implies that analysis tools with a detailed depiction of the demand side of the economy, including the interconnection of economic sectors, are better suited for the analysis of material efficiency than ones which focus on the supply side or supply-demand interactions without a detailed portrayal of the demand side. While capacity utilization and the funding of investments may be conceptually located on the supply side or supply-demand nexus, the implications for modeling can also be adequately portrayed by a demand centered approach (see Section 6.1.2).

3.3 Description of the main macroeconomic impulses and dynamics[2]

3.3.1 Investment

The first element in the implementation of material efficiency technologies consists of the necessary capital investments. Depending on their magnitude, these investments can have a considerable impact on the overall economy. However, as some commenta-

[1] A classification of different levels of substitutability is provided by Ziemann and Schebek (2010). The levels range from the level of individual materials, where the material itself is substituted by another one, over the functional level to the non-material level. Here it is referred to material-level substitutability.

[2] Part of this section has been published in an earlier version in Pfaff and Sartorius (2015).

tors note, they are often left out in impact assessments of efficiency measures, which leads to an incomplete picture (Dimitropoulos, 2007; Mizobuchi, 2008).

In studies which build on bottom-up data, the investments can be accurately portrayed in terms of absolute magnitude as well as the sectors delivering the investment goods. In the case of material efficiency, new production processes are often realized through the construction of a new production line, which mainly consists of new machinery and corresponding control systems. In monetary terms, the investment is split up between the relevant sectors and accrues to them as additional demand. At the same time, the investments also possess a material dimension in that their construction requires material inputs. Depending on the relationship between the magnitude of materials saved in the production process and the material requirement of the investment, this can theoretically have a noticeable effect on the net change of material demand of the efficiency innovation.

The efficiency technologies not only need initial investments but may also require replacement investments, which become necessary when the technologies wear down and finally get scrapped. This is especially important if the investment volumes are large and potentially have a large effect on the economy. At the same time, replacement investments change the shape of the investment trajectory, depending on the assumed lifetimes of the efficiency technologies (see Section A.7.1).

From a national accounting perspective, the outputs of the sectors which produce the investment goods are increased. Through the interconnectedness of all sectors, indirect effects ensue for those sectors which make intermediate deliveries to the directly affected sectors. This leads, ceteris paribus, to structural shifts within the economy. Since the additional investment demand not only accrues to domestic producers, the magnitude of the additional production per sector also depends on the respective sectoral import shares.

Theoretically, investment also "contributes to the future supply capacity of the economy" through the accumulation of capital and therefore also plays an important role beyond the short term (Fontana and Sawyer, 2016, p.187). It can therefore be understood as a link between the aggregate demand and the aggregate supply side of the economy. The supply side of the economy is in macroeconomic models often represented by abstract production functions, the most universal type being a Cobb-Douglas production function.[3] This type of function encompasses well the basic principle of production capabilities on an abstract level, where output is a function of the capital stock K, labor supply L and a factor describing the level of productivity a:

[3]The Cobb-Douglas production function is a special case of the more general type of Constant Elasticity of Substitution (CES) production functions. As the name suggests, these functions possess a constant elasticity of substitution between production factors – in the above case capital and labor (cf. Solow, 1956).

$$Y = aK^{\alpha}L^{\beta}; \quad \alpha + \beta = 1 \tag{3.1}$$

For simplicity, a is often assumed to be a combined indicator for all production inputs (in this case capital and labor), which is referred to as Total Factor Productivity (TFP). Productivity in relation to technological progress will be described in more detail in Section 3.3.4. The Cobb-Douglas production function possesses an elasticity of substitution of 1, which implies that the ratio of the production factors capital and labor equals the ratio of their marginal products. The exponents α and β are the output elasticities of capital and labor, respectively. They indicate the degree to which output changes in response to a change in the production factors and thus their respective contributions to output. In the above case, their sum is assumed to equal 1, which implies constant returns to scale of the combined production function. This means that an increase of both production factors by one unit leads to an equivalent increase in output.

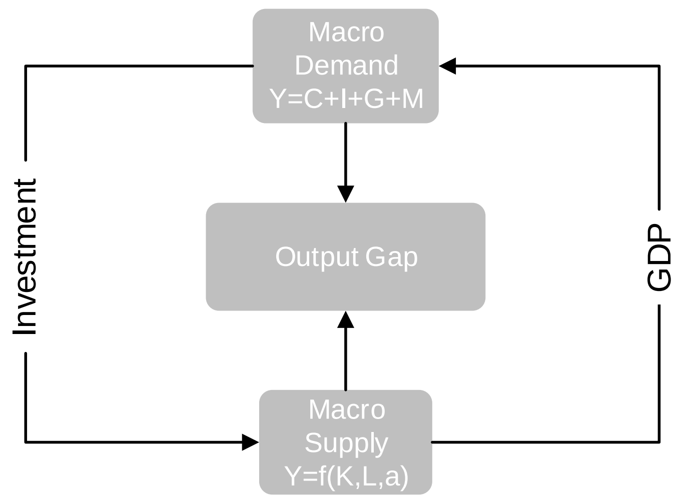


Figure 3.2: Simplified illustration of the demand-supply-interaction in the economy, based on Victor and Rosenbluth (2007, p.493).

The main insight to be gained from Equation 3.1, however, is the connection of aggregate output to investment through the capital stock, which is essentially the integral of investments less scrapped capital. Investments thus contribute to the expansion of the production potential of the economy. The supply side of the economy is therefore represented by a function indicating production capabilities based on production factors as well as the state of technology. While the development of the production factors is often assumed to be demand-driven in the short run, the supply side constitutes the necessary production potential of the economy, which is a determinant of the long run development of the economy (Davidson, 2011). The interplay of the supply and the demand side is roughly illustrated in Figure 3.2.

3.3.2 Operation and maintenance

The operation and maintenance impulse accrues to sectors which provide these services to those sectors implementing the efficiency innovations. To some extent, O&M services may be provided within the sector implementing the efficiency innovation itself, while the exact distribution of the O&M impulse across that and other sectors depends on the extent to which the technical details of the innovation are known. Even though the services are provided to other sectors in the form of intermediate deliveries to the sectors implementing the efficiency technology, the production "recipe" of the latter sectors does not necessarily change. The impulse for the affected sectors can therefore simply be portrayed as an increase in final demand for the services of these sectors. Similar to the increase in investment demand, this also has an effect on upstream sectors and raises aggregate production.

3.3.3 Material flows

The main aim of the implementation of material efficiency technologies is the reduction of material requirements of production processes, which result in changed material flows throughout the economy. The altered production processes may not only involve decreased material demands since the demand for some materials may actually increase, for example in the form of substitute materials. Thus, negative as well as positive changes in material flows have to be considered. In addition to these process-related positive changes in the demand for some materials, the investments in efficiency innovations also involve new material demands, as outlined in Section 3.3.1. The magnitude of these material demands depends on the material intensity of the investments. However, Ostertag et al. (2013) for example find that these material demands are relatively low in comparison with the materials saved in the new production processes. In this case, and if no significant increases in the demand for other materials is present, the aggregate change in material demands constitutes an overall negative impulse on the economy. The impulse only partially accrues to the domestic economy since a part of the material demand is satisfied through imports. From a national accounting perspective, the changed material flows can be understood as alterations to sectoral demand for materials, which influence the exchange between production sectors and thus the intermediate input coefficients. These direct demand alterations also cause indirect effects, and eventually induce further macroeconomic developments.

Three broad cases of the implementation of material efficiency technologies are conceivable. In the first, the efficiency technology is implemented in a specific production sector, e.g. machinery, so that the uniform production process employed in this sector requires less of a given material. This results in a reduction of intermediate deliveries from material producing sectors to the material demanding sector (e.g., to remain with the above example, from non-ferrous metals to machinery). In the second case, a universal material efficiency technology is developed and subsequently implemented in all sectors directly using raw materials (or a specific raw material). For instance, Meyer et al. (2012) run macroeconomic simulations based on a technical consulting study by Fischer et al. (2004). They estimate that the manufacturing part of the economy has a theoretical efficiency potential of 20 %. This would imply an even reduction of material demands across all material processing sectors. The third case is not a more efficient use of materials per se, but an increase in the availability of secondary material which allows for a reduction of primary material demand. In this case, the material savings cannot be allocated to individual material using sectors but have to be treated as an overall reduction in primary demand. An example of this will be seen in the simulation of economy-wide material flows below.

3.3.4 Technological progress

In addition to the effects discussed above, the technology investments potentially also have a lasting effect on productivity and overall technological progress. However, these effects are of a more abstract nature and therefore difficult to model. The following discussion outlines the theoretical basis for a formal treatment of technological progress.

While no specialized literature exists on the effects of material efficiency on technological progress, some general conclusions can be drawn from related discussions. There is a large body of literature in the (neo)classical tradition dealing with economic growth and technological progress in general. Two broad branches can be distinguished: theories treating technological progress as exogenous and theories treating it as endogenous. The major representatives of the first branch are Solow (1956, 1957) as well as Harrod (1948) and Domar (1947), while the most well known examples of endogenous growth theories were presented by Romer (1990) and Aghion and Howitt (1992).

In a modeling context, several concrete macroeconomic variables are conceivable as drivers of technological progress. Next to investments (in the form of yearly flows), the physical capital *stock* has been proposed as a determining factor of technological progress (Palley, 1996). Löschel (2002) describes a model based on Lee et al. (1990) in which technological progress is in a recursive relationship with investment and Research and Development (R&D) expenditures. However, in the context of material efficiency technology deployment, the most direct clue to technological progress lies in the investments necessary to implement the efficiency innovations. While the earliest growth theories did conceive of investments as a driver of technological progress, at the latest Solow (1956) has shown that capital buildup by itself can at best lead to a steady state under continuous population growth. This happened in conjunction with a conceptual separation between investment and technological progress (Scott, 1989). However, Scott (1989) and already Kaldor (1957) challenge this separation on the grounds that "technical progress cannot take place without a change in economic arrangements" (Scott, 1989, p.94). These "economic arrangements" constitute a multitude of factors which influence output, and investments are conceived of as the cost of changing the arrangements. Investments thus contain technological progress in two ways: they "realize" and "reveal" it. Therefore, "investment serves simultaneously as the means of expanding the capital stock, feeding technical innovations into the production process and uncovering further possibilities for innovation" (Palley, 2002, p.28).

3.3.5 Feedbacks from the economic to the physical level

The economic effects of the material efficiency technology deployment described above ultimately cause feedback effects on the physical level. Depending on the interplay of the economic effects, changes in material demand may ensue which amplify or counteract the technical savings originally generated by the efficiency technologies. The observed material savings may thus diverge from the technical savings potential of the efficiency technologies. If the observed absolute material savings are lower than the potential material savings, the effect is labeled under the umbrella term "rebound effect". The rebound effect turns into a so-called "backfire effect" if the material savings are more than offset, i.e. if material efficiency measures eventually lead to an absolute increase in material demand as opposed to a decrease. On the contrary, if the savings are higher than projected, the rebound effect is negative – a situation which is called "super conservation".

Generally speaking, positive economic effects lead to re-increases in material demand and therefore have the potential to cause rebound or backfire effects, while negative economic effects further reduce material demand, potentially inducing super conservation. However, since several impulses and economic mechanisms are at play, multiple effects are superimposed, making it difficult to predict total effects. In order to provide a full picture of the ultimate physical effects of material efficiency measures it is thus necessary to incorporate the economic layer in the analysis of material efficiency.

Useful overviews of the rebound effect and related concepts can be found in Maxwell and McAndrew (2011); UKERC (2007); Dimitropoulos (2007). According to the simplest definition, the rebound effect can be calculated by comparing the actual material savings (in this case the model results) to the potential material savings as defined in technology-based scenarios (Guerra and Sancho, 2010):

$$r = 1 - \frac{m^o}{m^p} \tag{3.2}$$

where r is the relative rebound effect, m^o are the observed and m^p the potential material savings.

A broadly accepted typology of rebound effects differentiates between direct, indirect, and economy-wide, though slight variations exist (Barker et al., 2009; Maxwell and McAndrew, 2011). If a specific good or service (e.g. transport) has become more efficient in its use of input i, the direct rebound effect describes the additional demand for this good or service, including its use of i, induced by the efficiency measure. The indirect rebound describes the additional demand for other goods or services, which also use i as an input. Finally, the economy-wide effect describes the changes in aggregate demand and required i resulting from a number of changes in the economy as a whole. The borders between these effects are somewhat fluid; indirect and economy-wide effects have a considerable degree of overlap. In the following the term "economy-wide rebound effect" is used when changes in the whole economy take place which influence demand for i. Within this categorization, the causes for rebound can be divided into income, substitution and growth mechanisms.[4] In the first case, the efficiency measure leads to an absolute increase in income with a resulting increase in resource demand. In the second case, the relative attractiveness of a given resource increases due to the efficiency measure and subsequent price adaptations. Growth effects can cause rebounds if the efficiency measure generates an aggregate growth impulse, for instance through investments, which subsequently increases resource demand.

The majority of the empirical literature on rebounds, including recent publications, has analyzed rebound effects of energy efficiency measures (de Haan et al., 2007; Dimitropoulos, 2007; Sorrell, 2009; Sorrell and Dimitropoulos, 2008; Saunders, 2000, 2013b; Turner, 2009; Thomas and Azevedo, 2013b,a; Guerra and Sancho, 2010; Borenstein, 2013). Only few studies have so far analyzed such effects for resources other than energy (Saunders, 2014; Meyer et al., 2007, 2012; Takase et al., 2005; Kok et al., 2006), while only Saunders (2014) has highlighted the importance of giving raw materials a more prominent role in rebound analysis and laid some theoretical foundations of raw material rebound effects. This is not surprising in light of energy being a universal input, which fosters comparability.

Different modeling approaches have been used so far to assess rebound effects of energy efficiency, with the state-of-the-art being coupled energy-environment-economy models based on a macroeconometric core (Barker et al., 2009) or on a computable general equilibrium (CGE) framework (Turner, 2009; Guerra and Sancho, 2010). In the case of materials, to the author's knowledge, only Meyer et al. (2007, 2012) have used a complex modeling approach, which takes various economic mechanisms into account. However, they neither account for the specific effects of material-efficient technologies nor for expenditures necessary for bringing about the efficiency improvements and their sectoral impacts. Instead, they take a top-down approach and make scenario-based global assumptions on efficiency improvements (see Section 3.3.3).

[4]While according to the Slutsky equation, income and substitution effects are the two components of price effects, we do not presume explicit price changes, as will be seen later. Instead, we posit that an implicit income effect independent of a price change can be present for a material if its use in a production process becomes more efficient.

3.4 Conclusions

This chapter outlined the rationale for Impact Assessment as a policy support tool and identified the specific characteristics of material efficiency to be considered when performing an IA in this context. For this, the three most important macroeconomic impulses ensuing from the deployment of material efficiency technologies were identified and discussed with respect to their implementation in a computer model. These impulses are the capital investments in material efficiency technologies, operation and maintenance expenditures for the upkeep of these technologies, and altered material flows between economic sectors. The macroeconomic effects ensuing from these impulses were classified into direct, indirect and induced effects. While direct effects may be relatively easy to predict, indirect and induced effects cannot be adequately captured without a suitable model setup. Such a model setup ideally combines the technological detail of bottom-up analyses with the systemic perspective of top-down approaches. Because macroeconomic dynamics in response to material efficiency measures are more strongly determined by technology-induced effects than by behavioral responses to price developments, a demand centered modeling approach is better suited for the IA of material efficiency. Other factors determined by the interaction of supply and demand can nevertheless be adequately captured in a demand centered model setup.

The insights from this and the previous chapter informed the development of the macroeconomic simulation model, ISI-Macro, which will be described in detail in the following chapter.

4 Model development and coupling[1]

In this chapter, the modeling tools and the data used for the empirical analyses are described. Section 4.1 provides a short description of a substance flow model for copper within Germany, which has been co-developed in this thesis based on previous work on the global and European level (Glöser et al., 2013; Soulier et al., 2018a). The newly developed macroeconomic simulation model, ISI-Macro, is described in Section 4.2. It contains a dedicated material module, which is described in Section 4.3. The first part of that section describes an aggregate material sub-module, which is used for the analysis of material efficiency scenarios. This part also serves as a mathematical description of MRIO analysis, with which the analysis of past material consumption in Germany is carried out in Chapter 5. The second part of the section describes a sub-module that connects the economic model with the copper flow model. This sub-module is used for the analysis of stock and flow dynamics within the copper cycle. Conclusions on the development of the simulation model and the material module in particular are presented in Section 4.4.

4.1 Substance flow model for copper

Anthropogenic metal cycles have been described in various ways, ranging from simple static descriptions to complex dynamic models (see Chen and Graedel (2012) and Müller et al. (2014) for overviews). The substance flow model for copper used in this thesis is a newly co-developed German version of a preexisting branch of dynamic models implemented in an SD environment. It builds upon previous work on global and European copper flows with respect to the modeling approach (Glöser et al., 2013; Soulier et al., 2018a). Within this thesis, material flow and trade data was collected for Germany. Together with structural information from the European model, this data serves as the empirical basis for the German model (a more detailed description of the data collection steps is provided in Section 4.3.2). In addition to data collection, structural changes were made to the model within this thesis. These changes are outlined in the scenario descriptions in Section 6.2.1.

As commonly realized in substance flow models, the supply chain in the present model is separated into refined copper production, fabrication of semi finished goods, manufacturing of end-use products and finally waste management and recycling (cf. Graedel et al., 2002). The general structure of the copper flow model for Germany,

[1]Part of this chapter has been published in an earlier version in Pfaff et al. (2018).

including major input data, is shown in Figure 4.1; a more detailed version can be found in Section A.2 in the Appendix.

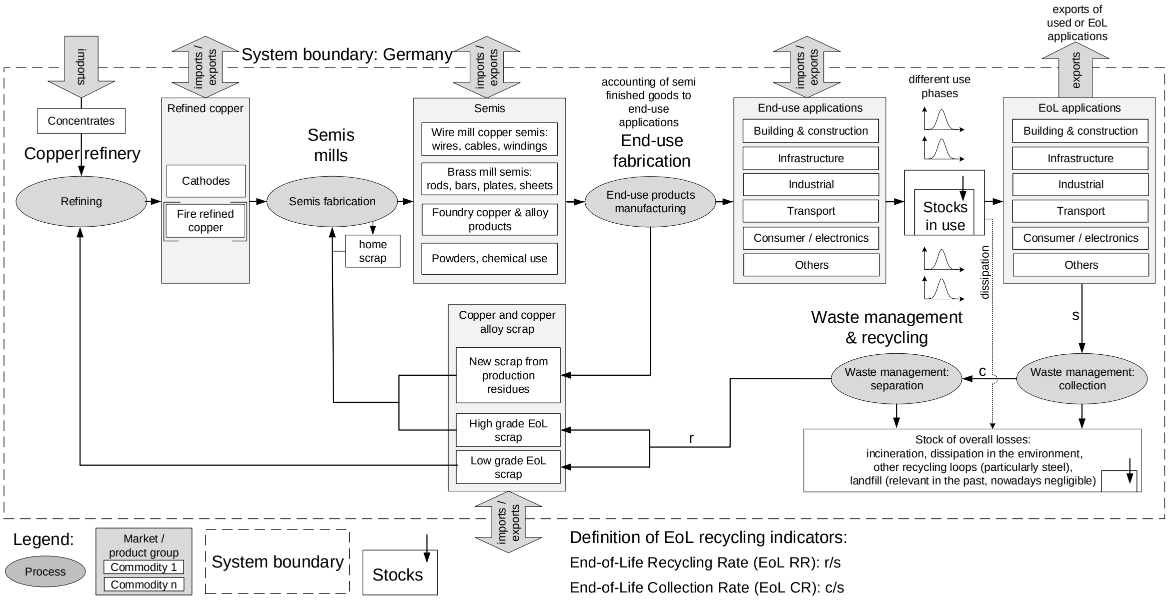


Figure 4.1: Structure of the copper substance flow model for Germany

The copper cycle starts with the production of refined copper from concentrate and/or scrap, which is followed by the production of semi-finished goods, where four broad types are distinguished. Like copper refinement, the production of semi-finished goods is also partly supplied by copper scrap. The semi-finished goods are then processed into end-use products.[2] A small fraction of the copper contained in semi-finished goods which enters the fabrication process of end-use goods becomes so-called new scrap (through cutting, trimming, shaping etc.). This new scrap is usually directly remelted in semis mills or by ingot makers which supply the semis fabricators, and thus enters the recycling stream. A total of 16 different end-use categories are distinguished, ranging from plumbing to electronic applications (see Table 4.1 for an overview of semi-finished and end-use goods). The semi-finished goods are allocated to end-use products with the help of a data set provided by the International Copper Association (ICA), which is described in more detail in Section 4.3.2.

Different lifetimes are assigned to the end-use categories in order to be able to differentiate between different stock accumulations. These lifetimes can either be implemented as simple averages or as lifetime distributions in the form of probability density functions, assuming that a certain number of products get scrapped before or after

[2] The term “end-use” in this case indicates that the copper contained in these products does not undergo further transformations itself. However, the products may go through several more stages of the supply chain and are therefore not to be mixed up with final use products, which satisfy the different final demand categories as defined in national accounts.

Table 4.1: Semi-finished and finished products containing copper

Semi-finished product categories	Finished product categories
Wire Mill	Architecture
Brass Mill Copper	Consumer Products
Brass Mill Alloy	Cooling
Foundry	Diverse
	Automotive Electrical
	Industrial Electrical
	Electrical Power
	Electronic Use
	Automotive Non Electrical
	Industrial Non Electrical
	Other Transport
	Powder Use
	Power Utility
	Telecommunication Use
	Building Plant
	Plumbing

they reach the average lifetime of the respective product category. The main assumptions regarding lifetime distributions and processing efficiencies of different end-use applications are summarized in Table A.1 in the Appendix. The simplest form of such a lifetime distribution is a normal (or Gaussian) distribution. In an SD framework, this can be realized through a delay function between the inflow of a product stock (production) and its outflow (scrapping). The total scrap level per product category is then the sum of all lifetimes multiplied by their respective likelihoods.

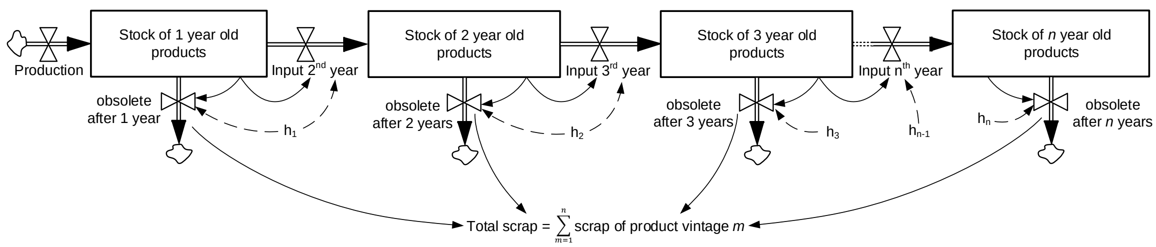


Figure 4.2: Illustration of an aging chain implemented in Vensim

This way of modeling the aging process of products does not allow for a distinction between different product vintages, which may possess different characteristics, e.g. regarding material composition or durability. The latter may have an effect on product lifetimes, which then has to be adapted in the model for each product generation with higher durability (this is explored in more detail in Section 6.2.1). In order to implement this in a dynamic model, so-called aging chains can be used which portray each product vintage separately. Products of a certain vintage can thus take two paths, depending on the likelihood of failure: they can either enter the next vintage or reach the end of their lifetimes. The likelihood of failure (and thus the end of the lifetime) of each product vintage can be calculated from the lifetime distributions (see Section A.2 in the Appendix). The general principle of an aging chain is illustrated in Figure 4.2.

Formally, the entire aging chain can be represented by the following equation:

$$S_{t,n} = S_{t-1,n} + I_{t-1,n} - O_{t-1,n} - A_{t-1,n}; \quad n = 1, \ldots, m \tag{4.1}$$

where S is the stock, I the inflow, O the end-of-life outflow and A the outflow into the next vintage n, all at time t. In expanded form, this yields:

$$\begin{aligned} S_{t,1} &= S_{t-1,1} + P_{t-1} - O_{t-1,1} - A_{t-1,1} \\ S_{t,2} &= S_{t-1,2} + A_{t-1,1} - O_{t-1,2} - A_{t-1,2} \\ &\vdots \\ S_{t,m} &= S_{t-1,m} + A_{t-1,m-1} - O_{t-1,m} - A_{t-1,m} \end{aligned} \tag{4.2}$$

where P is the domestic and imported production of end-use products. Note that the inflows into the stocks differ between the first and the successive vintages at any given point in time since only the first vintage is actually produced whereas the successive vintages feed from the preceding ones:

$$I_{t-1,n} = \begin{cases} P_{t-1} & \text{for } n = 1 \\ A_{t-1,n-1} & \text{for } n > 1 \end{cases} \tag{4.3}$$

The end-of-life outflow in each period is the fraction of the stock of a given vintage which gets scrapped in that period. This fraction depends on the failure rate h. The remainder of the stock moves on to the next vintage:

$$O_{t,n} = S_{t,n} \cdot h_{t,n} \tag{4.4}$$

$$A_{t,n} = S_{t,n} \cdot (1 - h_{t,n}) \tag{4.5}$$

Once the end-use products reach the end of their lifetimes, they get scrapped and a fraction of them gets recycled. As stated above, the recycled scrap either enters the refining process or goes into the production of semi-finished goods as direct melt. The recycling of scrap for copper production thus closes the copper cycle.

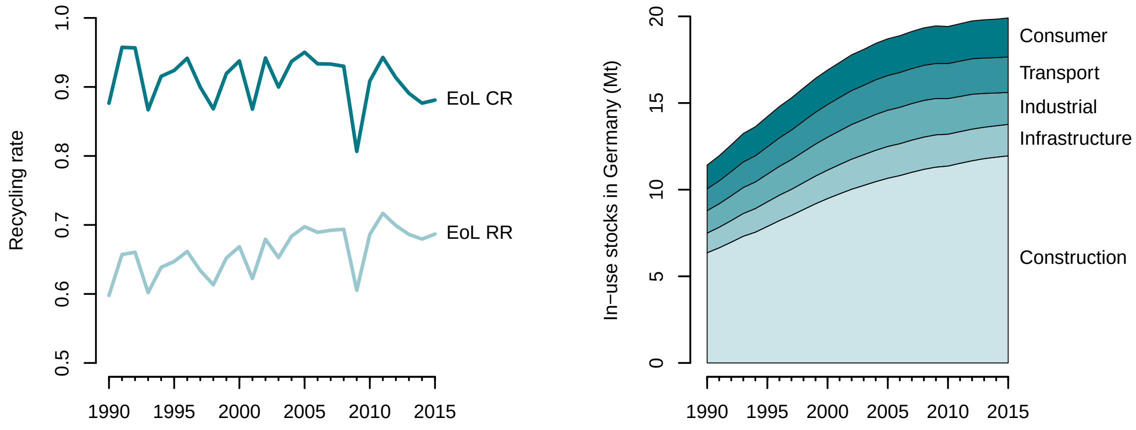
The model simulates the copper cycle from 1950 on in order to accurately portray the accumulation of current in-use stocks and the development of waste flows. This long time period is necessary as several applications, particularly in the building and construction area, have use phases of around 50 years with comparatively broad distributions (Spatari et al., 2005; Ciacci et al., 2017; Maung et al., 2017, see also Table A.1 in the Appendix).

At each step in the supply chain, copper and copper containing products are traded. The net copper contained in these trade flows is taken into account using data from the UN Comtrade database (United Nations, 2017), a list of copper contents of products based on Wittmer (2006), and an in depth-analysis of copper trade flows across world regions by Tercero Espinoza and Soulier (2016). Since no copper ores are mined in Germany, primary refined copper production is entirely based on concentrate imports, mainly from Chile. Next to copper concentrates, low grade and partly contaminated copper and copper alloy scrap serve as input material to the refining process, which consists of different furnace stages (shaft furnace, converter and anode furnace) and subsequent electrolytic refining.

Both the historical total amount of primary refined copper production and the total semi-finished goods production are well documented. New scrap flows are calculated based on assumptions on different processing efficiencies in end-use goods production (Ruhrberg, 2006). The annual flow of secondary copper from End-of-Life (EoL) scrap can therefore be calculated by subtracting primary copper production and new scrap from total copper use. This flow can in turn be used to calculate the collection rate of EoL scrap by comparing the theoretically available copper scrap from EoL products with the used EoL scrap in secondary copper production, thereby closing the mass balance. Copper is a special case with respect to recycling. The scrap of other industrial metals, such as steel or aluminum, is only directly remelted and hence a certain contamination and downcycling of secondary materials is inevitable. In the case of copper, low grade scrap is reintroduced to the converter or anode furnace and subsequent electrolytic refining gives secondary material the same quality as primary refined copper (Lossin, 2003).

Initially, the substance flow model is used as a retrospective tool in order to get a clear understanding of current stocks in use, EoL material flows and the respective recycling efficiencies based on mass balance calculations. Subsequently, these indicators serve as reference inputs for prospective simulations. The calculated recycling indicators and accumulated material stocks for Germany are the most important reference values derived from the retrospective simulation of the copper cycle. Their development from 1990 to 2015 is shown in Figure 4.3. The definitions of the recycling indicators are included in Figure 4.1.

The EoL collection rate (EoL CR), which excludes material losses due to exported used products (this is particularly relevant for electronic equipment and EoL vehicles) is estimated to be slightly above 90% on average over the simulated time frame, with relatively strong fluctuations due to volatility in production volumes and the concept of a closed mass balance over time (see Glöser et al., 2013; Soulier et al., 2018a, for



(a) Recycling rates

(b) In-use stocks

Figure 4.3: Recycling rates and copper stocks for Germany, model results

a detailed description of the methodology). Because of inefficiencies in the recycling process, the average EoL recycling rate (EoL RR) is lower at around 66% (see Figure 4.3a). The similarity of the two curves indicates a relatively constant recycling efficiency over the simulation period.

The calculated stocks in use for Germany (as shown in Figure 4.3b) are currently stagnating at a level of around 20 Mt, which equals about 240 kg per capita. This is significantly above previous estimations for the EU average stock of around 180 kg/capita (Ciacci et al., 2017; Soulier et al., 2018a). However, due to the comparatively high level of industrialization in Germany and well established infrastructure the simulated per capita stock level for Germany appears reasonable. It is also in the range of stock estimations for other industrialized countries. For instance, Wittmer and Lichtensteiger (2007) estimate for Switzerland a range of 175 to 265 kg/capita in the year 2000, and Gordon et al. (2006) estimate the copper stock in the US in the same year at around 240 kg/capita.

4.2 Macroeconomic simulation model ISI-Macro[3]

The macroeconomic simulation model developed in this thesis, ISI-Macro, is loosely based on ASTRA (ASessment of TRAnsport Strategies), a family of macroeconomic simulation models on the European level, which are implemented in System Dynamics and were first introduced by Rothengatter et al. (2000). As the name indicates, ASTRA was originally developed for the Impact Assessment of transport strategies and therefore possesses detailed transport modules next to a macroeconomic core and aux-

[3]Part of the model description has been published in the supplementary material to Sievers et al. (2019).

iliary modules. This macroeconomic core follows national accounting conventions and portrays the demand side of the economy through an input-output module, whereas the supply side is portrayed through an aggregate Cobb-Douglas[4] production function. For the calculation of GDP and other macroeconomic indicators, the supply and the demand side are brought together and balanced. Detailed descriptions of ASTRA can be found in Schade (2004) and Krail (2009).

ISI-Macro deviates in a number of respects from ASTRA. It was primarily designed for the Impact Assessment of technical material efficiency measures[5] in Germany and therefore does not contain any transport or related modules. At its core is a dynamic input-output module consisting of 72 production sectors[6] as defined in the current German sector classification, WZ 2008, which is based on the European NACE Rev. 2. classification (Destatis, 2008). This is more detailed than the European version of ASTRA, which only contains 25 production sectors based on NACE/CLIO, a precursor of the NACE Rev. 1.1 classification (OECD, 2005). A more detailed structure is especially important in the context of the analysis of sectoral material flows and technology-specific material efficiency measures.

Unlike open quantity models, final demand is not exogenously given but calculated endogenously within the model. Final demand drives sectoral production, which then determines the different components of Gross Value Added (GVA), i.e. compensation of employees (= wages and salaries), taxes on production less subsidies, capital depreciation (= consumption of fixed capital) and net operating surpluses (= net profits). According to the circular logic of the economy, these components in turn determine the levels of the final demand components which remain within Germany, i.e. private and government consumption, equipment and building investments. Exports (as another component of final demand) are determined by exogenous projections of the average GDP of the Organisation for Economic Co-operation and Development (OECD)-countries and China, which make up the majority of German export destinations (OECD, 2014). The supply side of the economy is not explicitly portrayed by the model. Its main focus are structural shifts in the economy arising from demand-side changes. Supply-side effects, such as productivity gains, do not endogenously emerge but have to be fed into the model in the form of exogenous data. The model is calibrated to match OECD long term projections of German GDP up to the year 2060 (OECD, 2014). This implies an exogenous inflation-adjusted growth trend of about 1.1% p.a., which also determines the rate of growth of final demand. The basic structure of the model is illustrated in Figure 4.4.

The links between the components of gross value added and final demand are portrayed in individual modules according to the principles of national accounts. The

[4]See Section 3.3.1 for a short description of the Cobb-Douglas production function.

[5]A separate branch of the newly developed model focuses on the IA of renewable energy sources. The core of this version has been developed in parallel to the present version, but contains modules dedicated to renewable energy instead of materials (cf. Sievers, 2019).

[6]A full list of the production sectors is provided in Section A.6 in the Appendix.

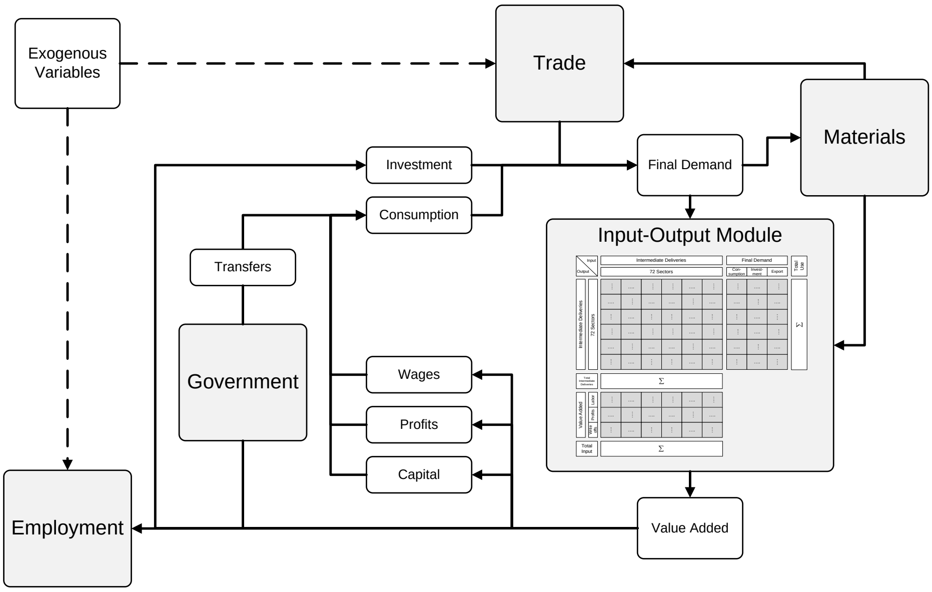


Figure 4.4: Simplified structure of the macroeconomic simulation model

mechanisms behind these links are explained in more detail in the module descriptions in the following sub-sections.

4.2.1 Final Demand

The model follows national accounting conventions. Final demand is thus defined as the sum of domestic private consumption, investments, government consumption and exports.[7] The different components of final demand are defined for each of the 72 sectors in the model. Unless stated otherwise, the vectors and matrices describing economic variables in the model always have 72 or 72x72 entries, respectively. As above, the notation follows the conventions of matrix algebra, where matrices are denoted as bold upper-case letters, vectors as bold lower-case letters and elements as simple lower-case letters. The indices i and j are used to denote sectors along rows and columns, respectively. For better readability, the time index t is mostly left out, except when it is relevant to make a distinction between different time periods. Final demand is thus calculated in the following way:

$$\boldsymbol{y} = \boldsymbol{c} + \boldsymbol{i} + \boldsymbol{g} + \boldsymbol{m} \tag{4.6}$$

where $\boldsymbol{y}$ = vector of domestic final demand, $\boldsymbol{c}$ = vector of domestic private consumption, $\boldsymbol{i}$ = vector of domestic investments, $\boldsymbol{g}$ = vector of domestic government

[7] IO tables usually contain an additional balancing term called ‘net additions to stock’, which is left out in the model.

consumption and $\boldsymbol{m}$ = vector of domestic exports. The individual components of final demand are calculated in separate modules which will briefly be explained in the following.

Private consumption

Sectoral private consumption at basic prices is calculated based on households' disposable income and a sectoral consumption split:

$$c_i^{bp} = (y_h - sy_h) \cdot \delta \cdot \sigma_i \tag{4.7}$$

where:
c_i^{bp} = private consumption at basic prices per sector i
y_h = household income
s = savings rate (constant)
δ = conversion factor from purchaser prices to basic prices (constant)
σ_i = split factor to split total consumption into sectoral consumption

This way of calculating sectoral consumption implies a supposed income elasticity[8] of 1 for the products of each sector, which appears to be a reasonable general assumption, seeing that income elasticities "tend to cluster around 1" (Varian, 2006, p.281). This assumption may on the other hand appear problematic for goods and services which are far away from being so-called "normal goods", such as necessary goods (positive income elasticity < 1), superior or luxury goods (income elasticity > 1) or inferior goods (income elasticity < 0). However, at the sectoral aggregation level used in the model, the conventional logic behind elasticities does not necessarily hold. For instance, basic (including inferior) foodstuffs are in the same sector as luxury food, making it difficult to define a combined income elasticity. In fact, a look at historical elasticities[9], i.e. percentage changes in sectoral consumption divided by percentage changes in disposable income, reveals a wide range of values for a number of sectors, including food. The elasticities for the period from 1995 to 2007[10] are shown in

[8] The income elasticity of demand can simply be defined as the percentage change of the quantity demanded of a certain good in response to a percentage change in income: income elasticity of demand = $\frac{\text{\% change in quantity}}{\text{\% change in income}}$ (Varian, 2006, p.281).

[9] The elasticities displayed here are in fact historically observed sectoral consumption changes that happened at the same time as income changes. Their calculation methodology did not control for changes in other variables, such as price changes. They are therefore not a perfect measure of sectoral demand changes associated with changed incomes but are rather intended to serve as a rough indicator of income-consumption dynamics.

[10] Since 2008, the new sector classification WZ 2008 is used in German economic statistics, which rearranged a number of sectors compared to the preceding WZ 2003 classification. For the model inputs, the historical data (in WZ 2003) has been converted to this new classification with a conversion matrix, which was devised based on employment and input-output data recorded in both classifications (Destatis, 2006, 2014b; Eurostat, 2015a, see also Section A.9 in the Appendix).

Figure 4.5. The gray dashed line in this figure indicates the value 1, i.e. perfect income elasticity, the black dashed line indicates the value 0, i.e. perfect inelasticity. It can be seen that especially some of the fossil fuel sectors have a large range of values. In the top left of the figure, the whiskers of the coke and mineral oil box are cut off for better visibility; they would reach up to approximately 45 and down to -45. Figure 4.5 also shows that some sectors possess average elasticities below 0, which indicates inferiority of these products, i.e. with higher incomes less of these products are consumed. This is not necessarily plausible for all of the products concerned.

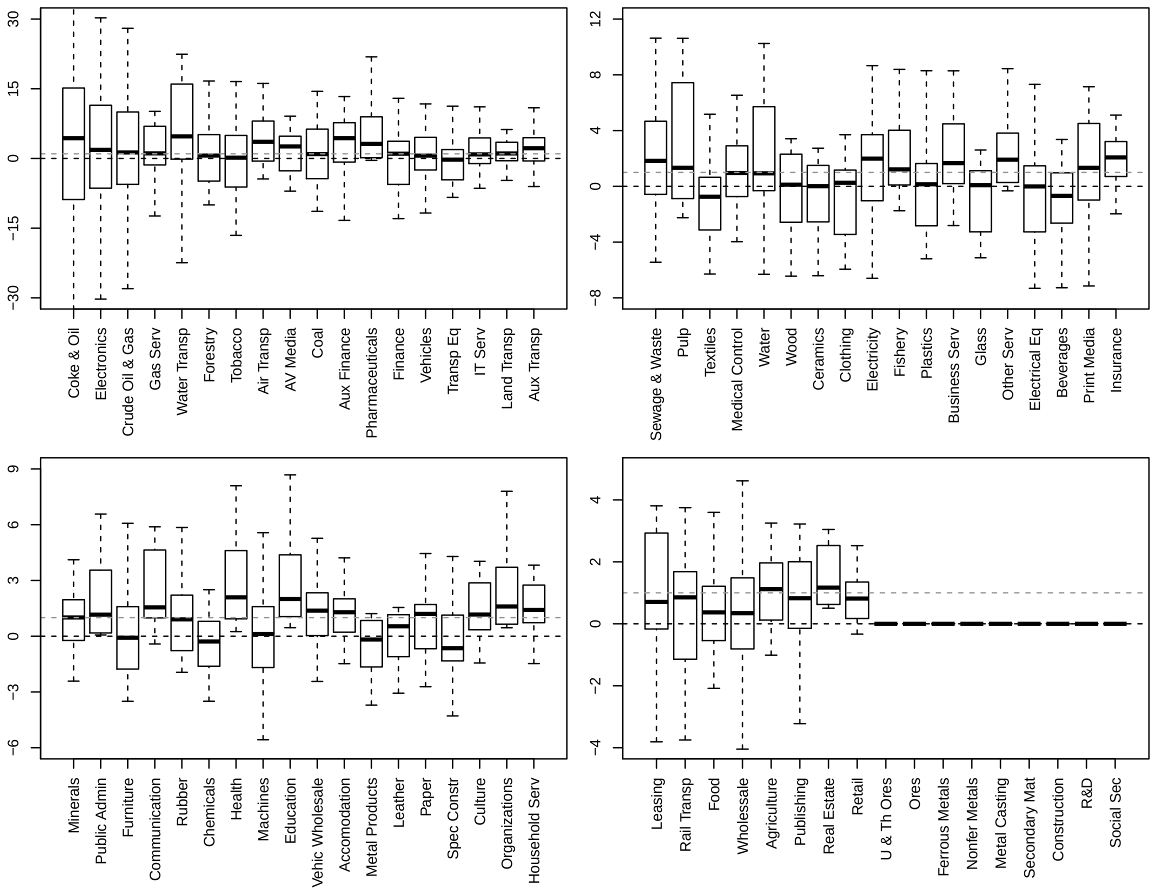


Figure 4.5: Boxplot of sectoral income elasticities of consumption; the dashed lines mark the values of 0 and 1, respectively; own calculation based on data from Destatis (2010b, 2016b)

Part of the large variations in income elasticities may be due to the omission of other factors, such as price elasticities and overarching price effects in the quantity

Even though the conversion works well for most sectors, minor breaks appear between 2007 and 2008 as a result of the conversion. For this reason, only the period from 1995 to 2007 is used for the comparison of elasticities. The 71 sectors are denoted in the original WZ 2003 classification and therefore deviate from the sectors in other parts of this thesis.

model (which cannot distinguish between quantity and price variations in reported data, see Section 2.3.1). Including price effects may reduce the variance of income elasticities. However, no official statistics contain detailed time series of sectoral price data; they can therefore not be included in the above analysis. At the same time, unlike equilibrium models, the present macroeconomic model does not endogenously portray price developments. It therefore appears reasonable to make the simplifying assumption of perfect income elasticities for the products of all sectors.

The domestic portion of consumption is then calculated with a constant split factor ϕ indicating the share of domestic consumption per sector i in overall consumption:

$$c_i^{bp,dom} = c_i^{bp} \cdot \phi_i \tag{4.8}$$

The imported portion of consumption is analogously calculated in the following way:

$$c_i^{bp,imp} = c_i^{bp} \cdot (1 - \phi_i) \tag{4.9}$$

Investment

The overall level of investment is calculated based on total gross value added v:

$$i = \theta \cdot v \tag{4.10}$$

where θ is a constant fraction indicating the magnitude of investment relative to GVA and v is the sum of sectoral GVAs:

$$v = \sum_{i=1}^{72} v_i \tag{4.11}$$

The share of investments delivered by each sector is determined through a constant split factor ρ.

$$i_i = \rho_i \cdot i \tag{4.12}$$

Since no reliable information is available on the distribution of sectoral investment demands, such a top-down allocation of investments is necessary. So-called investment matrices match sectoral outputs with demand for investment goods coming from different sectors. However, no current investment matrices are available for Germany.

Government consumption

Government consumption is portrayed simply as a fraction ψ of total GVA v. Even though other factors influence government spending, these are difficult to capture in a macroeconomic model. Therefore the simplifying assumption is made that government consumption roughly follows the overall performance of the economy as measured through aggregate gross value added.

$$g_i = \psi_i \cdot v \tag{4.13}$$

Exports

The calculation of exports is based on the assumption that the main driver of one country's or region's exports is the economic performance of the regions importing goods from that country or region.[11] The main regions in the world to which Germany exports its goods are the OECD countries and China. Since their economic development is not part of the present model, an exogenous growth trend for these countries provided by the OECD (2014) is used. The OECD growth projections are at the level of country GDPs, so only aggregate export values can be derived from them. An overall export level per year m is thus first determined and then split up into sectoral exports m_i according to a fixed split factor μ:

$$m_i = \mu_i \cdot m \tag{4.14}$$

4.2.2 Input-output module

The IO module is structured around the three quadrants of IO tables, i.e. the intermediate deliveries matrix (I), final demand (II) and gross value added (III). According to the standard logic of quantity models, final demand determines gross output through the interconnection of economic sectors as expressed in the intermediate deliveries matrix (see Section 2.3.1):

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \tag{4.15}$$

where $\boldsymbol{x}$ is gross output, $\boldsymbol{y}$ is final demand and $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the inverse coefficient matrix and $\boldsymbol{A}$ is the technical coefficient matrix, which is calculated in the following way:

[11] Other factors, such as competitiveness, can certainly play a role. Changes in competitiveness may thus cause shifts in the fractions that each country exports to these target countries. However, it is difficult to quantitatively account for competitiveness at this level of sectoral aggregation.

$$\boldsymbol{A} = \frac{\boldsymbol{Z}}{\hat{\boldsymbol{x}}} \tag{4.16}$$

where $\boldsymbol{Z}$ is the intermediate deliveries matrix and the hat symbol over $\boldsymbol{x}$ indicates diagonalization. For the time period between 1995 and 2012, the intermediate deliveries matrix is based on historical values. From 2013 on, it is calculated endogenously in the model:

$$\boldsymbol{Z}_t = \begin{cases} \boldsymbol{Z}_t^* & \text{for } t \leq 2012 \\ \boldsymbol{Z}_{t-\Delta t} + \left.\frac{d\boldsymbol{Z}}{dt}\right|_{t-\Delta t} \Delta t & \text{for } t > 2012 \end{cases} \tag{4.17}$$

$$\left.\frac{d\boldsymbol{Z}}{dt}\right|_t = \operatorname{diag}\left((\boldsymbol{I} - \boldsymbol{A}_t)^{-1} \left.\frac{d\boldsymbol{y}}{dt}\right|_t \right) \cdot \boldsymbol{A}_t \tag{4.18}$$

$$\boldsymbol{A}_t = \frac{\boldsymbol{Z}_t}{\hat{\boldsymbol{x}}_t} \tag{4.19}$$

As Equation 4.19 shows, the intermediate deliveries matrix is then used to calculate the technical coefficient matrix for every time step. The IO logic, however, implies that $\boldsymbol{A}_t$ remains constant after 2012 as long as no exogenous changes are made to $\boldsymbol{Z}_t$. Therefore, in the base run of the model, the production structure of the economy does not change. As discussed in Section 2.3.1, this is a somewhat limiting assumption. However, it is difficult to make predictions about mid- to long-term changes in technical coefficients since technological developments often happen in the form of shocks. Additionally, in quantity models technological developments can not be portrayed separately from economic developments, such as price changes, which can theoretically counteract these technological developments. As a look at historical data suggests that at this level of aggregation, structural change appears not to occur primarily between sectors but within them. Thus, while many new technologies may emerge, this is not expressed by changes in the relationship between sectors but in the internal structures of sectors, which is represented by the diagonal of the intermediate deliveries matrix. Figure 4.6 shows a heat map of the relative variance[12] of the 71x71 intermediate input coefficients for the time frame from 1995 to 2007.[13] It can be seen that the variance is generally low with the largest changes mainly on the diagonal and in the output coeffi-

[12]The relative variance of each technical coefficient $a_{i,j}$ for $i, j = 1, \ldots, 71$ is calculated in the following way: $\frac{\sigma^2_{i,j}}{\mu_{i,j}}$, where $\mu_{i,j}$ is the mean of each coefficient's time series and $\sigma^2_{i,j}$ is the statistical variance of the time series with n observations of each coefficient: $\sigma^2_{i,j} = \frac{\sum(a_{i,j}-\mu_{i,j})^2}{n-1}$.

[13]In order to avoid artifacts in the data, the time series is not extended beyond 2007, after which a new sector classification is used. The classification used in the variance calculation is WZ 2003 with 71 production sectors. See also footnote 10.

cients (rows) of the wholesale (no. 46) and business service (no. 62) sectors, though the majority of the historical output coefficients of these two sectors do not have a variance above 5% of their respective mean values. Overall, 98.5% of the 5041 coefficients have a relative variance of below 5%, while only three coefficients have a variance above 20%. It therefore appears reasonable to keep the coefficients unchanged in the base run, while allowing for exogenous changes in scenario calculations (see Section A.7.2 in the Appendix).

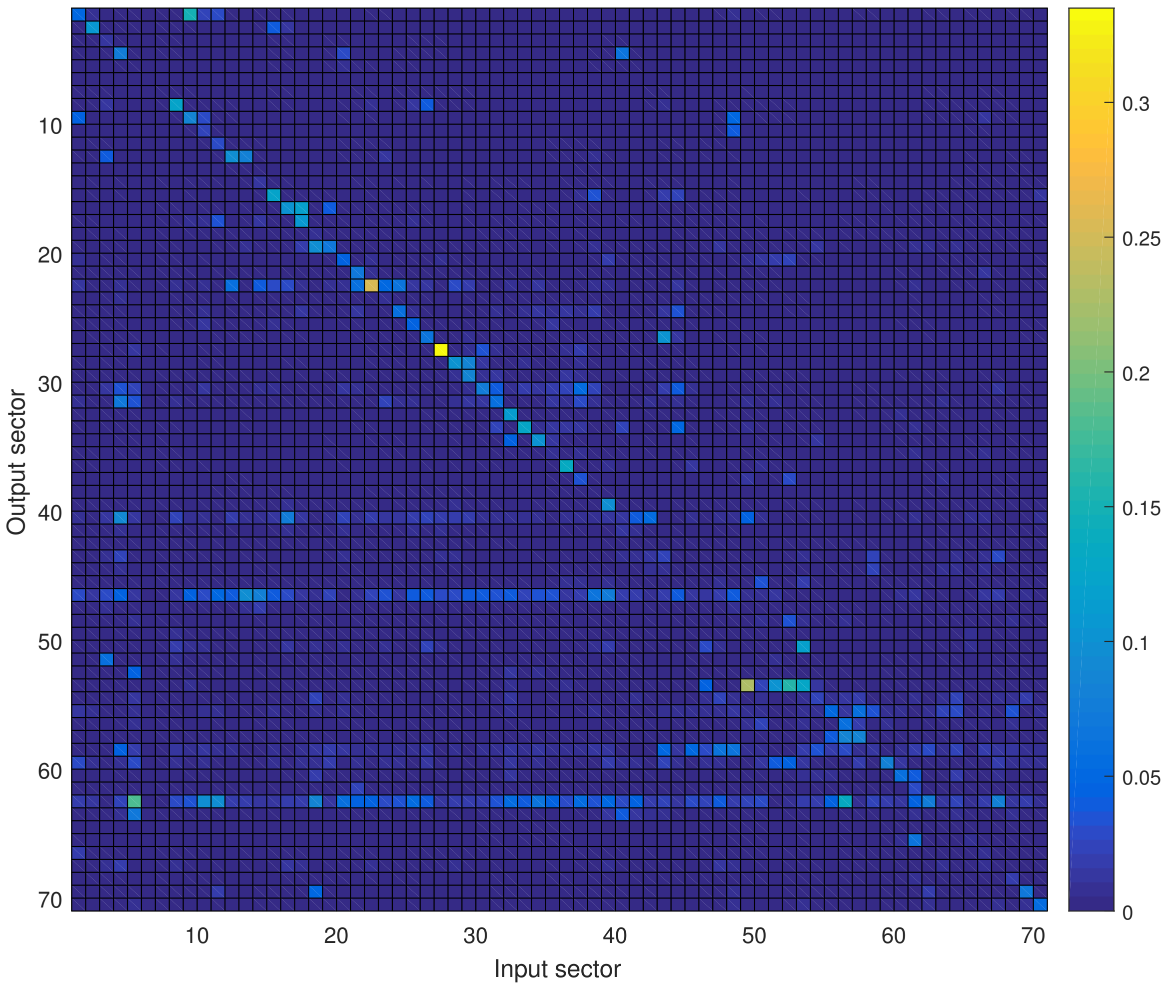


Figure 4.6: Heat map of relative technical coefficient variance from 1995 to 2007, own calculation based on data from Destatis (2010b)

The calculation of intermediate inputs in the IO module can then be used to calculate sectoral gross value added. This is done by subtracting the sum of domestic and imported intermediate inputs from gross output:

$$v_j = \sum_{i=1}^{72} x_{i,j} - \left(\sum_{i=1}^{72} z_{i,j} + \sum_{i=1}^{72} z_{i,j}^m \right) \tag{4.20}$$

where the superscript m indicates imports. Contrary to the domestic version, imported intermediate deliveries are not part of the standard IO calculation but are calculated as fixed fractions of gross output, which are held constant after 2012:

$$\boldsymbol{Z}_t^m = \begin{cases} \boldsymbol{A}_t^m \cdot \hat{\boldsymbol{x}}_t & \text{for } t \leq 2012 \\ \boldsymbol{A}_{2012}^m \cdot \hat{\boldsymbol{x}}_t & \text{for } t > 2012 \end{cases} \tag{4.21}$$

where $\boldsymbol{A}^m$ is the matrix of imported technical coefficients. With total sectoral GVA, its individual components can be calculated after production taxes and subsidies have been deducted:

$$\boldsymbol{v}^t = \boldsymbol{v} - \boldsymbol{t} \tag{4.22}$$

where $\boldsymbol{v}^t$ is the vector of sectoral gross value added less production taxes and subsidies $\boldsymbol{t}$, which are calculated as a fraction ω of the gross output of each sector j:

$$\boldsymbol{t}_j = \omega_j \cdot \sum_{i=1}^{72} x_{i,j} \tag{4.23}$$

After production taxes and subsidies have been deducted from GVA, wages w, profits p and consumption of gross fixed capital k for each sector j can be calculated with the help of the respective split factors ϵ_j^w, ϵ_j^p and ϵ_j^k:

$$w_j = \epsilon_j^w \cdot v_j^t \tag{4.24}$$

$$p_j = \epsilon_j^p \cdot v_j^t \tag{4.25}$$

$$k_j = \epsilon_j^k \cdot v_j^t \tag{4.26}$$

These different gross value added components are then used to calculate aggregate household income, which is the basis for private consumption as described in Section 4.2.1. The calculation of household income y^h is based on Sievers (2019) and briefly summarized in the following:

$$y^h = w^n + p^k + r - t^y \tag{4.27}$$

where w^n are net wages, p^k is capital income from corporate profits, r are government and other transfer payments to households, and t^y are income taxes. Net wages are gross wages w less employer-paid social security contributions, which are based on historical shares for the period 1995 to 2012 and held constant at 18% of gross wages after 2012. Capital income of households from corporate profits p is a constant fraction of 63% of aggregate profits, which is then split up into shares per decile based on a special evaluation of the Sample Survey of Income and Expenditure Destatis (2012). Transfer payments to households are made up of government and other transfers and are modeled as a decreasing fraction of total gross value added, ranging from about 15% in 2012 to 11% in 2050. Income taxes are defined per income decile as fractions of the gross income of each decile, ranging from 3.1% to 16% (Destatis, 2016a).

As described in Section 4.2.1, according to the circular logic of the economy the other components of final demand, investments and government consumption, are also derived from gross value added. In contrast to the detailed calculation of private consumption, their calculation is simply based on total GVA. In the model, gross value added also determines the level of employment. However, this calculation is performed with sectoral values since each sector's value added, in conjunction with sectoral labor productivity, determines the level of sectoral employment. The calculation of employment is described in the following section.

4.2.3 Employment

Sectoral employment is modeled as a function of sectoral gross value added and sectoral labor productivity. The aggregate labor supply of the economy as expressed in person hours can then be calculated by multiplying total employment by the average number of hours worked per year:

$$l_i = \tau_i v_i \tag{4.28}$$

$$L = h \sum_{i=1}^{72} l_i \tag{4.29}$$

where:
l = employment in Full-Time Equivalents (FTEs)
τ = labor productivity factor
v = gross value added
h = average hours worked per year
L = labor supply in million hours
i = index for sector i

The sectoral labor productivity factors τ_i are based on historical values of employed persons in each sector per sectoral value added for the period from 1995 to 2012. In this period, overall labor productivity has been increasing at a rate of about 1.1% per year[14] (Destatis, 2014a). After 2012, this yearly increase in overall labor productivity is implemented in the model as a continuing exogenous trend.

The absolute number of employed persons l_i^p, is calculated by multiplying employment in FTE with a sectoral part-time factor ι_i:

$$l_i^p = \iota_i l_i \tag{4.30}$$

Unemployment can then be calculated by subtracting the number of employed persons from the active labor force, which is based on the first variant of the 13th coordinated population projection of the German Statistical Office. This projection assumes a near constant birth rate of 1.4 children per woman, a moderate increase in life expectancy and a stepwise development of net migration into Germany towards 100,000 persons per year (Destatis, 2015).

The depiction of employment in this model can be understood as employment demand based on economic activity. No adaptation mechanisms are implemented if the demand for employment is lower or higher than the active labor force. It is assumed that employment demand is always met. Unemployment can therefore be understood as the difference between the theoretical labor supply and labor demand. This can theoretically result in a situation where a level of employment demand is met which actually surpasses the size of the active labor force.

4.3 Material module

The material module consists of two parts. The first part is conceived as a general environmental extension to the macroeconomic model. It is based on data taken from the MRIO database EXIOBASE, which was adapted to fit into the national macroeconomic model. The second part is dedicated to a detailed portrayal of copper stocks and flows within the German economy as well as direct and indirect trade flows of copper. It is based on detailed data on sectoral copper uses provided by the International Copper Association (ICA). Both sub-modules will be described in the following sub-sections.

4.3.1 Aggregate material sub-module

The logic of the aggregate material sub-module is oriented along the lines of the aggregate material flow indicators outlined in Section 2.2.3, which are also used by the German Statistical Office. The aggregate material modules splits material use categories into domestic extraction, imports and exports. Domestic extraction comprises of the total extraction within Germany, regardless of whether it is intended to serve

[14] The crisis year 2009 has been left out in this calculation in order not to distort results.

German or foreign final demand. Exports include domestic extraction but also extraction in the rest of the world that is imported to Germany in the form of intermediate products, which are used in intermediate or final products that are re-exported. Imports include extraction from the rest of the world contained in intermediate and final products imported to Germany.

EXIOBASE as data source

The material data for the aggregate sub-module is taken from EXIOBASE, which is an MRIO database with detailed environmental extensions. Among the available MRIO databases with environmental extensions, including the World Input-Output Database (WIOD; Dietzenbacher et al., 2013), EORA (Lenzen et al., 2013) and the MRIO tables of the Global Trade Analysis Project GTAP (Peters et al., 2011), EXIOBASE is especially well suited for an analysis of material use due to its comparatively high sectoral resolution and detailed environmental extensions. EXIOBASE has been developed as part of various projects within the European Commission's 6th and 7th framework programmes, including EXIOPOL, DESIRE, CREEA and Carbon-Cap (Tukker et al., 2009, 2013a; Wood et al., 2014, 2015; Stadler et al., 2018). In this thesis, the latest release of EXIOBASE (version 3.4) is used, which contains yearly IO and base tables as well as environmental and primary factor extensions for the years 1995 to 2011. Newer tables are available for internal use but have not been fully validated yet and are therefore not released. The IO tables used for this thesis are the product by product version with 200 product categories (see Table A.8 in the Appendix) and 49 countries and world regions (see Table A.6 in the Appendix). A short overview of the environmental and primary factor extensions is provided in Table 4.2.

Table 4.2: Environmental and primary factor extensions of EXIOBASE

Category	**Detail**	**Entries**
Factor inputs	Labor, capital	23
Emissions	Differentiated by air and water (GHG, pollutants, eutrophication etc.)	423
Land use	Caused by agriculture, forestry and infrastructure	20
Resource use	Energy use, energy carrier use and supply	4
	Domestic extraction (used/unused): Agriculture / forestry / livestock / fishery, metal ores, minerals, fossil energy carriers	440
	Water consumption/-withdrawal: green, blue by use	194

Within the environmental extensions, only the material use categories are relevant for this thesis, though the other categories are also implemented in the model. Table 4.3 summarizes the categories of used domestic extraction, while Table A.7 in the

Appendix provides a full list. They include biotic as well as abiotic categories, with the latter being divided into metal ores[15], non-metallic minerals and fossil fuels. For illustrative purposes, the metal ore category is expanded to show all the metal ores contained in the environmental extension. A total of 12 distinct metal ores are covered, while the last entry is a combined category of "other non-ferrous metal ores", which includes low volume and sparsely documented metals. In accordance with European environmental economic accounts (European Union, 2011), uranium and thorium ores are treated as metal ores and not as energy carriers, even though their primary application is in nuclear energy (Kaumanns and Lauber, 2016). The unused domestic extraction categories are almost identical, with a few exceptions (see Table A.7 in the Appendix).

Table 4.3: Material use categories in EXIOBASE

No.	**Category**	**Detail**
1-196	Biotic materials	Primary crops, crop residues, fodder crops, grazing, timber and aquatic animals
197-208	Metal ores	Uranium and thorium ores Iron ores Copper ores Nickel ores Bauxite and aluminium ores Gold ores PGM ores Silver ores Lead ores Tin ores Zinc ores Other non-ferrous metal ores
209-216	Non-metallic minerals	Agricultural, industrial and construction minerals
217	Fossil fuels total	Aggregated entry for 11 fossil fuel types[16]

MRIO models follow a different logic than single-region (e.g. national) IO models regarding trade flows. In MRIO models, the trade flows are integrated into the interregional product flows as portrayed by the intermediate deliveries and the final demand matrices $\boldsymbol{Z}$ and $\boldsymbol{Y}$, respectively. This is illustrated in a simplified way in Fig. 4.7,

[15] In the following, the metal ore categories will sometimes be referred to as "metals" because metals are ultimately extracted from these ores. However, it is clear that the different types of metal ores have different metal concentrations which also vary across extraction locations, and so 1 ton of metal ore does not equal 1 ton of corresponding metal.

[16] Due to licensing issues, from version 3.4 on, fossil fuels are only portrayed as an aggregated category within used extraction and not divided into different types. For unused extraction, a distinction is made between different types of coal, oil and gas.

which splits the global economy into two blocks: Germany (DE) and the Rest of the World (RoW). Both regions produce intermediate deliveries as well as final demand goods for themselves, respectively, but also for each other. Analogous to single-region IO analysis, intermediate deliveries and final demand add up to gross output $\boldsymbol{X}$. In Fig. 4.7 it can be seen that one region's gross output can thus be allocated to itself or to the other region(s).

This way of accounting for trade flows leads to the effect that a region's final demand matrix does not include exports as a final demand category. Similarly, domestic and imported final demand are not differentiated by portraying them in separate matrices, but as different parts of the wider MRIO table. Likewise, there is no differentiation between a domestic intermediate delivery matrix and one which includes imported intermediate deliveries, since both are contained in the larger multi-regional intermediate deliveries matrix.

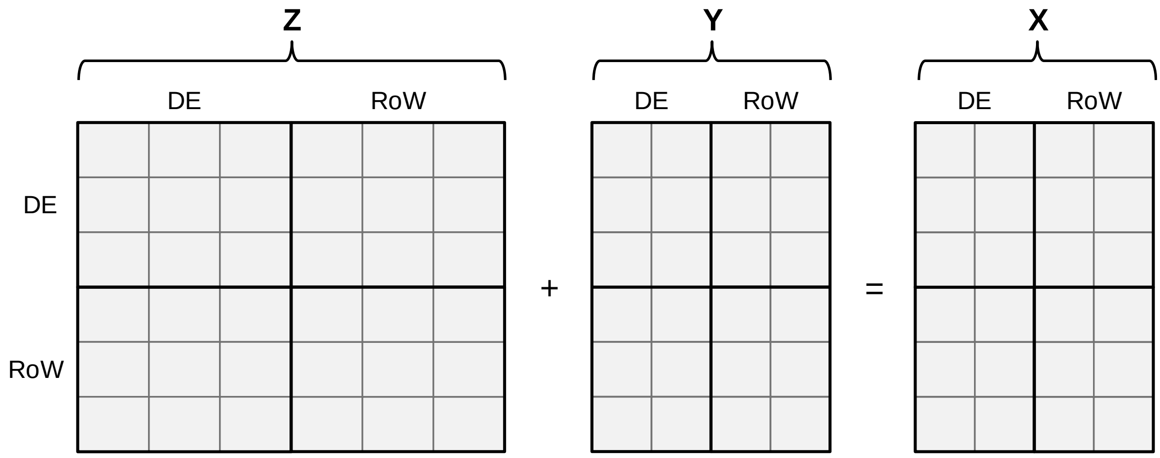


Figure 4.7: Schematic representation of an MRIO model

This has a number of important consequences for the analysis of a region's material use. First, the production necessary to fulfil a region's final demand can be split up into domestic and foreign, each with its own indirect requirements. This implies that the quadrants in the gross output matrix contain not only a region's production which directly serves domestic or foreign final demand, but also the intermediate deliveries that go into domestic as well as foreign production. Thus, for instance, even if it is known that a certain final use good is produced domestically, it may induce foreign production in the form of imported intermediate deliveries. In an MRIO context, these amounts of direct and indirect sectoral production can be calculated by multiplying the respective final demand matrices with the inverse coefficient matrix. An advantage over the national IO perspective is the knowledge on the sectoral and national distribution of indirect requirements. Therefore, unlike national IO models, MRIO analysis does not rely on the Domestic Technology Assumption (DTA), or what Su and Ang (2013) call the assumption of "non-competitive imports". According to the DTA, the international production structure is identical to the domestic production structure and therefore demand for imports would theoretically lead to the same sectoral gross outputs and corresponding material demands (this issue is discussed in more detail in Section 4.3.2).

A second consequence of the design of MRIO tables is that the gross output required to satisfy exports cannot be calculated in the regular way, i.e. by multiplying the export vector with the inverse coefficient matrix. Instead, the gross output for exports can be calculated by multiplying the export portions of both the total intermediate deliveries and the final demand matrix with the domestic inverse coefficient matrix (see section below).

In a simplified MRIO model for Germany such as the one portrayed in Figure 4.7, the following activities can be distinguished:

1. German final demand satisfied by German production ($\boldsymbol{Y}_{DE,DE}$ in the upper left quadrant of the final demand matrix $\boldsymbol{Y}$ in Fig. 4.7), including:
   - Intermediate inputs produced in Germany ($\boldsymbol{Z}_{DE,DE}$)
   - Intermediate inputs imported from other regions ($\boldsymbol{Z}_{RoW,DE}$)
2. German final demand satisfied by foreign production ($\boldsymbol{Y}_{RoW,DE}$), including:
   - Intermediate inputs produced in these regions ($\boldsymbol{Z}_{RoW,RoW}$)
   - Intermediate inputs imported from Germany ($\boldsymbol{Z}_{DE,RoW}$)
3. Foreign final demand satisfied by German production ($\boldsymbol{Y}_{DE,RoW}$), including:
   - Intermediate inputs produced in Germany ($\boldsymbol{Z}_{DE,DE}$)
   - Intermediate inputs imported from other regions ($\boldsymbol{Z}_{RoW,DE}$)
4. Foreign final demand satisfied by foreign production ($\boldsymbol{Y}_{Row,RoW}$), including
   - Intermediate inputs produced in these regions ($\boldsymbol{Z}_{RoW,RoW}$)
   - Intermediate inputs imported from Germany ($\boldsymbol{Z}_{DE,RoW}$)

The basic input-output framework introduced in Section 2.3.1 can thus be expanded to indicate sources and destinations of gross outputs and therefore material requirements. The basic formula $\boldsymbol{x} = \boldsymbol{L}\boldsymbol{y}$ thus turns into Equation 4.31 (Koopman et al., 2014, pp.464). For better readability, 1 is used as index for DE and 2 for RoW:

$$\begin{aligned}
\begin{bmatrix} \boldsymbol{x}_{1,1} & \boldsymbol{x}_{1,2} \\ \boldsymbol{x}_{2,1} & \boldsymbol{x}_{2,2} \end{bmatrix} &= \begin{bmatrix} \boldsymbol{L}_{1,1} & \boldsymbol{L}_{1,2} \\ \boldsymbol{L}_{2,1} & \boldsymbol{L}_{2,2} \end{bmatrix} \begin{bmatrix} \boldsymbol{y}_{1,1} & \boldsymbol{y}_{1,2} \\ \boldsymbol{y}_{2,1} & \boldsymbol{y}_{2,2} \end{bmatrix} \\
&= \begin{bmatrix} \boldsymbol{L}_{1,1}\boldsymbol{y}_{1,1} + \boldsymbol{L}_{1,2}\boldsymbol{y}_{2,1} & \boldsymbol{L}_{1,1}\boldsymbol{y}_{1,2} + \boldsymbol{L}_{1,2}\boldsymbol{y}_{2,2} \\ \boldsymbol{L}_{2,1}\boldsymbol{y}_{1,1} + \boldsymbol{L}_{2,2}\boldsymbol{y}_{2,1} & \boldsymbol{L}_{2,1}\boldsymbol{y}_{1,2} + \boldsymbol{L}_{2,2}\boldsymbol{y}_{2,2} \end{bmatrix}
\end{aligned} \tag{4.31}$$

where, as above, $\boldsymbol{x}_{r,s}$ indicates the gross output of source country r necessary to satisfy final demand in destination country s. The lower part of Equation 4.31 further splits up the four elements of the gross output matrix. Thus, $\boldsymbol{x}_{1,1}$ can be decomposed into $\boldsymbol{L}_{1,1}\boldsymbol{y}_{1,1} + \boldsymbol{L}_{1,2}\boldsymbol{y}_{2,1}$. The first summand, $\boldsymbol{L}_{1,1}\boldsymbol{y}_{1,1}$, is the part of gross output in Germany that is required to produce final products in Germany which are also consumed in Germany. The second summand, $\boldsymbol{L}_{1,2}\boldsymbol{y}_{2,1}$, is the part of Germany's gross output which is exported as an intermediate good to the rest of the world but is then re-imported from there as a final product. Similarly, $\boldsymbol{x}_{1,2}$ can be split up into $\boldsymbol{L}_{1,1}\boldsymbol{y}_{1,2}$, which is Germany's gross output for the production of German final goods exported to the rest of the world, and $\boldsymbol{L}_{1,2}\boldsymbol{y}_{2,2}$, which is Germany's gross output exported in the form of intermediate goods for the production and consumption of final goods in the rest of the world.

The above description indicates the complexity of global production interlinkages. However, it does not fully illustrate the multiple ways in which products and the materials embodied in them flow back and forth between countries. For this purpose, the production system as portrayed by MRIO tables can be further decomposed, which is done in Section A.8.1 in the Appendix.

Integration of MRIO data into the national model

In order to integrate the information from an MRIO perspective into the perspective of national IO modeling, four main steps have to be carried out. First, all sectoral and national outputs necessary to satisfy the three use categories outlined above (domestic extraction, exports, imports) are calculated. Second, the material requirements associated with the three categories are calculated with the help of the material use factors provided in the EXIOBASE data. To ensure comparability[17], the calculations in this thesis follow the general EW-MFA principles used by the German Statistical Office (Destatis, 2017b; Kaumanns and Lauber, 2016).

For ease of illustration, the two-region (i.e. Germany (DE) and the Rest of the World (RoW)) notation introduced above is kept for the following sections. However, the calculations are performed with the full MRIO database as pre-computation aggregation would result in a loss of information that can have considerable effects on the results of aggregate material use calculations (de Koning et al., 2015).

Domestic extraction $\boldsymbol{M}_{DE}$ per sector is calculated simply by multiplying the domestic material use matrix for Germany $\boldsymbol{E}_{DE}$ with the German gross output matrix $\boldsymbol{X}_{DE}$:

$$\boldsymbol{M}_{DE} = \boldsymbol{E}_{DE}\boldsymbol{X}_{DE} \tag{4.32}$$

[17] A recent publication by the German Environmental Agency revealed that the methodological differences between the German Statistical Office and MRIO approaches can lead to considerable differences in results (Lutter et al., 2016b). This will also be seen in Section 5.1.2. However, conceptually the approaches are very similar in the sense that they theoretically account for all embodied material.

The German gross output matrix is the upper part of the total gross output matrix $\boldsymbol{X}$, which is an expansion of the total output vector $\boldsymbol{x} = \sum_{j=1}^{72} x_{i,j}$ through the multiplication of the Leontief inverse $\boldsymbol{L}$ with the aggregated diagonal final demand vector $\hat{\boldsymbol{y}}$ of the entire MRIO system. The gross output matrix thus allocates each sector's gross output to the final demand of all sectors.

$$\boldsymbol{X} = \boldsymbol{L}\hat{\boldsymbol{y}} \tag{4.33}$$

where:

$$\boldsymbol{X} = \begin{bmatrix} \boldsymbol{X}_{DE,DE} & \boldsymbol{X}_{DE,RoW} \\ \boldsymbol{X}_{RoW,DE} & \boldsymbol{X}_{RoW,RoW} \end{bmatrix}; \quad \boldsymbol{y} = \begin{bmatrix} \boldsymbol{y}_{DE,DE} & \boldsymbol{y}_{DE,RoW} \\ \boldsymbol{y}_{RoW,DE} & \boldsymbol{y}_{RoW,RoW} \end{bmatrix}$$

The partial matrices of total national (or regional) gross outputs can then be calculated by summing over columns:

$$\boldsymbol{X}_{DE} = \boldsymbol{X}_{DE,DE} + \boldsymbol{X}_{DE,RoW} \tag{4.34}$$

$$\boldsymbol{X}_{RoW} = \boldsymbol{X}_{RoW,DE} + \boldsymbol{X}_{RoW,RoW} \tag{4.35}$$

The interpretation of $\boldsymbol{X}_{DE}$ is that it entails the entirety of German production, triggered by domestic and foreign final demand, including the associated demand for intermediate products in both regions.

The sectoral material content of exports $\boldsymbol{M}_{DE,RoW}$ is calculated by accounting for the cumulative outputs from Germany as well as the rest of the world that go into German exports:

$$\boldsymbol{M}_{DE,RoW} = \boldsymbol{E} \cdot \boldsymbol{L} \cdot \mathrm{diag}(\boldsymbol{y}^{*}_{DE,RoW} + \boldsymbol{Z}^{*}_{DE,RoW}\boldsymbol{i}) \tag{4.36}$$

where:
$\boldsymbol{E}$ = full material use matrix for DE
$\boldsymbol{L}$ = full inverse coefficient matrix of intermediate inputs
$\boldsymbol{y}^{*}_{DE,RoW}$ = vector of exports of final products from DE to RoW
$\boldsymbol{Z}^{*}_{DE,RoW}$ = matrix of exports of intermediate products from DE to RoW
$\boldsymbol{i}$ = column summation vector consisting of ones

Note that the German final product export vector $\boldsymbol{y}^{*}_{DE,RoW}$ and the intermediate product export matrix $\boldsymbol{Z}^{*}_{DE,RoW}$ have the same dimensions as the full final demand vector and the full intermediate delivery matrix of the MRIO system, respectively. They are constructed by concatenating the partial vector $\boldsymbol{y}_{DE,RoW}$ and the partial matrix $\boldsymbol{Z}_{DE,RoW}$ with vectors/matrices containing zeroes where the flows are not from Germany to the rest of the world.

The material content of imports to Germany $\boldsymbol{M}_{RoW,DE}$ can be calculated as exports from the rest of the world to Germany, analogously to German exports to the rest of the world:

$$\boldsymbol{M}_{RoW,DE} = \boldsymbol{E} \cdot \boldsymbol{L} \cdot \mathrm{diag}(\boldsymbol{y}^{*}_{RoW,DE} + \boldsymbol{Z}^{*}_{RoW,DE}\boldsymbol{i}) \tag{4.37}$$

where the above variables are essentially mirror images of the variables in Equation 4.36. The third step of the integration of the MRIO information into the national macroeconomic model is the conversion of the material demands into the sector structure of the national model, i.e. an aggregation from 200 to 72 production sectors based on Tables A.12 to A.15 in the Appendix. Fourth, based on these material demands and the respective German gross outputs, new virtual material use coefficients are calculated for domestic extraction, exports and imports, respectively.

Implementation in the model

In the macroeconomic model, the material requirements of domestic extraction, exports and imports can then be calculated separately by multiplying the sectoral production values with the respective environmental coefficients. In the case of domestic extraction, this is simply the aggregate production in Germany to fulfill the final demands of Germany and the rest of the world. The production necessary for exports is part of aggregate production, so the respective material requirements are calculated by multiplying this production with the material coefficients for exports. The production necessary for imports is based on the DTA, which assumes that the foreign production structure is identical to Germany's. However, as will be described in Section 4.3.2, the use of virtual import coefficients alleviates this error to some extent. Formally, domestic extraction is calculated in the following way:

$$\boldsymbol{M} = \boldsymbol{E}\boldsymbol{X} \tag{4.38}$$

$$\boldsymbol{X} = \boldsymbol{L}\hat{\boldsymbol{y}} \tag{4.39}$$

where:
- $\boldsymbol{M}$ = domestic extraction
- $\boldsymbol{E}$ = domestic extraction coefficient matrix
- $\boldsymbol{X}$ = gross output matrix
- $\boldsymbol{L}$ = domestic Leontief inverse
- $\hat{\boldsymbol{y}}$ = diagonal domestic final demand vector (the hat symbol indicates diagonalization)

The material coefficients are contained in a matrix as several materials are portrayed in parallel. This matrix contains 217 biotic and abiotic material/resource categories relating to used domestic extraction and 223 material categories relating to unused domestic extraction. In both cases, primary crops make up the majority with close to 170 entries (see Table A.7 in the Appendix). The materials contained in German exports are calculated in the following way:

$$\boldsymbol{M}^e = \boldsymbol{E}^e \boldsymbol{X}^e \tag{4.40}$$

$$\boldsymbol{X}^e = \boldsymbol{L}\hat{\boldsymbol{y}}^e \tag{4.41}$$

$$\boldsymbol{y}^e = \boldsymbol{y} - \boldsymbol{y}^d \tag{4.42}$$

where: $\boldsymbol{M}^e$ = material use matrix for exports
$\boldsymbol{E}^e$ = material use coefficient matrix for exports
$\boldsymbol{X}^e$ = gross output matrix for exports
$\hat{\boldsymbol{y}}^e$ = diagonal domestic export vector
$\boldsymbol{y}^d$ = domestic final demand vector

Following a national accounting logic, exports are thus calculated as a part of overall final demand. A different set of material use coefficients is employed for the calculation of the material intensity of exports. As stated above, the material content of imports is calculated with adapted import coefficients and virtual gross output for imports based on the DTA:

$$\boldsymbol{M}^m = \boldsymbol{E}^m \boldsymbol{X}^m \tag{4.43}$$

$$\boldsymbol{X}^m = \boldsymbol{L}\hat{\boldsymbol{y}}^m \tag{4.44}$$

where: $\boldsymbol{M}^m$ = material use matrix for imports
$\boldsymbol{E}^m$ = material use coefficient matrix for imports
$\boldsymbol{X}^m$ = gross output matrix for imports
$\hat{\boldsymbol{y}}^m$ = diagonal import vector

Calculation of aggregate material use indicators

The aggregate material sub-module allows for the calculation of a number of aggregate material use indicators. These indicators were outlined in Section 2.2.3 and differentiated along three dimensions: input vs. consumption perspective, direct vs. indirect material use of imported products, and used vs. unused extraction of raw materials. The calculation of material use outlined above primarily allows for the distinction between input- and consumption-based material use calculations, while another distinction is made between whether unused extraction is excluded as in the case of the “raw” material indicators (e.g. RMC and Raw Material Input (RMI)), or included as in the case of “total” material indicators (e.g. Total Material Consumption (TMC) and TMR). The direct material use indicators are left out henceforth since by not including embodied material requirements they do not provide a holistic picture of economy-wide material use. The following relationships between the different material use indicators can be established (Destatis, 2017b; Kaumanns and Lauber, 2016):

- RMI = domestic extraction + imports
- RMC = RMI – exports
- TMR = domestic extraction (incl. unused) + imports (incl. unused)
- TMC = TMR – exports (incl. unused)

In order to calculate the indicators, the different material categories in the material use matrices are aggregated (see Table A.7 in the Appendix for the list of categories). RMI contains the following components:

$$\mathrm{RMI} = \underbrace{\sum_{i=1}^{192}\sum_{j=1}^{72} m_{i,j}}_{\text{Crops, timber}} + \underbrace{\sum_{i=193}^{196}\sum_{j=1}^{72} m_{i,j}}_{\text{Fishery}} + \underbrace{\sum_{i=197}^{208}\sum_{j=1}^{72} m_{i,j}}_{\text{Metals}} + \underbrace{\sum_{i=209}^{216}\sum_{j=1}^{72} m_{i,j}}_{\text{Minerals}} + \underbrace{\sum_{j=1}^{72} m_{217,j}}_{\text{Fossil fuels}} \tag{4.45}$$

where $m_{i,j}$ is the element in the ith row and jth column of the domestic material use vector. In order to get the totals, the material use matrix is first summed over the 72 columns corresponding to economic sectors. The individual groups are then summed across the respective number of rows.

RMC is then the difference between RMI and exports, the individual elements of the material requirements of exports are subtracted from RMI:

$$\mathrm{RMC} = \mathrm{RMI} - \Bigg(\underbrace{\sum_{i=1}^{192}\sum_{j=1}^{72} m^e_{i,j}}_{\text{Crops, timber}} + \underbrace{\sum_{i=193}^{196}\sum_{j=1}^{72} m^e_{i,j}}_{\text{Fishery}} + \underbrace{\sum_{i=197}^{208}\sum_{j=1}^{72} m^e_{i,j}}_{\text{Metals}} + \underbrace{\sum_{i=209}^{216}\sum_{j=1}^{72} m^e_{i,j}}_{\text{Minerals}} + \underbrace{\sum_{j=1}^{72} m^e_{217,j}}_{\text{Fossil fuels}}\Bigg) \tag{4.46}$$

where $m^e_{i,j}$ are elements of the material use matrix for exports. TMR, the analogous input indicator to RMI that includes unused extraction is calculated by adding the rows of the material use matrices which contain unused extraction:

$$\mathrm{TMR} = \mathrm{RMI} + \underbrace{\sum_{i=218}^{407}\sum_{j=1}^{72} m_{i,j}}_{\text{Crops, timber}} + \underbrace{\sum_{i=408}^{411}\sum_{j=1}^{72} m_{i,j}}_{\text{Fishery}} + \underbrace{\sum_{i=412}^{423}\sum_{j=1}^{72} m_{i,j}}_{\text{Metals}} + \underbrace{\sum_{i=424}^{431}\sum_{j=1}^{72} m_{i,j}}_{\text{Minerals}} + \underbrace{\sum_{i=432}^{440}\sum_{j=1}^{72} m_{i,j}}_{\text{Fossil fuels}} \tag{4.47}$$

To get to TMC, i.e. domestic material consumption including unused extraction, the material content of exports has to be subtracted:

$$\text{TMC} = \text{TMR} - \left(\underbrace{\sum_{i=218}^{407} \sum_{j=1}^{72} m^e_{i,j}}_{\text{Crops, timber}} + \underbrace{\sum_{i=408}^{411} \sum_{j=1}^{72} m^e_{i,j}}_{\text{Fishery}} + \underbrace{\sum_{i=412}^{423} \sum_{j=1}^{72} m^e_{i,j}}_{\text{Metals}} + \underbrace{\sum_{i=424}^{431} \sum_{j=1}^{72} m^e_{i,j}}_{\text{Minerals}} + \underbrace{\sum_{i=432}^{440} \sum_{j=1}^{72} m^e_{i,j}}_{\text{Fossil fuels}} \right) \tag{4.48}$$

A convenient feature of MRIO analysis is that the consumption-based indicators can also be directly calculated by using total domestic final demand $\boldsymbol{y}_{DE}$:

$$\boldsymbol{M}^* = \boldsymbol{E}\boldsymbol{L}\hat{\boldsymbol{y}}_{DE} \tag{4.49}$$

The use of the full German final demand vector takes into account imports necessary to fulfil German final demand and excludes those exports which serve foreign final demand. RMC can then be calculated by summing over the relevant categories of total domestic material consumption:

$$\text{RMC} = \left(\underbrace{\sum_{i=1}^{192} \sum_{j=1}^{72} m^*_{i,j}}_{\text{Crops, timber}} + \underbrace{\sum_{i=193}^{196} \sum_{j=1}^{72} m^+_{i,j}*}_{\text{Fishery}} + \underbrace{\sum_{i=197}^{208} \sum_{j=1}^{72} m^*_{i,j}}_{\text{Metals}} + \underbrace{\sum_{i=209}^{216} \sum_{j=1}^{72} m^*_{i,j}}_{\text{Minerals}} + \underbrace{\sum_{j=1}^{72} m^*_{217,j}}_{\text{Fossil fuels}} \right) \tag{4.50}$$

Likewise, TMC can be calculated by summing over the relevant categories:

$$\text{TMC} = \left(\underbrace{\sum_{i=218}^{407} \sum_{j=1}^{72} m^*_{i,j}}_{\text{Crops, timber}} + \underbrace{\sum_{i=408}^{411} \sum_{j=1}^{72} m^*_{i,j}}_{\text{Fishery}} + \underbrace{\sum_{i=412}^{423} \sum_{j=1}^{72} m^*_{i,j}}_{\text{Metals}} + \underbrace{\sum_{i=424}^{431} \sum_{j=1}^{72} m^*_{i,j}}_{\text{Minerals}} + \underbrace{\sum_{i=432}^{440} \sum_{j=1}^{72} m^*_{i,j}}_{\text{Fossil fuels}} \right) \tag{4.51}$$

4.3.2 Copper sub-module

The copper sub-module is similar to the aggregate material sub-module but follows a somewhat different logic. Its core is an interface which translates the technical data on copper flows into the economic sector structure of the larger macroeconomic model, and vice versa. The data on copper flows is based on a confidential data set provided by the International Copper Association (ICA). For different world regions and the years 2006 to 2014, this data set allocates semi-finished goods to their 'end uses' in the form of finished goods.[18] It distinguishes four categories of semi-finished goods and 16 categories of finished goods (see Table 4.4). The deliveries from semi-finished goods producers to finished goods producers are documented in a physical deliveries matrix similar to use tables in national accounts. Since no deliveries matrix exists for Germany, for this thesis the EU 27 version is used to calculate a relative matrix. Even though this is a large and heterogeneous geographical area, this step can be considered a reasonable approximation of the structure of the copper industry in Germany. The relative European matrix is then scaled to the German level and thus turned into an absolute matrix. For this, total production and trade data from the German Metals Statistic is used (WirtschaftsVereinigung Metalle, 2015). The trade data is cross-checked with data from the UN Comtrade database (United Nations, 2017). It can be seen in Figure 4.8 that the values match well for the time frame from 1998 to 2015. The German Statistical Office also uses material flow tables from industrial associations to validate their own material flow data; in the case of copper, the data match well (Kaumanns and Lauber, 2016).

The semi-finished and finished product categories identified by the ICA are, however, not in accordance with common classification systems. In order to unambiguously match the product categories with the production sectors in the input-output table, a systematic allocation is necessary. To this end, a comprehensive list of copper containing goods and associated copper contents compiled by Wittmer (2006) is used. After some minor adjustments and validation, the final list contains 365 goods denoted in HS codes and can be found in Section A.5 in the Appendix. The six-to-eight-digit HS codes are on the one hand used because they are compatible with national accounts, on the other hand because the UN Comtrade is among the most comprehensive and complete economic databases at the level of highly disaggregated goods (see Section 2.3.5). The latter point is especially important because the accuracy of the copper content of each listed good increases with increased product differentiation.

The copper containing goods identified in the list are subsequently assigned to the product categories in the ICA data set. The codes of the international HS classification can be easily matched with the codes of the European Statistical Classification of Products by Activity (CPA), which makes it possible to also assign each copper containing good identified in the list a production sector of the German input-output table (see Table A.9 in the Appendix). Table 4.4 shows the production sectors which are identified as either producing semi-finished goods or using semi-finished goods to produce finished goods.

The matching of the HS code denoted products including their copper contents with the sectoral CPA classification also allows for a detailed portrayal of copper contained in sectoral trade flows. Sectoral physical copper imports contained in finished goods are shown in Figure 4.9, exports in Figure 4.10. Electrical equipment, metal products, vehicles and machines make up the majority of both trade flows but absolute quantities

[18] The term "finished" is not to be mixed up with final use products in the logic of national accounts, see footnote 2.

Table 4.4: Semi-finished and finished products containing copper

ICA product categories	CPA production sectors	
Semi-finished product categories	**Semi-finished product sectors**	
Wire Mill	24.4	Non-ferrous Metals
Brass Mill Copper	25	Metal products
Brass Mill Alloy	27	Electrical equipment
Foundry		
Finished product categories	**Finished product sectors**	
Architecture	43	Construction
Consumer Products	27	Electrical Equipment
Cooling	28	Machines
Diverse	25	Metal Products
Automotive Electrical	29	Vehicles
Industrial Electrical	26	Electronics
Electrical Power	30	Transport Equipment
Electronic Use	20	Chemicals
Automotive Non Electrical	24.4	Non-ferrous Metals
Industrial Non Electrical		
Other Transport		
Powder use		
Power Utility		
Telecommunication Use		
Building Plant		
Plumbing		

and distributions obviously differ. This information is later used to construct separate copper use coefficients for imports and exports.

Some of the production sectors identified in this way do not uniquely belong to one respective semi-finished or finished product category as defined by the ICA; most of the product categories contain HS codes from different production sectors. For instance, the final product category "Industrial Electrical" contains HS codes from the production sectors electrical equipment as well as machines. The shares of each of these sectors within the broader product category are not apparent from the ICA based deliveries matrix. It therefore cannot simply be translated into a CPA based deliveries matrix but first has to be disaggregated. This is again done with the help of trade data from the UN Comtrade database (United Nations, 2017). Assuming that the production structure of copper containing finished goods resembles that of the composition of imports of copper containing finished goods, the shares of each production sector can be approximated by the import shares of the goods from this sector. The results for the year 2012 are displayed in Table 4.5, where the sectors

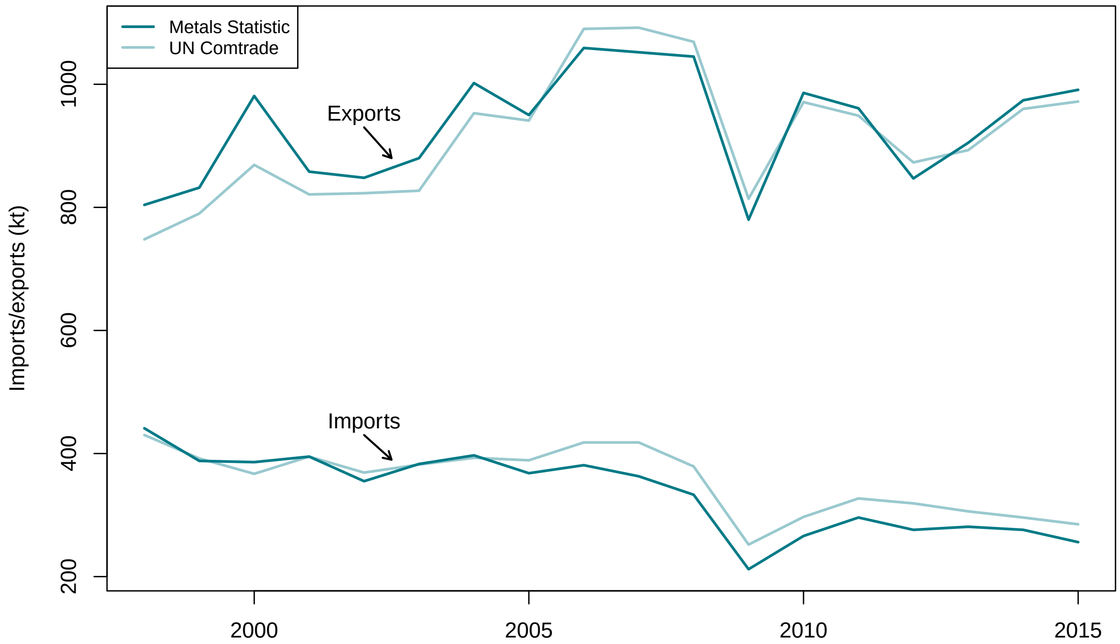


Figure 4.8: Trade of copper semi-finished goods, own calculation based on data from WirtschaftsVereinigung Metalle (2015) and UN Comtrade (United Nations, 2017)

denoted in rows make deliveries to the sectors denoted in columns.[19] 2012 is the most recent year for which data from all used sources is available.

Table 4.5: Total copper flows from semi-finished product sectors to finished product sectors for the year 2012, in kt

Sector	**20**	**24.4**	**25**	**26**	**27**	**28**	**29**	**30**	**43**	**Total**
24.4	7.59	5.08	94.10	16.62	169.26	147.54	85.32	21.16	213.98	**760.65**
25	0	0.71	14.99	0.74	2.43	20.81	0	7.30	1.98	**48.96**
27	0	0.41	12.47	38.83	48.19	7.92	0	6.58	4.99	**119.39**
Total	**7.59**	**6.21**	**121.56**	**56.19**	**219.87**	**176.27**	**85.32**	**35.03**	**220.95**	**929.00**

In addition to the product code based matching, some manual adaptations were necessary. A case in point are cables for use in buildings, which are made from semi-finished wires and are subsequently installed in buildings by the construction sector. According to the allocation through HS codes, the wires are delivered from the non-ferrous metals sector to the electrical equipment sector, which then produces the cables.

[19]See Section A.6 in the Appendix for a full sector list.

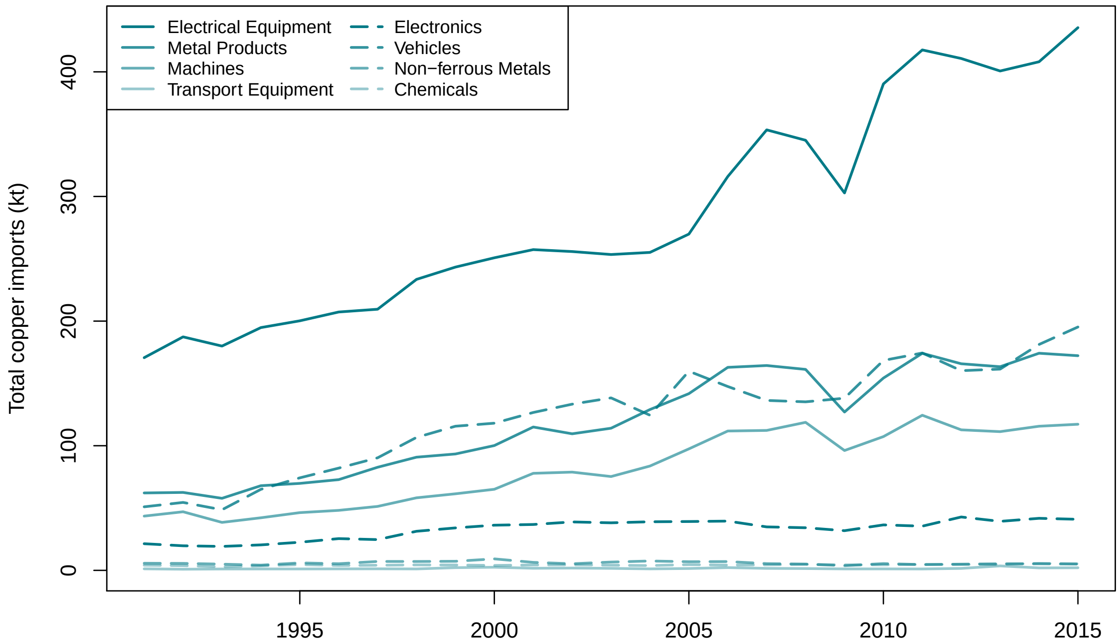


Figure 4.9: Copper contained in imports of finished goods, own calculation based on UN Comtrade (United Nations, 2017)

Since only the distribution from semi-finished to finished goods is covered by the ICA matrix, the more aggregated logic of the input-output table has to be followed for subsequent stages of the supply chain. The successive intermediate deliveries of the broader electrical equipment sector are, however, not a good proxy for the distribution of these cables, because the deliveries are made to many sectors and not just the construction sector. It therefore appears reasonable to skip this stage of the supply chain and assign the intermediate deliveries of cables for use in buildings directly to the construction sector (see Figure 4.11).

The result of the allocation procedure described above is validated through a comparison with copper use data for France, which is assumed to be of a somewhat similar structure to that of Germany. Figure 4.12 shows the distribution of semi-finished products across sectors for Germany based on the calculation outlined above and for France based on calculations by Beylot and Villeneuve (2015). It can be seen that apart from a few deviations, the composition of sectors using copper for the production of finished goods is relatively similar.

The information on sectoral copper use (aggregated over the three semi-finished product sectors) is used to construct an environmental extension of the macroeconomic model in the form of copper use coefficients. The main part of this extension covers the consumption after the “first transformation” (Beylot and Villeneuve, 2015) of copper within the domestic production structure. This is a critical stage of the copper supply

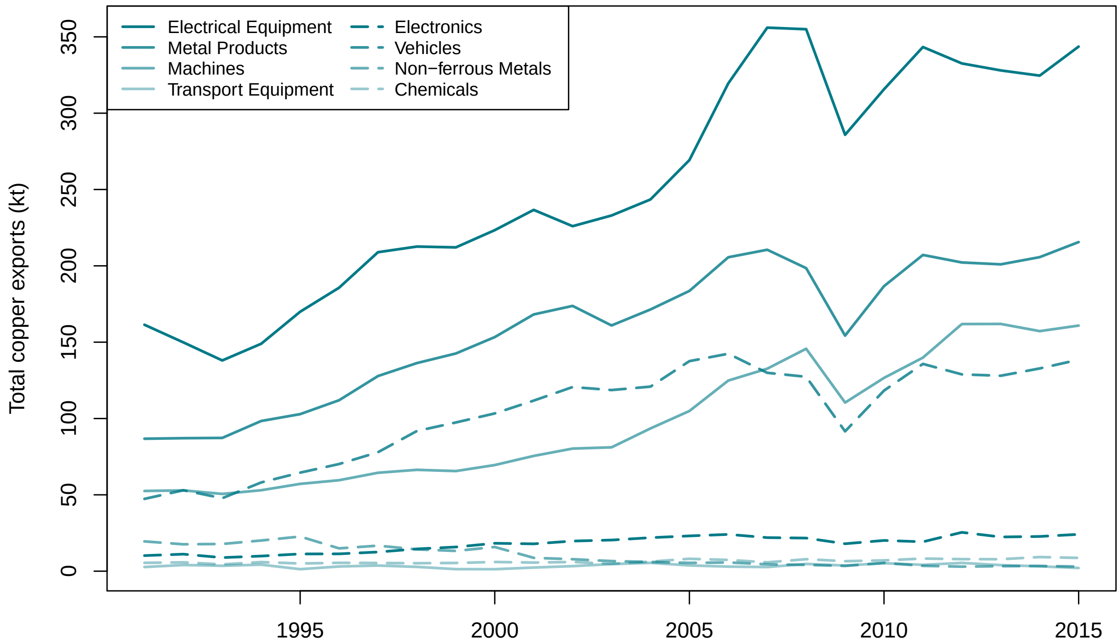


Figure 4.10: Copper contained in exports of finished goods, own calculation based on UN Comtrade (United Nations, 2017)

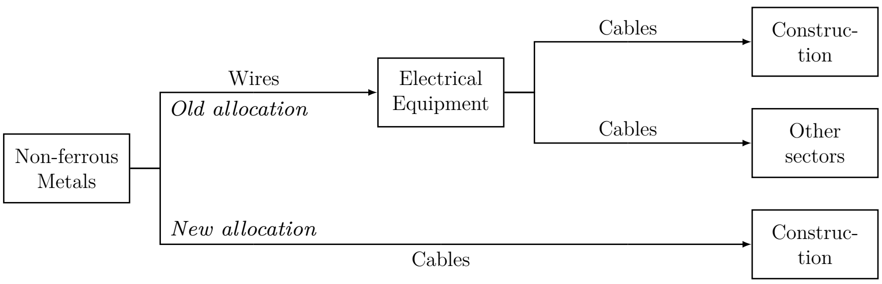


Figure 4.11: Adaptation of product allocation

chain in terms of sectoral distribution of copper flows, since the physical flows of copper deviate substantially from the monetary flows in the input-output table. Figure 4.13 illustrates this exemplarily by comparing physical and monetary flows from the non-ferrous metals sector, which produces 81% (by weight) of all semi-finished goods, to the finished goods producing sectors. By accounting for the actual physical flows, the error made through the homogeneity and proportionality assumptions in the input-output table (see Section 2.3.1) is 'postponed' to later stages in the supply chain and therefore reduced.

The domestic production structure entails not only domestic flows, but also imports and exports of semi-finished goods. Exports of finished goods are also covered within

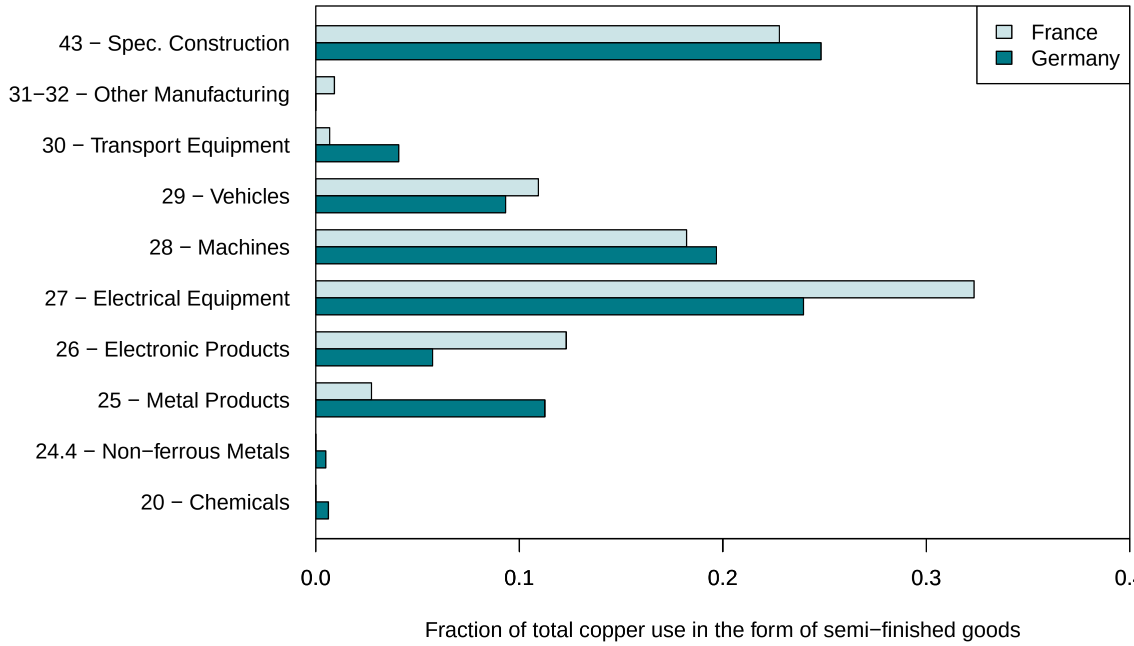


Figure 4.12: Comparison of copper semis use by sectors in Germany and France in 2008, own calculations based on ICA data and Destatis (2014a), and data from Beylot and Villeneuve (2015)

the domestic production structure since exports are part of final demand. However, export data from the UN Comtrade database shows that the composition of these goods in terms of copper contents is different from the domestic use structure described above. Therefore, analogously to the aggregate material sub-module, separate sectoral export coefficients are calculated based on the UN Comtrade data (United Nations, 2017).

Imports of finished goods are not accounted for in the domestic production structure. So in order to still be able to calculate copper imports within the national model, the DTA is used analogously to the treatment of imports in the aggregate material sub-module (see Section 4.3.1). Obviously, in its basic form, this is a gross simplification since production technologies vary widely across countries (Bouwmeester and Oosterhaven, 2013; de Koning et al., 2015; Schoer et al., 2012; Tukker et al., 2013b). Therefore, the UN Comtrade trade data is used to calculate the actual sectoral copper requirements of imports, which allows for a calculation of separate import coefficients (United Nations, 2017). The approach used in this thesis is thus essentially an IO approach implying the DTA on the level of monetary sectoral interconnection but with adapted coefficients to account for different material requirements. This is along the lines of the adjusted coefficient approach in Schoer et al. (2013). The different copper use coefficients of the non-ferrous metals sector for the exemplary year 2012

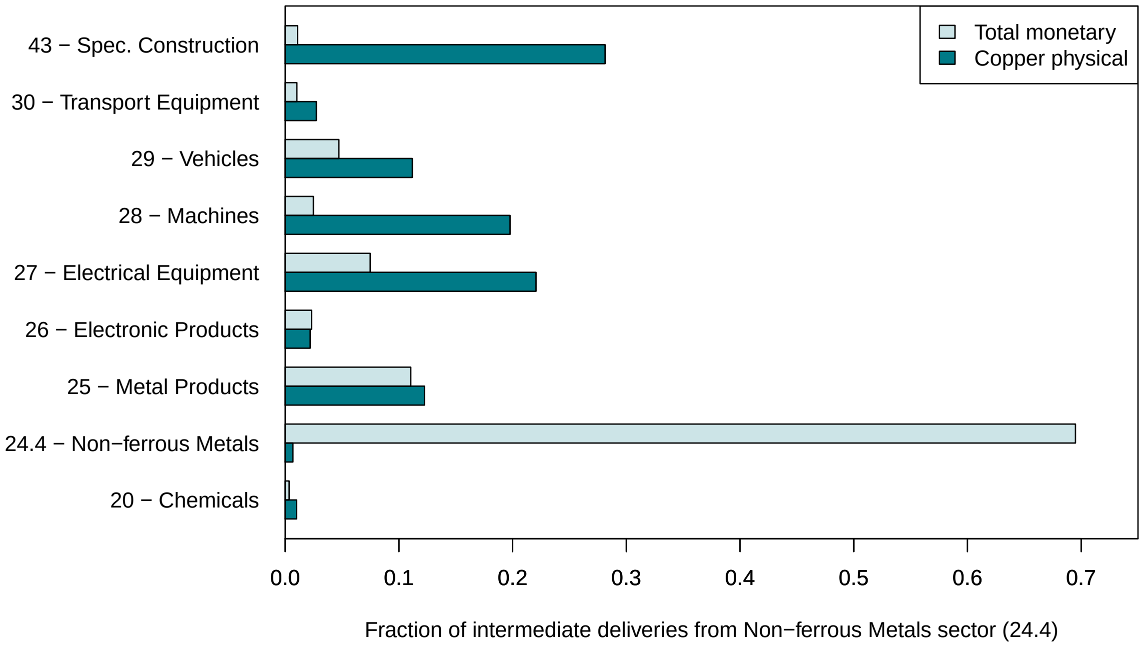


Figure 4.13: Shares of total monetary intermediate deliveries and intermediate deliveries of copper from non-ferrous metals sector, own calculation based on ICA data and Destatis (2014c)

are summarized in Table 4.6. Note that the coefficients of the construction sector (no. 43) are zero for both imports and exports, and Figures 4.9 and 4.10 do not contain values for the construction sector. The reason for this is that only the domestic copper use coefficients are manually adapted as described above (see Figure 4.11) because the construction sector almost exclusively operates domestically. Assigning a high copper use to this sector for trade flows would therefore result in an underestimation of copper imports and exports.

Table 4.6: Copper use coefficients in the year 2012, in t/M€

Sector	**20**	**24.4**	**25**	**26**	**27**	**28**	**29**	**30**	**43**
Domestic	0.05	0.15	1.04	0.94	2.44	0.82	0.27	1.06	1.23
Imports	0.14	0.80	6.63	0.71	13.59	2.36	2.83	0.07	0.00
Exports	0.05	0.08	2.95	0.46	5.45	0.99	0.57	0.20	0.00

The production system as portrayed in the model is illustrated in the simplified metal cycle in Figure 4.14. As outlined above, the domestic production system starts with the use of semi-finished goods for the production of finished goods. Domestic demand for semi-finished goods is calculated by adding imports to domestic production and subtracting exports. The input of refined material, including trade flows, is implicit (import/export arrows are shaded for implicit trade flows) as it is contained in the production of semi-finished goods. For these calculation steps, the main data source is the German Metals Statistic (WirtschaftsVereinigung Metalle, 2015). The exports of finished goods are calculated as part of final demand. However, no distinction is made between “finished goods” and “final goods” of the input-output logic, which may be subject to further processing steps before they end up in final demand (see beginning of this section). This makes trade flows of the subsequent stages in the supply chain therefore implicit. The main data source for the calculation of the trade flows of finished goods is the UN Comtrade database (United Nations, 2017), which also records trade flows of secondary material. However, the copper sub-module does not by itself distinguish between primary and secondary material demand since comprehensive information on the relationship between the two is not provided by the ICA or other data sources. Even if this information was available for a reference year or in the form of historical time series data, the future use of this information would be problematic because it does not contain any information on the future *availability* of secondary copper. The input of secondary copper into production processes may therefore be exaggerated. However, this issue is addressed by the coupling of ISI-Macro and the copper flow model, as described further below.

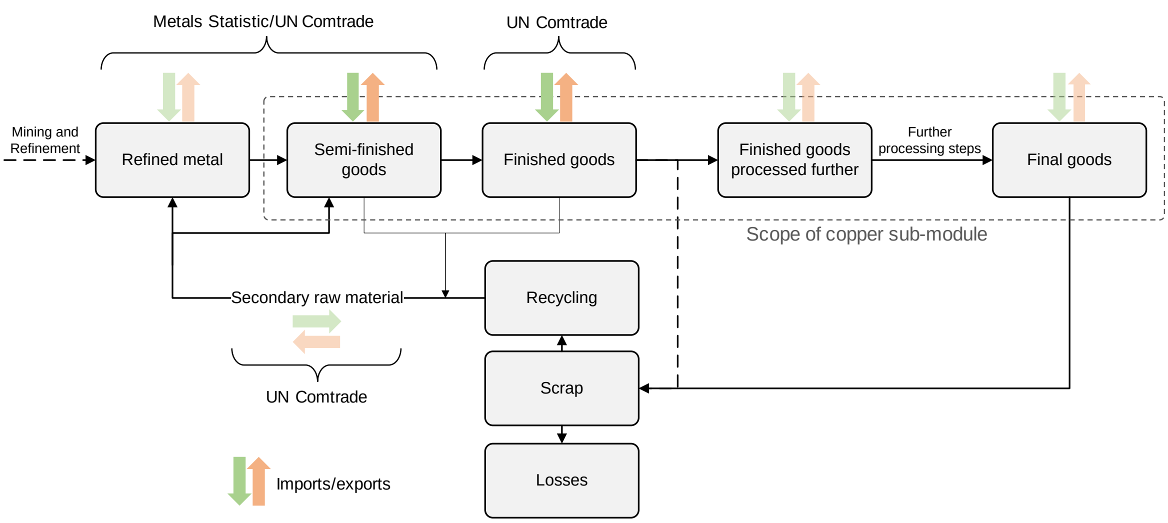


Figure 4.14: Illustration of production system as portrayed in copper sub-module

In order to assess whether the copper use coefficients have changed over time, they are calculated for all years for which data is available. As an example, the time series of domestic coefficients of the non-ferrous metals sector is shown in Figure 4.15. At the beginning of the time series there is a downward trend in (physical) copper use per (monetary) sectoral output for electrical equipment, construction, metal products and machines. However, in all four cases this trend levels off from 2009 on. The coefficients for the other sectors show no considerable trend. Without deeper knowledge of technological developments in the future, fixed copper use coefficients[20] thus appear to be an acceptable approximation of sectoral copper intensities for prospective baseline simulations.

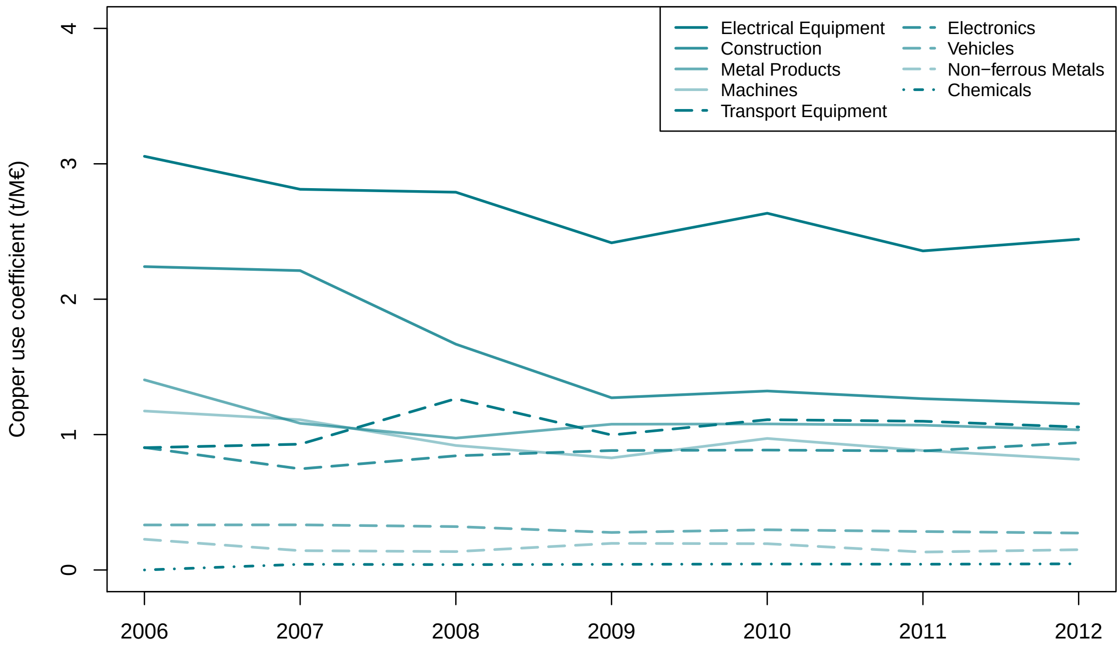


Figure 4.15: Time series of domestic copper use coefficients, own calculation based on ICA data and Destatis (2014c)

Implementation in the model

Analogously to the aggregate material sub-module, the copper sub-module is implemented in the larger macroeconomic model following an EEIO approach, which assigns the copper use coefficients to sectoral gross outputs. Total domestic copper use is thus calculated in the following way (the notation is the same as in Section 4.2):

$$\boldsymbol{m}^c = \boldsymbol{e}^c \boldsymbol{X} \tag{4.52}$$

$$\boldsymbol{X} = \boldsymbol{L}\hat{\boldsymbol{y}} \tag{4.53}$$

[20]The analysis in Chapter 5 provides some insights into the historical development of material coefficients in general. However, these coefficients only refer to the first stage of the supply chain and can therefore not be directly compared to the copper coefficients here.

where:	$\boldsymbol{m}^c$	=	copper use vector
	$\boldsymbol{e}^c$	=	copper use coefficient vector (row vector)
	$\boldsymbol{X}$	=	gross output matrix
	$\boldsymbol{L}$	=	domestic Leontief inverse
	$\hat{\boldsymbol{y}}$	=	diagonal final demand vector

For simplicity, the different final demand categories are aggregated to a 72 by 1 vector, portraying aggregate final demand for each of the 72 sectors. This precludes a later allocation of copper use to different final demand categories, but still allows for a sectoral differentiation in the gross outputs necessary to fulfil final demand. In contrast to the material use coefficient matrix in the aggregate material sub-module, the copper coefficients can be portrayed in a single vector since only this one material use category is covered. The copper use vector $\boldsymbol{m}^c$ thus displays the direct and indirect copper use of each sector's final demand. As Equations 4.52 and 4.53 indicate, this is done by adding up the gross outputs necessary to fulfill the respective final demands and calculating the corresponding copper requirements. Total copper use is calculated using the entire final demand vector, including exports. The portion only accruing to domestic final demand is then calculated by subtracting copper use for exports from total use:

$$\boldsymbol{m}^{c,d} = \boldsymbol{m}^c - \boldsymbol{m}^{c,e} \tag{4.54}$$

$$\boldsymbol{m}^{c,e} = \boldsymbol{e}^{c,e}\boldsymbol{X}^e \tag{4.55}$$

$$\boldsymbol{X}^e = \boldsymbol{L}\hat{\boldsymbol{y}}^e \tag{4.56}$$

(4.57)

where:	$\boldsymbol{m}^{c,d}$	=	domestic copper use vector
	$\boldsymbol{m}^{c,e}$	=	copper use vector of exports
	$\boldsymbol{e}^{c,e}$	=	copper use coefficient vector for exports
	$\boldsymbol{X}^e$	=	gross output matrix for exports

Domestic and exported copper use are calculated in this way because the original allocation of copper use to different economic sectors based on data from the ICA supposes a homogeneous distribution of products across different final demand categories. The copper use vector $\boldsymbol{e}^c$ therefore does not distinguish between domestic use and exports. However, as explained above, the composition of exports in terms of copper containing products is different from domestic uses. This can be addressed by calculating a separate copper use vector coefficient for exports $\boldsymbol{e}^{c,e}$, which is based on the recorded export values of copper reaching from concentrates to finished goods. For this, data from WirtschaftsVereinigung Metalle (2015) as well as the UN Comtrade database (United Nations, 2017) was used.

As mentioned above, for the calculation of copper embodied in imports, the DTA is used. In order to account for the resulting difference in material requirements between domestic and foreign production technologies, the copper use coefficients for imports $\boldsymbol{e}^{c,m}$ were adapted to match recorded imports of copper. The copper contained in imports is thus calculated in the following way:

$$\boldsymbol{m}^{c,m} = \boldsymbol{e}^{c,m}\boldsymbol{X}^{m} \tag{4.58}$$

$$\boldsymbol{X}^{m} = \boldsymbol{L}\hat{\boldsymbol{y}}^{m} \tag{4.59}$$

where: $\boldsymbol{m}^{c,m}$ = copper use vector of imports
$\boldsymbol{e}^{c,m}$ = copper use coefficient vector for imports
$\boldsymbol{X}^{m}$ = gross output matrix for imports
$\hat{\boldsymbol{y}}^{m}$ = diagonal final demand vector for imports

This way of calculating the copper use of imports therefore does not draw on the differentiation between imports of intermediate and final goods but instead assigns different copper use coefficients to "virtual" domestic sectoral production.

The input-output calculation allows for a comparison between direct sectoral copper use in the form of semi-finished goods deliveries to finished goods producing sectors and indirect sectoral copper use in later stages of the supply chain. This comparison is illustrated in Figure 4.16, the left hand side of which maps the deliveries of semis to sectors which produce end-use goods. The allocation of semis to end-use goods producing sectors follows the logic outlined above. Part of these end-use products are delivered to other sectors – in many cases through several cycles – in order for these sectors to provide final goods and services to consumers, which is depicted on the right hand side of Figure 4.16. The basis for this allocation is the IO calculation described above, in which each sector's gross output and the corresponding copper use are computed based on the structure of German final demand for goods and services in 2012.

A relatively large share of copper is indirectly used by non-manufacturing sectors. In fact, about 10% of total copper use is attributable to economic sectors belonging to the primary and tertiary sector, i.e. to agriculture and various services, ranging from wholesale to personal services. Figure 4.16 also reveals shifts between direct copper use of end-use goods producers and indirect copper use through final demand within the same sectors. This can be most clearly seen in the cases of the electrical equipment and the metal products sector. Only about 80% of the copper used by the electrical equipment sector as semis ends up in final demand goods of that sector. This effect is even more pronounced for the metal products sector; about half of its products are components of other sectors' final goods, mainly in the form of vehicles and machines, and therefore do not serve final demand for products of this sector.

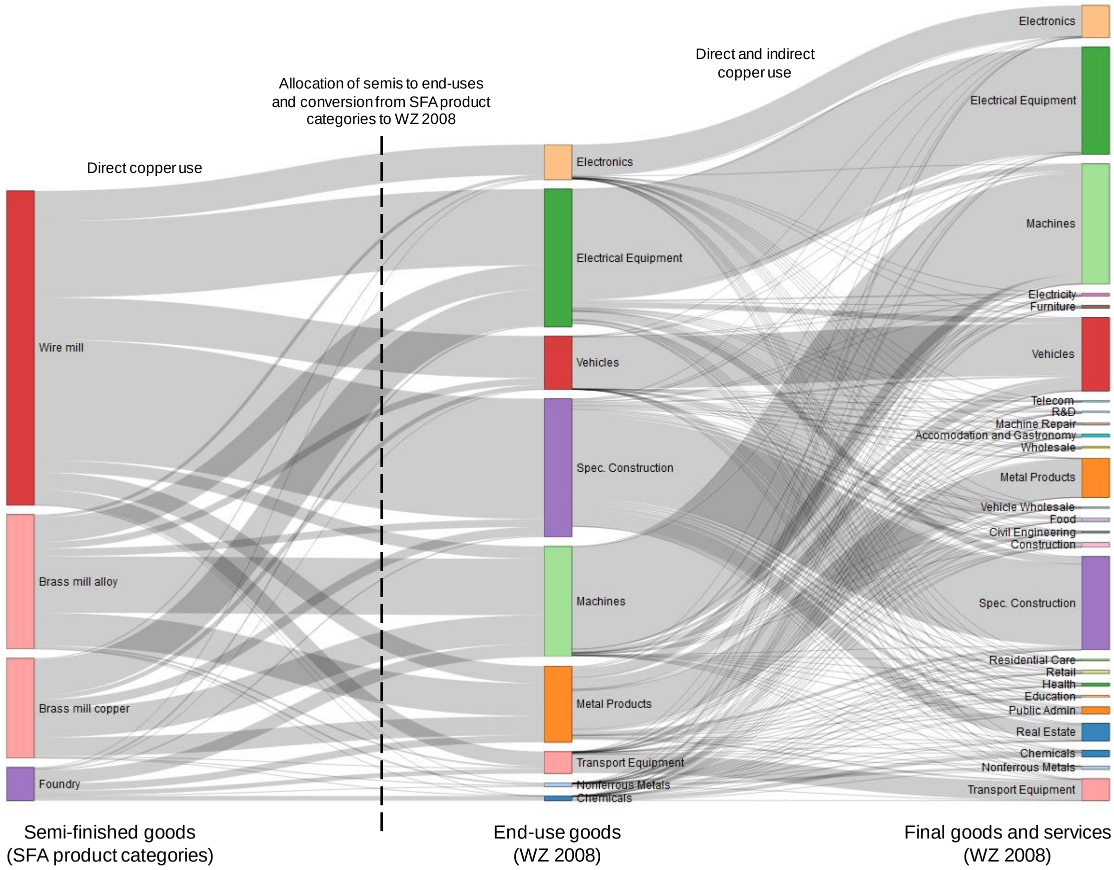


Figure 4.16: Distribution of copper in semis, end-use production and provision of final goods and services in Germany in 2012 (in kt), own calculation based on ICA data and Destatis (2014c); sectors with either total in- or outflows below 2 kt are excluded for better visibility

On the contrary, total copper use in the vehicles sector induced by final demand is underestimated when solely looking at the direct use of copper semis in this sector. Along the supply chain, the indirect copper use of final demand for vehicles is close to 40% higher than this sector's use of semis. The majority of this indirect use is due to copper containing intermediate deliveries of the metal products sector, followed by a smaller amount of intermediates from the machinery sector. Thus, for a number of sectors there is a clear difference between direct copper demand and indirect copper use as driven by final demand in these sectors. These results and other indirect uses of copper are also summarized in Figure A.6 in the Appendix.

This sectoral distribution is quite different from what it would have been if the adaptation to the copper use coefficients as described above had not been made. Figure A.5 in the Appendix shows the alternative distribution in which the electrical equipment sector dominates both end-use goods production in the SFA logic as well as copper use induced by final demand in the logic of national accounts. In this alternative distribution, only about 4% of total copper use from domestic production is induced by final demand in the three construction-related sectors, construction, civil engineering and special construction activities. In contrast, using the adapted copper coefficients, copper use by final demand in the construction sectors is 17%. Overall, in the alternative distribution, copper use in manufacturing sectors is considerably higher, whereas other sectors, especially services (now only 4%), have a much lower share of copper demand.

Linkage with the substance flow model for copper

The copper sub-module also serves as a two-way interface between the macroeconomic and the substance flow model, which translates monetary flows denoted in the economic sector structure of the macroeconomic model into copper flows contained in end-use goods and vice versa. Thus, on the one hand, the sectoral economic development within the macroeconomic model serves as the driver for copper production in the substance flow model and therefore the development of in-use copper stocks. Likewise, trade dynamics of copper containing end-use goods are driven by the economic model. On the other hand, changes in physical copper flows can translate into changes in the demand for final products, intermediate deliveries between sectors and imports and subsequently induce other macroeconomic effects ("macroeconomic dynamics" in Figure 4.17), such as changes in the sectoral composition of the economy or the overall demand level.

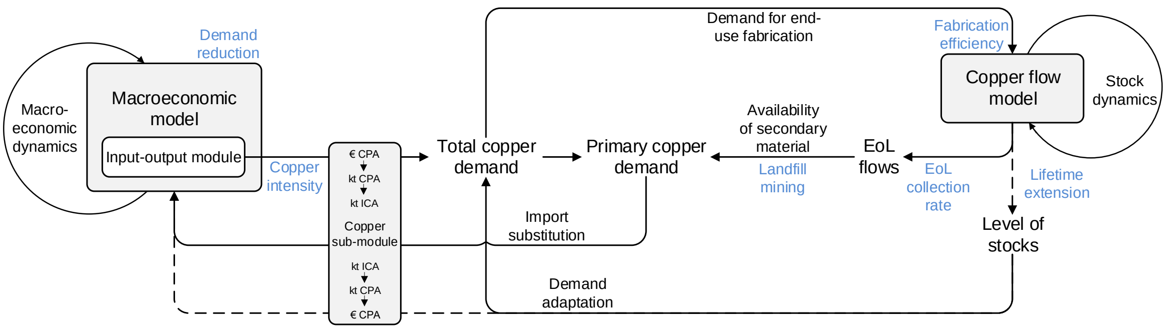


Figure 4.17: Illustration of model coupling, scenarios in blue

This model setup is schematically illustrated in Figure 4.17. On the left side, the macroeconomic model is depicted as the driver of overall sectoral production in monetary terms (in the WZ 2008/CPA classification). The model interface translates sectoral monetary demand into physical demand according to the end-use categories used in the copper flow model (in the ICA-classification). The conversion from the economic to the physical level is performed in three main steps. First, sectoral gross output (in monetary terms) is calculated based on final demand according to the input-output logic outlined above (see also Equation 4.53). Second, with the help of the copper use coefficients summarized in Table 4.6, sectoral use of semi-finished goods (in physical terms) for the production of end-use goods is calculated (see also Equation 4.52). Third, sectoral copper demand is translated into demand of copper for different end-use categories with the help of an allocation matrix (see Table A.9 in the Appendix). The conversion from the physical to the economic level goes the other way around, where changes in copper flows translate into changes in sectoral gross output and corresponding macroeconomic effects.

The economically driven total demand for copper thus drives the physical fabrication and imports of copper containing end-use goods in the copper flow model on the right side of Figure 4.17. The stock dynamics resulting from varying lifetime distributions of different end-uses allow for the calculation of available secondary material. Ultimately, the comparison between available secondary material and total copper demand yields the demand for primary copper. As outlined in Section 4.1, the quality of secondary copper is sufficient to be used in all applications. It is therefore assumed that all available secondary copper is used first and only then primary sources are tapped. Primary copper demand is thus the difference between total copper demand and available secondary copper (see also Figure 4.17).

The efficiency scenarios, which will later be analyzed with this model setup, are depicted in blue in Figure 4.17. A more detailed explanation of the scenarios and simulation results is provided in Section 6.2. Depending on the part of the industrial system they target, they have different impacts on overall copper demand or supply of secondary copper. For instance, the lifetime extension on the one hand serves to reduce demand for new products but also delays the availability of secondary copper as products only get scrapped at a later point in time. In contrast, a reduction of the copper intensity of products directly reduces physical copper demand per unit of monetary output. However, it also leads to a reduction in the availability of secondary material since the products yield less copper when they eventually get scrapped. All scenarios that lead to a reduction in primary copper demand also lead to a substitution of imports (since primary copper is exclusively imported) with domestic secondary material. Additional dynamics of the scenarios are described in more detail in Section 6.2.

4.4 Conclusions

In this chapter, the model setup for the empirical analyses of the following chapters was presented. The core of this setup is a newly developed macroeconomic simulation model, ISI-Macro. It is based on current macroeconomic data for Germany and has the same resolution as the German input-output statistics. As a simulation model, it is capable of portraying the economic effects of the implementation of material efficiency technologies, which will be subject of Section 6.1. Next to a detailed input-output and auxiliary modules, ISI-Macro contains a dedicated material module, which contains an aggregate part for the analysis of economy-wide material flows, and a part concentrating on copper stocks and flows within the German copper cycle.

The aggregate sub-module is conceived as an environmental extension of the macroeconomic model and is thus able to calculate a wide range of material use and other environmental indicators, including direct and indirect trade flows of raw materials. Because of its design, the sub-module is not only capable of portraying flows of unprocessed raw materials, but also of those contained in different products along the supply chain. With this setup, it is thus also possible to assess the environmental implications of the macroeconomic dynamics ensuing from material efficiency measures, which will also be covered in Section 6.1. Direct reduction potentials can thus be compared to overall material demand once all macroeconomic adaptation mechanisms have played out, allowing for estimations of rebound effects. The basis for the aggregate material sub-module form the high-resolution environmental extensions of the MRIO database EXIOBASE.

The second part of the material module is dedicated to the German copper cycle, which is based on detailed economy-wide copper flow data provided by the copper industry. This sub-module on the one hand allows for the calculation of copper demand based on economic development on a sectoral level and on the other hand portrays the influence of physical copper flows on the economic sphere. It also serves as the link to a new substance flow model of the German copper cycle, which has been co-developed in this thesis and was briefly described in the first part of this chapter. Since the copper flow model is also implemented in SD, it can easily integrated with the copper sub-module of the simulation model. With this setup, calculated copper stocks can be used to determine the amount of secondary material, from which primary copper demand can be inferred. This combination of a macroeconomic simulation and a substance flow model therefore provides a unique tool to determine copper demand not just based on economic flows but also on physical stocks. The coupled model is thus used to run simulations on the stock and flow dynamics of different efficiency measures in the German copper cycle, which will be subject of Section 6.2.

5 Analysis of material consumption in Germany[1]

In this chapter, the results of the analysis of past material consumption in Germany are presented. Section 5.1 depicts material consumption in Germany in the time frame from 1995 to 2011 based on MRIO analysis with the help of the EXIOBASE database. In addition, it critically discusses the results of the analysis in comparison to other historical analyses and with respect to the methodology used. The drivers of this historical material consumption are then identified in Section 5.2 using Structural Decomposition Analysis (SDA). The effects of changes in different decomposition factors are discussed in detail in individual sub-sections. Section 5.3 closes with a conclusion of this chapter.

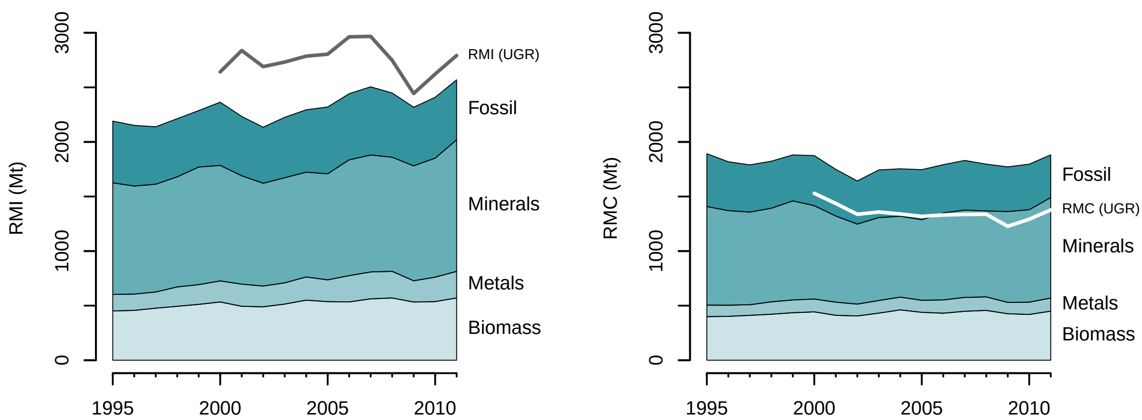
5.1 Past development

5.1.1 Overview of results

In order to get an overview of economy-wide material flows in Germany, the results of the retrospective analysis are presented in this section. Overall, material consumption has remained relatively steady in the time frame from 1995 to 2011, while material input (i.e. including exports) has increased by close to 20%. Figures 5.1 and 5.2 show the developments of the different aggregate material use indicators in the time period from 1995 to 2011. The calculations are based on the time series data in EXIOBASE as explained in Section 4.3.1. Figure 5.1 displays the development of the consumption indicators only taking used extraction into account (RMI and RMC). It additionally contains a comparison with the numbers from the environmental-economic accounts (Umweltökonomische Gesamtrechnung – UGR) of the German Statistical Office (Destatis, 2011, 2018) and a recent publication by the German Environment Agency (Lutter et al., 2016b). Figure 5.2, which displays the development of the indicators also taking unused extraction into account (TMR and TMC), contains a comparison with numbers from a study commissioned by the German Environment Agency (Schütz and Bringezu, 2008), though the database for the indicators which include unused extraction is less extensive and has not been updated a systematic

[1]Part of this chapter has been prepared for re-submission to *Journal of Industrial Ecology* as Pfaff, M. and Walz., R. (2019). Analysis of raw material use in Germany: Historical trends and structural decomposition.

way. The calculations of the Statistical Office and the the Environment Agency are primarily based on a national IO model, which relies on the Domestic Technology Assumption (see Section 4.3), coupled with a number of auxiliary statistics, including production, trade, agricultural, forestry and fishery data, material flow accounts and LCA coefficients (Kaumanns and Lauber, 2016; see Lansche et al., 2007 and Giegrich et al., 2012 for a list of material import coefficients).



(a) Raw material input (b) Raw material consumption

Figure 5.1: Time series of aggregate material use indicators, own calculation based on EXIOBASE v.3.4; data for comparison from Destatis (2011, 2018) and Lutter et al. (2016b)

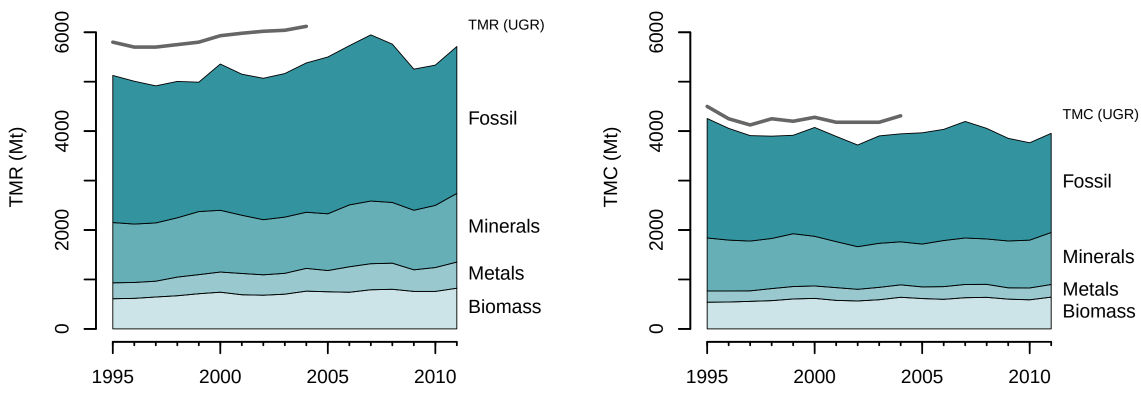
According to the calculations in this thesis, the majority of both RMI and RMC is made up of minerals, followed by biomass and fossil fuels. Metals make up the smallest fraction. As Figure 5.1a shows, Germany's RMI has been increasing since 1995 from about 2200 Mt to about 2600 Mt in 2011, which equals an increase of 17%. In relative terms, the biggest increase happened for the category of metals, followed by biomass and – to a lesser extent – minerals. The raw material input of fossil fuels has slightly decreased. In contrast to these calculations, the numbers of the Statistical Office suggest that an increase of only 6% has taken place between 2000 and 2011, though the curve indicates that the recovery after 2009 may continue and a further increase in the future is possible. Unfortunately, newer data is so far unavailable. The main reason for the deviations in magnitude and trend between the present results and those of the Statistical Office is a difference in the methodologies applied. As explained in more detail below, the MRIO approach used here provides a more detailed representation of international supply chains than the coefficient-based national IO approach used by the Statistical Office.

In the case of RMC, the development between 1995 and 2011 does not have a clear direction, despite some fluctuations. As Figure 5.1b shows, RMC is at approximately the same level in 2011 as it was in 1995. However, internal shifts between the material categories within RMC took place. The consumption of metals has increased by 14% in the period from 1995 to 2011 and that of biomass by 13%. The use of minerals has remained relatively steady, while fossil fuel consumption has decreased by almost 20% in the same period.

Since RMC is calculated by subtracting exports from RMI, the difference in absolute growth between these two indicators implies that materials embodied in exports must have driven the increase in RMI. Different conclusions regarding the development of RMI and RMC can therefore be drawn. While RMI shows a clear upward trend (which, however, need not continue in the future), RMC, which indicates the raw material consumption that is required for domestic consumption purposes, does not. Therefore, from the perspective of material efficiency, the steady material intensity of German domestic final demand is a positive signal as it implies relative decoupling between material consumption and economic growth (see Section 2.2.3). However, it could also be argued that Germany's economy depends heavily on exports and therefore it is also important to look at the material intensity of these exports (see Chapter 7 for a more extensive discussion of this issue).

Exports are also the main cause of the difference between the RMI values calculated with EXIOBASE and those of the Statistical Office. For instance, the Statistical Office arrives at more than double the RME of exports in 2010 than what results from the EXIOBASE calculations. Imports are also slightly higher in the results of the Statistical Office, while only domestic extraction is approximately the same in both cases. Together, these differences lead to the different pictures portrayed in Figures 5.1a and 5.1b. Compared to the EXIOBASE results, the Statistical Office thus overestimates RMI, while the high value for exports leads to an underestimation of RMC (since more material is exported and therefore does not count as domestic consumption). It should be noted, however, that a 2010 publication of the Statistical Office states RMI numbers considerably above (on average approximately 4000 Mt/year) and RMC numbers slightly above (on average 2000 Mt/year) those calculated here (Destatis, 2010a). This report is based on an old calculation methodology (cf. Buyny et al., 2009), which utilizes a since then revised version of the coefficient-based approach and appears to assume considerably higher RME for metals than later studies (e.g. Destatis, 2011, 2018; Lutter et al., 2016b). It is unclear which steps the revisions of the coefficient-based approach entailed. However, the wide range of results indicates a relatively high degree of uncertainty with respect to material intensities. The methodologically more transparent MRIO approach appears to be better equipped to deal with such uncertainties.

If unused extraction is added to the above indicators, the picture changes mostly with respect to the composition of the contributing material categories. As Figure 5.2 shows, the majority of TMR and TMC is made up of fossil fuels, in particular brown



(a) Total material requirement (b) Total material consumption

Figure 5.2: Time series of aggregate total material use indicators, own calculation based on EXIOBASE v.3.4; data for comparison from Schütz and Bringezu (2008)

coal from domestic extraction[2]. This has to do with the large amounts of unused material in coal mining activities, which are not of relevance when only looking at used material (see Section 2.2.3). The main driver of the growth in TMR (+11% from 1995 to 2011) are again exports, mostly in the form of metals and to a lesser extent biomass. In the same time frame, TMC has actually decreased by about 7%, mainly due to a reduction in fossil fuel use. However, similar to RMC, the total material consumption of metals and biomass has increased in this time period.

The differences between the TMR and TMC results of the EXIOBASE calculations and those of the Environment Agency and other sources published in Schütz and Bringezu (2008) are in this case not mainly due to differences in exports. They are slightly higher in the latter case, which is also apparent from the fact that the TMR curve of the UGR in Figure 5.2a is considerably above the calculated TMR values here, while the TMC curve in Figure 5.2b is only slightly above the calculated values. However, domestic extraction is also higher in Schütz and Bringezu (2008). This becomes clear when looking more closely at the TMC curve, which is still above the calculated EXIOBASE values after subtracting exports, and not below as in the case of the RMC curve. TMR values reported in another publication commissioned by the Environment Agency (Dittrich et al., 2013) lie somewhere in between the results reported in Schütz and Bringezu (2008) and the calculations presented here. The former use a slightly different methodology, which is based on material flow data compiled by the Vienna University of Economics and Business (WU) and the Sustainable Europe

[2]This result is informed by preliminary calculations with a previous version of EXIOBASE (v3.3), which differentiated between different fossil fuel categories. Due to data licensing issues, the current version (v3.4) does not differentiate between different fossil fuel categories anymore.

Research Institute (SERI) that is now located within the UN International Resource Panel (IRP) Global Material Flows Database (UN IRP, 2017) and a physical trade data base compiled by Dittrich (2011). This again indicates a certain degree of uncertainty and variation in the material use coefficients employed by Dittrich et al. (2013) and Schütz and Bringezu (2008).

5.1.2 Discussion of results

Overall, there are a number of possible reasons for the deviations between the results presented here and those of the Statistical Office (for RMI and RMC) / the Environment Agency (for TMR and TMC). The primary reason is likely the underlying data of each respective approach. EXIOBASE uses various data sources, including the UN's National Accounts Main Aggregates Database (United Nations, 2017) for economic aggregates, national accounting data from individual national statistical offices for IO data and the UN IRP Global Material Flows Database (UN IRP, 2017). The data is harmonized to fit into a balanced MRIO framework, which provides consistency on the one hand, but may lead to inaccuracies on the other hand. Since its first version, EXIOBASE (now in the third version) has undergone many rounds of validation and refinement, though the large amounts of data from various sources still remain a challenge (Stadler et al., 2018). The German Statistical Office utilizes its own national IO model with satellite data on material flows and the RME of trade flows based on Giegrich et al. (2012), Lansche et al. (2007) and other sources, including industry associations, such as the German Copper Institute. Many parts of the original data base as described in Buyny et al. (2009) have been revised, suggesting that inaccuracies as well as inconsistencies have been alleviated to some extent. This especially concerns the underlying material flow tables and indirect material use coefficients (Kaumanns and Lauber, 2016). Thus, the national production structure, including the material flows within it, is probably more accurately portrayed than in EXIOBASE. It is more difficult to assess the quality of the Statistical Office's data with respect to trade flows. Compared to EXIOBASE, more detail and targeted manual adaptations are likely, while consistency within a global economic context may not be fully given. The publications associated with the Environment Agency (Schütz and Bringezu, 2008; Dittrich et al., 2013) use the same material flow database as EXIOBASE, though an earlier version, but different information on global trade flows (Dittrich, 2011). Therefore, the difference between data bases should in this case not weigh as heavily as in the comparison with the results of the Statistical Office, though noticeable differences may still be present.

Another but connected reason for diverging results are the different methodologies employed in handling the data, i.e. the MRIO approach used here vs. a coefficient-based approach in the publications associated with the Statistical Office and the Environment Agency. As outlined above, the MRIO approach relies on a consistent depiction of the global economy and associated material flows. The aggregate material use of a country thus results from global economic interactions. Depending on the accuracy of

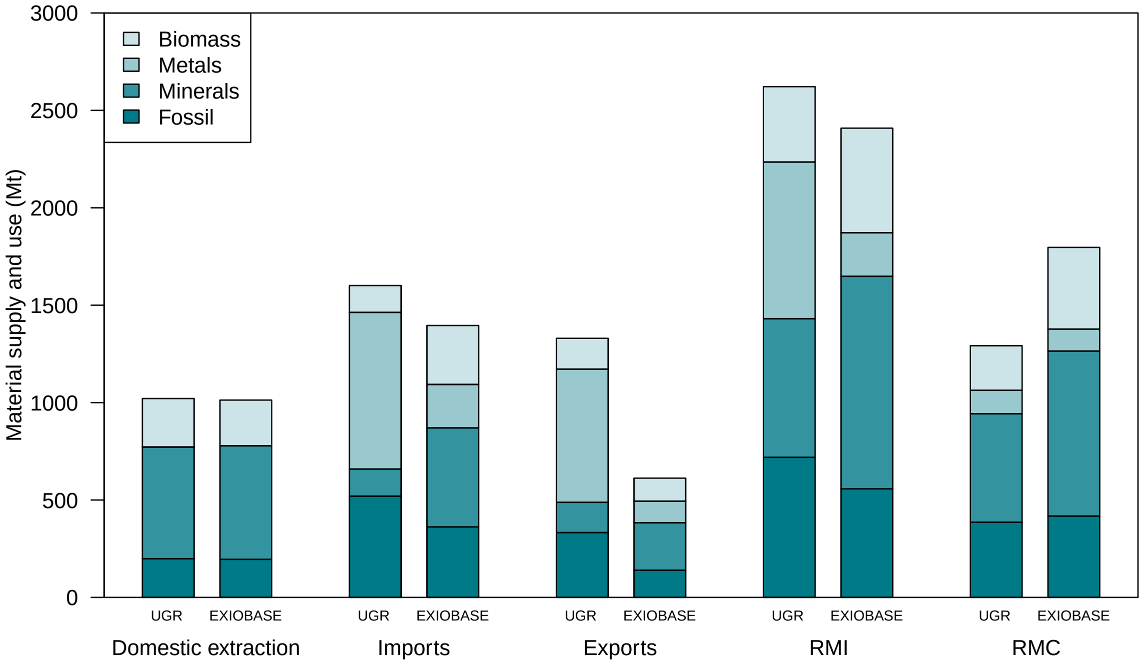


Figure 5.3: Comparison of RMI and RMC results for 2010, own calculation based on EXIOBASE v.3.4 and UGR data from Destatis (2018)

the portrayal of these interactions, the associated material flows can be precisely and transparently attributed to countries and economic sectors (see Section 4.3.1). For instance, as Figure 5.3 shows for the exemplary year 2010, trade in minerals appears to be relatively high in the EXIOBASE results considering that many materials in this category are high mass and low price minerals and therefore only traded to a limited extent. However, the category of minerals which most heavily contributes to these trade flows is “other minerals”, which excludes the main aggregates, such as sand, clay, building stones, limestone etc. It is therefore unclear whether this is an overestimation based on too highly aggregated sectors (see Section 2.3.1), or whether minerals, specifically industrial minerals, may actually be traded to that extent.

In a coefficient-based approach such as that employed by the Statistical Office, material use is driven by national economic activity. The contribution of global economic structures to national material use is implicit in the employed material use coefficients. A country’s material use is therefore more directly related to its own activity, including the direct exchange with other countries, than with the global economic structure.[3] It therefore appears reasonable, for example, that a global manufacturer of machinery and automobiles such as Germany imports high volumes of metals (measured in RME

[3] As explained above, this is somewhat alleviated by adapting the coefficients to the average material contents of imports. However, the intricacies of the global production network are not portrayed with this approach.

of metal ores), processes them into products, and partially re-exports them (see Figure 5.3). Accordingly, the results of the Statistical Office and the Environment Agency suggest that metal ores by far make up the largest fraction of material imports and exports. In contrast, the calculations with EXIOBASE arrive at a noticeably different share of metals in trade flows. In fact, among the four material categories they make up the smallest fraction of both imports and exports. However, a breakdown of the contributions to metal imports and exports in the results of the Statistical Office reveals that the majority is made up of non-ferrous metal ores, excluding copper and aluminum/bauxite. Thus, the main contribution comes from relatively low volume but partly high monetary value metals (nickel, zinc, tin, lead, gold, silver, Platinum Group Metals (PGMs) etc.), some of which have comparatively large material footprints (e.g. 740 kt KRA per t of gold) and therefore high leverage on aggregate material use indicators (Giegrich et al., 2012). This has been identified as a potential problem since these numbers are associated with high uncertainties and the potential to considerably affect aggregate results even through small variations (Kaumanns and Lauber, 2016). In contrast, the metal imports and exports calculated with EXIOBASE are dominated by iron and copper ores, followed by much smaller contributions from the other metals. These results therefore do not appear to be subject to such a strong leverage effect of the environmental coefficients of the low volume metals. Nevertheless, the traded quantities of these high volume metals do not match the numbers of the Statistical Office / the Environment Agency. Therefore, additional factors determining these differences must be at play.

An indication of the general validity of the MRIO approach is the proximity of the import values of materials which are predominantly traded in raw form, such as the different coal types ranging from brown coal to anthracite and fertilizer minerals, to the import numbers of the Statistical Office. Since these materials are mostly not contained in traded products, it is likely that their trade flows can be confidently recorded by the Statistical Office. As similar trade numbers are produced with the EXIOBASE calculations, it appears that the MRIO logic and thus the attribution of direct and indirect material demands to global inter-industry flows functions well. Hence, it can be assumed that the trade flows of more heavily processed materials, which are calculated according to the same logic, are also accurately portrayed.

Other methodological differences that may be responsible for the diverging results include the treatment of secondary raw material and the double counting of trade flows. The product by product version of EXIOBASE includes secondary material product groups (wood, paper, plastic, glass, steel, precious metals, aluminum, lead, copper, other non-ferrous metals, construction material, and other secondary material; see Table A.8 in the Appendix) but the respective cells in the intermediate deliveries matrix table have no entries due to the way the product by product table is constructed from supply and use tables (cf. Eurostat, 2008a). Thus, while the portrayal of secondary material flows is in principle possible in EEIO, they are not covered in the product by product version of EXIOBASE. However, EXIOBASE is constructed in such a way that primary material demand is triggered by economic activity without having to account for secondary material.[4] In the approach of the Statistical Office and the Environment Agency, secondary material is subtracted from material demand when calculating primary demand. While the original approach of Buyny et al. (2009) has been refined, this may still be a source of inaccuracies (Kaumanns and Lauber, 2016). The above results would indicate that EXIOBASE either underestimates primary material demand (and thus potentially overestimates the implicit use of secondary material), or that the Statistical Office and the Environment Agency underestimate the use of secondary material and thus overestimate the demand for primary material.

Double counting of trade flows can occur in complex global production systems where multiple exchanges of intermediate goods take place (see Section A.8.1 in the Appendix). This can potentially lead to overestimates of 'real' trade flows. From the perspective of one country, the double counted trade flows occur either in the form of re-exports (of previously imported goods) or re-imports (of previously exported goods). Some studies using a coefficient-based approach exclude re-exports (cf. Schoer et al., 2012, 2013) because they are irrelevant for consumption-based indicators (as they only constitute a throughput and do not remain in the economy). While there is explicit mention of re-exports in these publications, re-imports are not addressed, probably because it is nearly impossible from a national accounting perspective to identify those exports which may later re-enter the domestic economy. In an MRIO setting, the portrayal of trade flows can be expanded so as to include multiple types of cycles, which allows for the identification of re-exports as well as re-imports of individual countries (Koopman et al., 2014).

According to such an expansion, Germany's re-exports (the last three terms of Equation A.13 in the Appendix) made up over 50% of the material contained in Germany's exports (in RME) in 2011. Part of these re-exports (part of the ninth term in Equation A.13) are, however, re-imported again into Germany, which ultimately makes them imports (see Section A.8.1 in the Appendix). Re-imports, on the other hand, are negligible in size compared to total imports or exports. Despite their relatively large magnitude, re-exports should by themselves not be a source of large deviations between the MRIO and the coefficient-based results for the consumption-based indicators RMC and TMC, since they are subtracted from both imports and exports. To the contrary, the exclusion of re-exports should by itself actually lead to a lowering of the input indicators RMI and TMR. Considering that the MRIO results reported here include re-exports, the difference between them and the coefficient-based results would thus be larger. However, based on the different methodologies, the estimates for re-exports probably diverge considerably.

The above discussion shows that it is already difficult to establish unambiguous definitions of seemingly simple concepts like imports and exports in a globally interlinked economy. Considerable blur can therefore be expected when comparing ag-

[4] This, however, may imply that the economic interactions between sectors do not match economic statistics since the latter include implicit flows of secondary materials in mixed goods sectors.

gregate material use results of these different approaches. While the advantages of a coefficient-based national IO approach have been outlined above, the methodologically more consistent and more transparent MRIO approach provides a better basis for discussing the results of analyses on national material consumption. In an MRIO setting, it is also possible to identify different structural determinants of material consumption, while trade flows and the associated material use coefficients in a national IO approach are the results of external analyses and therefore have a “black box” character. The following section provides an MRIO-based structural decomposition of past material consumption in Germany and thus sheds some light on its underlying drivers.

5.2 Structural decomposition of past material consumption

5.2.1 Overview

The development of Germany’s raw material consumption between 1995 and 2011 can be attributed to different influencing factors. In this section, the focus will be on the consumption-based indicator only capturing used extraction, RMC. As described above, RMC is calculated as the summed product of the relevant entries of the material coefficient matrix and gross output, which in turn is the product of the Leontief inverse and final demand (see Equations 4.46 and 4.49). The change in RMC can thus be attributed to either a change in material coefficients, the structure of the global economy (as portrayed by the multi-regional Leontief inverse), or the level or composition of final demand for goods and services in Germany. In an MRIO context, Structural Decomposition Analysis (SDA) is the most comprehensive method to assess the individual contributions of these factors to the total change in RMC, since it is able to capture the entirety of global sectoral production and demand interlinkages (cf. Dietzenbacher and Los, 1998; Geng et al., 2013; Hoekstra and van den Bergh, 2002; Weinzettel and Kovanda, 2011). One form of SDA is additive decomposition, in which the changes in individual factors are summed to get the total change. When additively decomposed, Equation 4.49 thus turns into:

$$\Delta \boldsymbol{M} = \underbrace{\Delta \boldsymbol{E} \boldsymbol{L} \boldsymbol{y}}_{\text{Material coefficient change}} + \underbrace{\boldsymbol{E} \Delta \boldsymbol{L} \boldsymbol{y}}_{\text{Structural change}} + \underbrace{\boldsymbol{E} \boldsymbol{L} \Delta \boldsymbol{y}}_{\text{Final demand change}} \tag{5.1}$$

For simplicity, Equation 5.1 does not contain time indices. However, when comparing two years as in the present case, either one can be used as the respective reference value for the decomposition terms. Depending on which reference year is chosen, the individual terms have different values, even though the overall value for $\Delta \boldsymbol{M}$ remains the same. This yields a number of equally valid decomposition variants, none of which is conceptually strictly preferable to the other ones (Baiocchi and Minx, 2010; Dietzenbacher and Los, 1998; de Haan, 2010; Miller and Blair, 2009). The number of possible decompositions depends on the number of decomposition factors: if the number of factors is n, there are $n!$ possible decompositions. Since RMC is the product of the three factors, 1) material use coefficients, 2) Leontief inverse and 3) final demand, there are $3! = 6$ possible decomposition equations (Baiocchi and Minx, 2010, p.S7):

$$\begin{aligned}
\Delta\boldsymbol{M} &= \Delta\boldsymbol{E}\boldsymbol{L}^{11}\boldsymbol{y}^{11} + \boldsymbol{E}^{95}\Delta\boldsymbol{L}\boldsymbol{y}^{11} + \boldsymbol{E}^{95}\boldsymbol{L}^{95}\Delta\boldsymbol{y} && \text{(5.2a)}\\
&= \Delta\boldsymbol{E}\boldsymbol{L}^{11}\boldsymbol{y}^{11} + \boldsymbol{E}^{95}\Delta\boldsymbol{L}\boldsymbol{y}^{95} + \boldsymbol{E}^{95}\boldsymbol{L}^{11}\Delta\boldsymbol{y} && \text{(5.2b)}\\
&= \Delta\boldsymbol{E}\boldsymbol{L}^{95}\boldsymbol{y}^{11} + \boldsymbol{E}^{11}\Delta\boldsymbol{L}\boldsymbol{y}^{11} + \boldsymbol{E}^{95}\boldsymbol{L}^{95}\Delta\boldsymbol{y} && \text{(5.2c)}\\
&= \Delta\boldsymbol{E}\boldsymbol{L}^{95}\boldsymbol{y}^{95} + \boldsymbol{E}^{11}\Delta\boldsymbol{L}\boldsymbol{y}^{11} + \boldsymbol{E}^{11}\boldsymbol{L}^{95}\Delta\boldsymbol{y} && \text{(5.2d)}\\
&= \Delta\boldsymbol{E}\boldsymbol{L}^{11}\boldsymbol{y}^{95} + \boldsymbol{E}^{95}\Delta\boldsymbol{L}\boldsymbol{y}^{95} + \boldsymbol{E}^{11}\boldsymbol{L}^{11}\Delta\boldsymbol{y} && \text{(5.2e)}\\
&= \Delta\boldsymbol{E}\boldsymbol{L}^{95}\boldsymbol{y}^{95} + \boldsymbol{E}^{11}\Delta\boldsymbol{L}\boldsymbol{y}^{95} + \boldsymbol{E}^{11}\boldsymbol{L}^{11}\Delta\boldsymbol{y} && \text{(5.2f)}
\end{aligned}$$

The superscripts 11 and 95 indicate the respective base years 2011 and 1995 for the variables. In order not to distort the decomposition results through price jumps, the intermediate deliveries and final demand matrices are transformed into constant 2005 prices before conducting the decomposition calculations. For this, country and sector specific price indices from Stadler et al. (2018) are used.

Despite relatively large variations between the decomposition variants, it is useful to calculate an average for each decomposition term in order to get an overview of its contribution to total RMC change (Guan et al., 2008; Peters et al., 2007). The average values of the above decomposition are shown in Figure 5.4 for overall RMC and in Figure 5.5 for the four material categories it comprises: biomass, metals, minerals and fossil fuels. In order to show the ranges of results from the different decomposition variants, whiskers are added to both figures that indicate the minimum and maximum value of each decomposition term within Equation 5.2. The results reported in the following sections usually represent the average of the six decomposition variants. Where appropriate, the full set of variants is shown.

While the overall RMC change is relatively small (a reduction from 1,892 Mt in 1995 to 1,881 Mt in 2011), the changes attributable to the individual components are larger and partly counteract each other. Overall, material coefficient changes had a negative impact on German RMC while the structural change in the global economy as well as the development of Germany's final demand had a positive impact. Plank et al. (2018), who also use SDA and the World Input-Output Database (WIOD) with slightly different decomposition terms, arrive at similar results. For Western Europe, they find a negative material intensity (as expressed by material coefficients) effect and a positive influence of final demand on RMC. However, in contrast to the present results, they find a slightly negative effect of the structure of the global economy. Pothen and Schymura (2015), using Index Decomposition Analysis (IDA) on a less detailed global dataset with only two extraction sectors, also find a positive influence of final demand and a negative influence of material intensity on the material consumption of Germany.

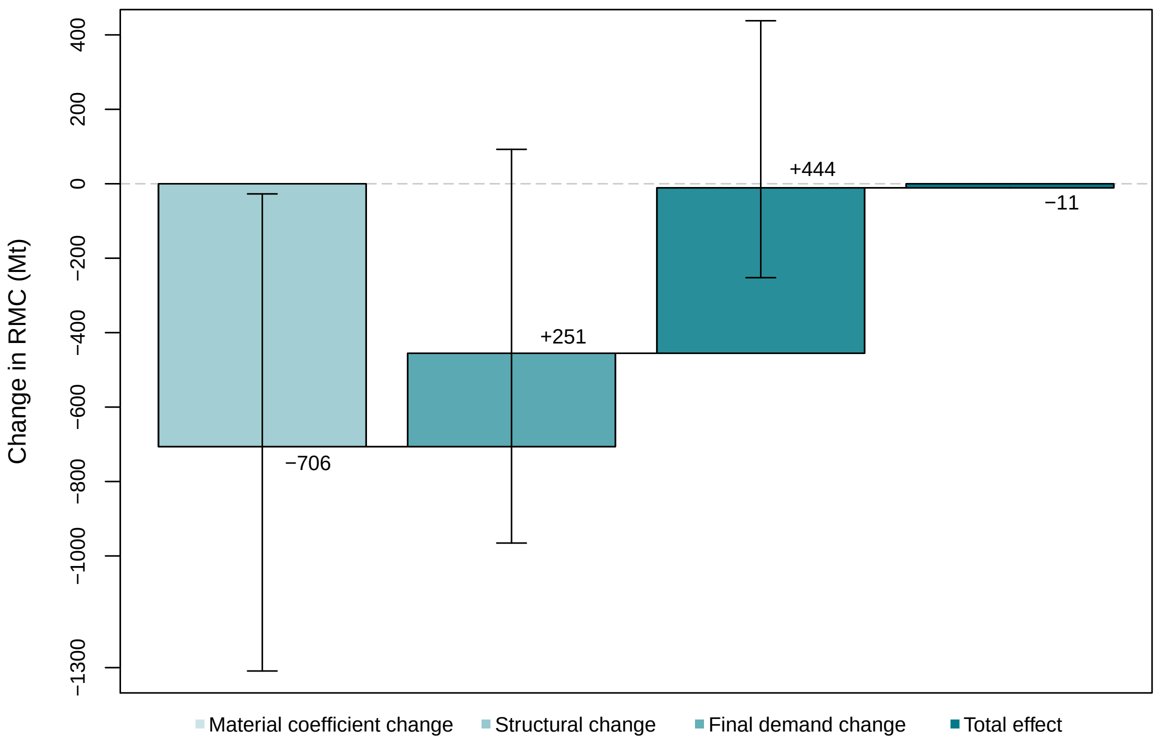


Figure 5.4: Decomposition of RMC change between 1995 and 2011, own calculation based on EXIOBASE v.3.4

However, like Plank et al. (2018), they find a negative influence of the structure of the economy. Similarly, Pothen (2017), also using IDA to analyze the determinants of global material consumption, finds a positive effect of the global final demand level and a negative intensity effect, but also a negative effect of the global economic structure as well as the structure of final demand (which he interprets as the increasing importance of less material-intensive services in developed countries).

As Figure 5.4 shows, the average contribution of the material coefficient changes is the highest with a potential RMC reduction of over 700 Mt, followed by a final demand driven potential RMC increase of close to 450 Mt. The structural changes in the global economy had the smallest average contribution with a potential RMC increase of about 250 Mt. The whiskers indicate a wide spread for each decomposition term. In the case of the material coefficient changes, the effect ranges from almost no RMC reduction to close to double the average reduction. A similar relative range, though with the opposite sign, can be observed for the final demand change, where the highest value (upper whisker) of the hypothetical RMC increase is almost double the average value indicated by the bar. In the case of the structural change of the economy, the lower whisker even represents a change of sign since it indicates a hypothetical RMC reduction as opposed to the average increase. The largest absolute deviation from the average value can also be observed in this category, where the upper whisker indicates a hypothetical RMC increase of close to 800 Mt, which is almost half of Germany's RMC in 2011.

The disaggregated results for Germany confirm the findings of Section 5.1 that in the case of biomass, metals and minerals, a small increase in material consumption has actually taken place between 1995 and 2011, while an overall reduction has been achieved for fossil fuels. As can be seen in Figure 5.5, the contribution of material coefficient changes is negative for all material categories except minerals, where a slight increase in RMC would have taken place if only the coefficients had changed. The opposite is true for structural changes of the global economy, which would have led to an increase of Germany's RMC for all material categories except minerals. Only the change in final demand uniformly has a positive impact across all material categories.

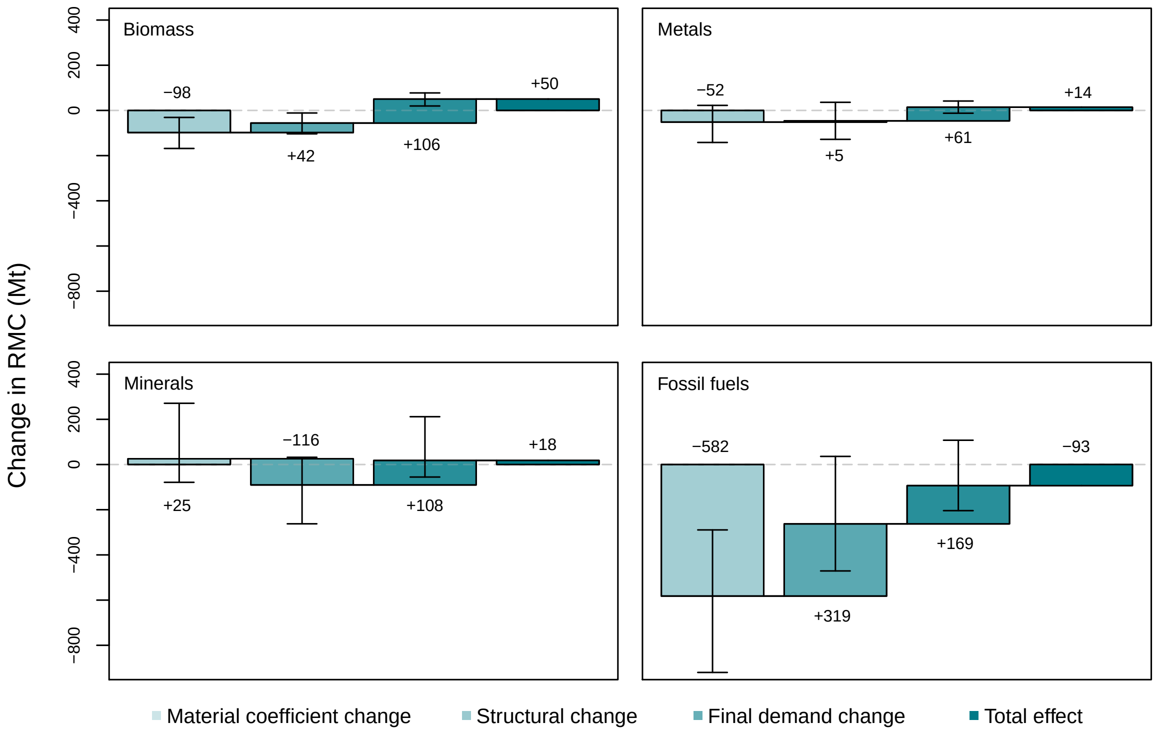


Figure 5.5: Decomposition of RMC change between 1995 and 2011 per material category, own calculation based on EXIOBASE v.3.4

Figure 5.5 also shows that the ranges of the different decomposition results indicated by the whiskers vary considerably between the different components of RMC. In relative terms, the largest variation can be observed for the structural change within the metals category, where the maximum value (upper whisker) indicates an increase of metal consumption between 1995 and 2011, whereas the minimum value (lower whisker) indicates a reduction that is multiple times the average value portrayed by the bar. Considerable variation can also be observed for fossil fuels and minerals, with the largest absolute variation for fossil fuels. It is also noteworthy that in a number of cases, the extremes as indicated by the whiskers would lead to effects with opposite signs, such as the material coefficient change in the metals and minerals category, as well as the structural change of the economy in the biomass, metals and minerals category. As stated above, only the final demand change consistently leads to hypothetical RMC increases. In the following, the contributions of the decomposition components are discussed in greater detail.

5.2.2 Effect of material coefficient change

The largest part of the overall RMC change in absolute terms is caused by a reduction in the material intensity of sectoral production, i.e. through a decrease in material coefficients. This effect is clearly dominated by fossil fuels, while biomass and metals also show intensity reductions, though on a considerably smaller scale. For minerals, a small intensity increase can be observed. In the case of fossil fuels, the intensity reduction could be interpreted as a reflection of the widespread efforts at reducing CO_2 emissions through the reduced use of fossil fuels. In the other cases, similar interpretations are possible, which can be summarized under the term material efficiency. However, as described in Section 4.3.1, EXIOBASE is constructed in such a way that the material coefficients refer to extraction sectors at the first stages of the supply chain. Reductions in these coefficients (expressed as a change in kt per M€ gross output of a given sector) thus imply, for example, that the copper ores and concentrates sector uses less physical copper per Euro of its gross output, or that the crude petroleum sector uses less crude oil per Euro of its gross output.[5] These intensity reductions are passed on to downstream sectors in the sense that less material is transported per Euro of intermediate inputs from the extracting sectors. However, in the decomposition it is assumed that the other factors in the input-output calculation remain constant, including the monetary value of intermediate inputs from extraction to downstream sectors. In a quantity model such as that employed here, constant monetary transactions imply constant quantities at fixed unit prices (see Section 2.3.1), and cannot be interpreted, e.g., as reduced quantities sold at higher prices yielding constant monetary values. Therefore, the passing down of less material intensive intermediate inputs from extraction sectors cannot be interpreted as an effort on the part of downstream sectors to reduce their material input. It follows that smaller material use coefficients cannot be understood as a general reduction of the material intensity of the economy. In fact, as will be discussed below, in all cases except for minerals, this material intensity reduction is counteracted by a change in the structural com-

[5]The coefficient reductions therefore do not imply changes at later stages in the supply chain which are often analyzed in the context of material efficiency, for example the use of thinner sheet metal plates in automobile construction. Such a measure would be represented by a change in the intermediate delivery from the metal products sector to the automobile sector (see Sections 2.3.1 and 4.3.2).

position of the economy, which by itself would have caused an increase in German material consumption in the period from 1995 to 2011. In addition, it is likely that the intensity reduction will not continue indefinitely as there are physical limits to this. The relatively constant values of RMC and TMC as portrayed in Figures 5.1b and 5.2b can thus be expected to increase in the future if changes in final demand and the structural composition of the economy continue to have a positive influence on material consumption.

Nevertheless, the negative effect of coefficient changes on Germany's RMC in the biomass, metals and fossil fuel categories indicates that less physical input was needed in 2011 than in 1995 to produce a given monetary amount of output in the raw material processing sectors. Since the monetary transactions in the underlying input-output tables have been transformed into constant prices, this development cannot be explained by price hikes and concurrent steady material inputs. Thus, raw material processing sectors in the biomass, metals and fossil fuel categories must have reduced their material intensities. In the case of metals, this apparently happened despite declining ore grades for some metal ores (Calvo et al., 2016; Frenzel et al., 2017; van der Voet et al., 2018), which would imply a higher ore input requirement per unit of output.

The change in material coefficients can be further decomposed into a change in domestic material coefficients and a change in the material coefficients of the rest of the world. For this, the $\Delta \boldsymbol{E}$ of Equation 5.1 is split up into one part in which the change only applies to German material coefficients and one part in which only foreign coefficients are changed. According to this decomposition, the change in Germany's coefficients only accounts for about 31% of the effect. The remaining 69% are due to intensity reductions in the rest of the world, which have an influence on imported material consumption. Therefore, more than two thirds of Germany's material efficiency induced RMC reduction can be attributed to material intensity changes outside Germany. This clearly highlights the importance of considering international supply chains when calculating national material footprints.

Table 5.1: Contribution of domestic and imported coefficient change to RMC change; negative numbers represent effects with the opposite sign of the overall effect.

	Biomass	Metals	Minerals	Fossil	Total
Domestic	-2%	0%	-499%	16%	31%
International	102%	100%	599%	84%	69%

When looking at the individual material categories of RMC, large variations can be observed in the shares of domestic and international coefficient changes. The average results for the above decomposition of the material coefficient changes are summarized in Table 5.1. A surprising result are the contrary effects of the domestic and the foreign coefficient changes in the biomass and especially the minerals categories. Thus, while in the case of biomass, RMC would have gone up slightly in response to domestic coefficient changes, a much larger negative effect results from changes in foreign coefficients. This is much more pronounced in the case of minerals, where the overall average coefficient changes would have led to a minor increase in RMC. However, if only the domestic coefficients had changed, a decrease of RMC almost five times the overall effect would have taken place. In contrast, if only the foreign coefficients had changed, an even larger RMC *increase* would have taken place. The contrast between domestic and foreign effect is driven by coefficient changes in the "other minerals" category (see Table A.7 in the Appendix), which is the most heavily traded mineral category but still has a large domestic share. The hypothetical RMC reduction due to the domestic coefficient change mainly results from a small negative domestic coefficient change (-1.5%) paired with the large domestic share of other minerals extraction. In contrast, the hypothetical RMC increase due to foreign coefficient changes mainly results from large increases in the coefficients of the largest trading partners Denmark, Brazil and – to a lesser extent – Great Britain. The development of the other minerals coefficients of these four countries are exemplarily summarized in Figure 5.6.

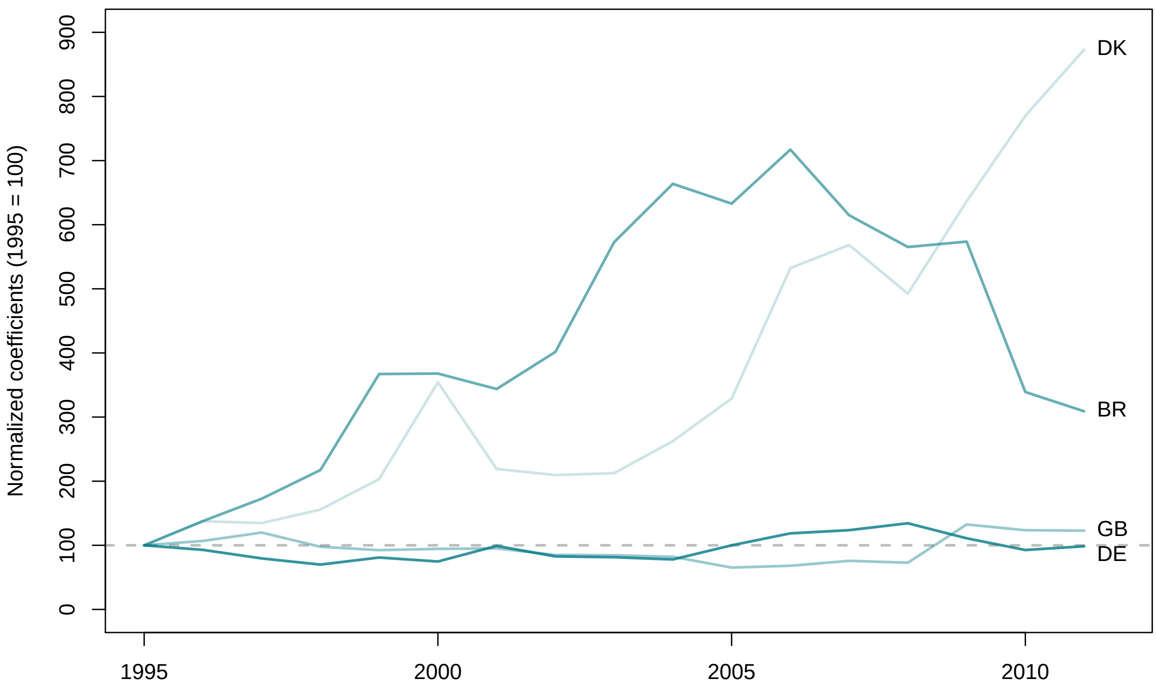


Figure 5.6: Development of other minerals coefficients from 1995 to 2011, own calculation based on EXIOBASE v.3.4

The small domestic contribution to the overall coefficient change induced RMC development in the fossil fuel category appears plausible since fossil fuels other than brown coal are largely imported. Similarly, virtually no domestic extraction of metals takes place, so there cannot be any domestic contribution to coefficient change induced RMC developments.

5.2.3 Effect of structural change

As indicated above, international structural changes, i.e. shifts in sectors' direct and indirect production recipes as portrayed by the multi-regional Leontief inverse, would by themselves have led to overall increases in German RMC. Thus while the relative use of unprocessed material inputs per unit of output of the extracting sectors has been reduced (material coefficient change), for the categories biomass, metals and fossil fuels the inter-industry demand for products which contain these raw materials has changed in such a way that Germany's material consumption would be higher in 2011 than in 1995. This effect cannot be attributed to changes in a few intermediate input coefficients of the multi-regional input-output table but is likely the result of a number of shifts in the multi-regional deliveries between sectors along the supply chain. For example, the copper products sector could have a higher demand for copper concentrate from the copper ores and concentrates sector. Alternatively, the shift could be later in the supply chain. For example, the motor vehicles sector could have a higher demand for copper wires in the wake of an increased production of electric cars. The changes may also happen in areas which may not be associated with direct material demands. The increase in cloud-based services for instance requires a buildup of physical infrastructure, which also contains copper. Such developments are likely to increase in the future.

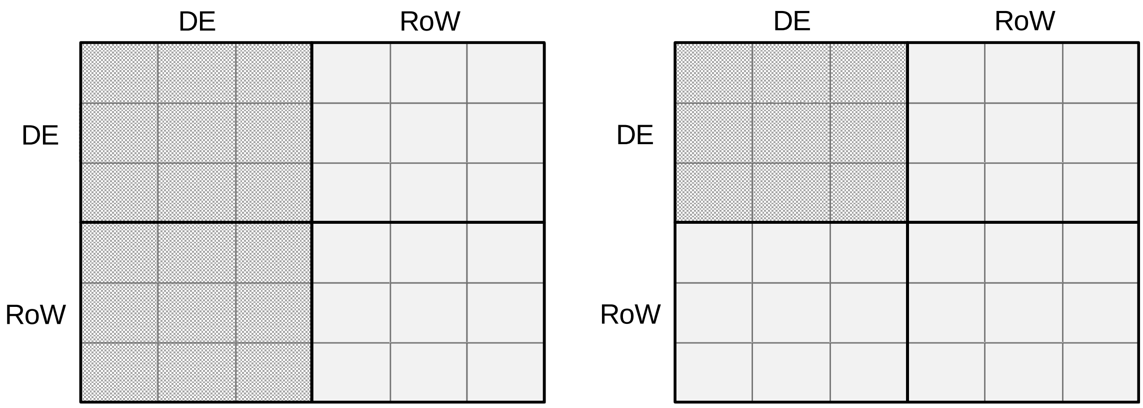
In an MRIO setting, the structural change (i.e. a change of the production structure) can in fact be interpreted as a mixture of a technology change in the form of changed domestic production recipes and a change in international trade patterns.[6] This difference can be addressed in yet another decomposition, where the two effects are portrayed separately. The change in the total Leontief inverse can be split up into two terms, one reflecting a change in Germany's production structure, the other reflecting a change the in trade between the countries of the MRIO system, excluding intermediate imports into Germany (which are part of Germany's internationally sourced production recipe):

$$\Delta \boldsymbol{L} = \underbrace{\boldsymbol{L}^{11} - \boldsymbol{L}^{11*}}_{\text{Technology change}} + \underbrace{\boldsymbol{L}^{11} - \boldsymbol{L}^{95*}}_{\text{Trade pattern change}} \tag{5.3}$$

where $\boldsymbol{L}^{11*}$ is constructed by using the L-matrix from the year 2011 in which only the intermediate inputs (domestic and imported) of Germany are changed to 1995 values. $\boldsymbol{L}^{95*}$ is in turn constructed by using the L-matrix from the year 1995, where only the intermediate inputs (domestic and imported) of Germany are changed to 2011

[6] International trade patterns of course also have underlying production recipes. However, in order to allow for a better differentiation between components, this simplified terminology is used.

values (see Figure 5.7a). The respective shares can then be calculated by using these partial Leontief inverses in the calculation of RMC. This decomposition reveals that the technology change within Germany accounts for 77% of the hypothetical RMC increase, while changes in international trade patterns, including German exports, account for the remaining 23%. Thus, close to one fourth of the technology change effect on German RMC is due to changes in international trade linkages which do not directly have to do with the German production structure.



(a) Change of all inverse input coefficients for deliveries to Germany

(b) Change of domestic inverse input coefficients for deliveries to Germany

Figure 5.7: Illustration of changes to inverse input coefficients

The technology change in Germany can further be split up into an effect caused by a change in just the domestic production structure and one caused by overall changes in intermediate inputs into Germany's production (including intermediate imports). For this, only the domestic intermediate input coefficients are changed according to the above logic (see Figure 5.7b). If only the domestic production structure had changed, German RMC would have in fact decreased by about 100 Mt, which is in line with the findings of Plank et al. (2018), Pothen and Schymura (2015) and Pothen (2017) on the effects of structural demand. On the contrary, a change only in the structure of imported intermediate inputs would have increased RMC by about 480 Mt. Therefore, the German economy could be characterized as dematerializing between 1995 and 2011 if only viewed domestically. In contrast, the intermediate deliveries it receives from the rest of the world appear to induce higher material demand in 2011 than in 1995. This again illustrates how international supply chains can have considerable impacts on national material footprints and may develop differently from national industrial structures.

5.2.4 Effect of final demand change

The changes in final demand would have by themselves driven up Germany's RMC in all material categories. For biomass, metals and minerals, the change in final demand represents the main driver of these hypothetical RMC increases. In the case of fossil fuels, the structural change of the economy would have by itself increased RMC more strongly than the change of final demand. However, in absolute terms, the contribution of the final demand change to RMC in the fossil fuel category is larger than in the other categories (see bottom right of Figure 5.5).

As outlined above, the effect of final demand changes is also positive across all decomposition variants. Hence, it appears that the development of final demand in Germany unambiguously led to increases in raw material consumption between 1995 and 2011. While the absolute effect appears plausible in a continuously growing economy, there may be changes in the composition of final demand that counter this development. In order to investigate this, the effect of final demand change can be further decomposed into a level and a composition effect. The first is simply the absolute level of aggregate final demand, while the latter is the distribution of sectoral shares in final demand. If products from more material intensive sectors are more strongly demanded than others, an increase in RMC can theoretically take place without an overall increase of final demand, and vice versa. Formally, the decomposition of final demand change $\Delta \boldsymbol{y}$ can be calculated in the following way (Miller and Blair, 2009, p.601):

$$\Delta \boldsymbol{y} = \underbrace{\frac{1}{2} \Delta \sum_{i=1}^{n} y_i (\boldsymbol{b}^{95} + \boldsymbol{b}^{11})}_{\text{Level effect}} + \underbrace{\frac{1}{2} (\sum_{i=1}^{n} y_i^{95} + \sum_{i=1}^{n} y_i^{11}) \Delta \boldsymbol{b}}_{\text{Composition effect}} \tag{5.4}$$

where $\sum_{i=1}^{n} y_i$ is aggregated final demand across all sectors i, and $\boldsymbol{b}$ is a distributional vector which contains the relative sectoral shares of final demand. This calculation reveals that virtually all of the final demand effects in Figure 5.5 are due to a change in the level of final demand, while the change in final demand composition plays no role. This somewhat refutes the supposition that changes in consumption preferences, e.g. in the form of a stronger demand for services or goods that are considered more environmentally friendly, reduce Germany's raw material consumption. More broadly, it suggests that material consumption in the considered time frame does not follow the pattern suggested by the Environmental Kuznets Curve (EKC). The EKC describes the relationship between affluence and environmental pressure as an inverted U, where environmental pressure first increases with rising affluence but then decreases again as even higher levels of affluence induce people to place more value on environmental quality (cf. Grossman and Krueger, 1991). Germany, with its relatively high level of affluence, is in general conceptually placed on the right hand side of the EKC, implying that consumption preferences have been changing in such a way that environmental impacts are reduced. However, the decomposition results suggest that this does not seem to apply to the material content of the consumption bundle in Germany over the considered time frame.

5.2.5 Temporal dimension

In order to shed more light on the differences between the individual decomposition terms and to assess whether their contributions to the development of RMC have changed over time, each decomposition variant is calculated as a time series with base year 1995. The results are shown in Figure 5.8, where each of the six graphs refers to one of the decomposition variants in Equation 5.2. All graphs have the feature in common that the change in material intensity has a negative influence on RMC whereas Germany's final demand has a positive influence. The changes in the structural composition of the global economy have a positive effect in the variants a), b) and e) but a small negative effect in the other three. The latter result aligns with that of Plank et al. (2018), who find a small negative effect of the changes in the global production structure on Western European RMC. The former three variants use the material coefficients from 1995 in the calculation of the structural change term (middle term in Equation 5.2), while the latter variants use the material coefficients from 2011. Excluding the changes in the other terms, the structural change of the global economy would have thus have led to an increase in German RMC if sectoral material intensities had remained the same as in 1995, while it would have led to a decrease if they had changed to 2011 levels.

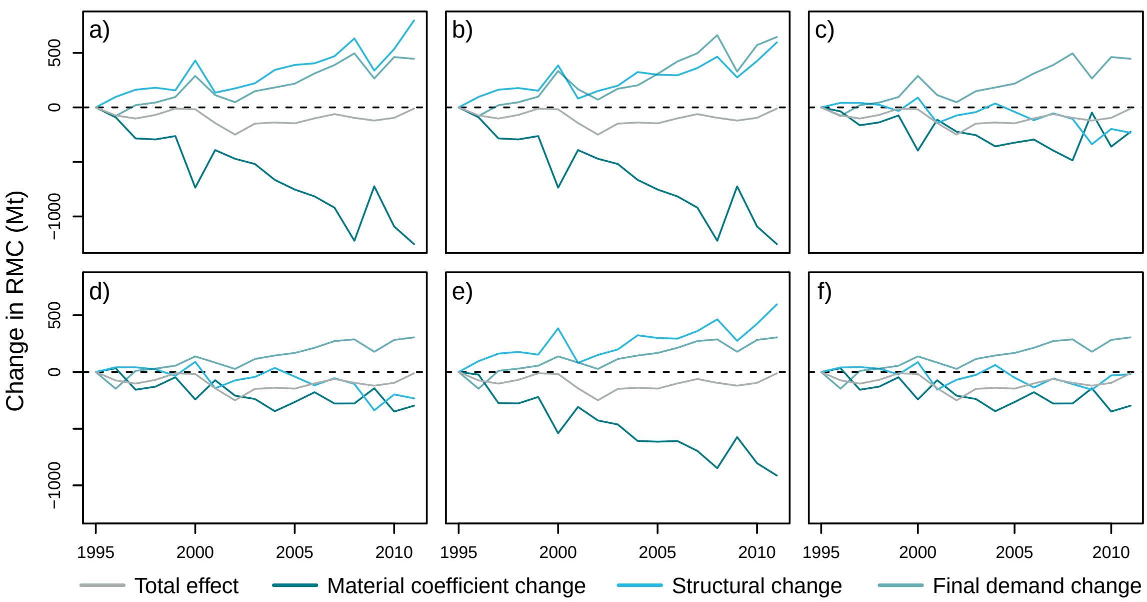


Figure 5.8: Time series of RMC decomposition variants from 1995 to 2011, own calculation based on EXIOBASE v.3.4

Among the different decomposition variants, a), b) and e) also have the largest spread, suggesting that considerably different results would be possible if only changes in individual factors were taken into account. Variants a) and b) share the formula for the material coefficient term, implying that the largest RMC reduction would have theoretically been possible if the economic structure and final demand of 2011 had already existed in 1995 and material intensities had developed in the historically observed way. Variants b) and e) share the formula for the technology change term, implying that the largest increase in RMC would have theoretically happened if material intensities and final demand had remained at their 1995 levels while the Leontief inverse had changed to 2011 values. The largest effect of the final demand component can also be observed in variant b), where a mixture of 1995 intensities and 2011 Leontief inverse would have led to the largest RMC increase if final demand had changed from 1995 to 2011 levels.

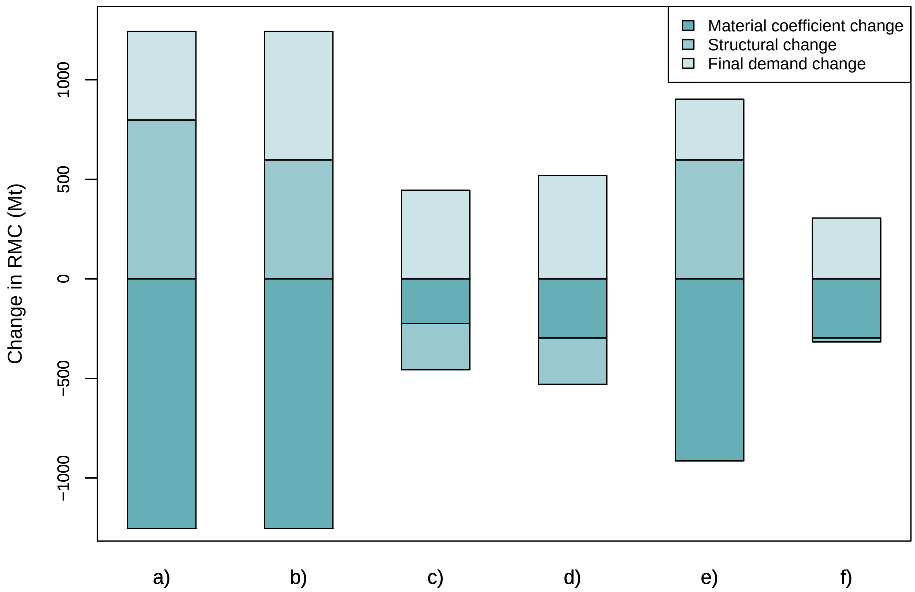


Figure 5.9: Contributions of decomposition components to RMC change between 1995 and 2011 for different decomposition variants, own calculation based on EXIOBASE v.3.4

The relatively large kinks in the year 2009 in variants a), b) and e) are more plausible for the technology change and final demand curves than for the material coefficient curve. The economic crisis in that year led to a noticeable decrease in economic activity, which can be expected to show up in any economic statistic. In contrast, the temporary increase in material intensity as indicated by the local maximum in the material coefficient curve may not make as much intuitive sense since these coefficients are denoted relative terms (i.e. kt/M€) and it is difficult to imagine that suddenly more physical material would be required for a given amount of monetary output. One possible explanation is a steady physical inflow of raw materials to processing sectors, possibly due to long term contracts. A concurrent reduction in economic activity would thus lead to an increase in the relative coefficients. Such a coefficient increase would thus have more to do with accounting practice or the way in which the MRIO system is constructed than with an actual, technology-driven increase in material intensities.

The contributions of the RMC components (material coefficients, structure of the economy and final demand) to the change between 1995 and 2011 are summarized for all decomposition variants in Figure 5.9. It can again be seen that there is a large spread between the decomposition variants, both in terms of absolute magnitude as well as relative importance of individual components. When looking at the decomposition in this way, final demand appears to play a more important role in some variants than may be apparent from Figure 5.5, specifically in c), d) and f). A comparison between these and the other variants also illustrates the difference of sign for the structural change effect. Overall, the changes in material coefficients and the structural composition of the economy (as expressed through the Leontief inverse) dominate the aggregate results.

5.3 Conclusions

The retrospective MRIO-based analysis revealed that material consumption in Germany, both excluding and including unused extraction, has remained relatively steady from 1995 to 2011. In the same time frame, the RME of exports have increased noticeably for both used and unused extraction. The main conclusion to be drawn from these results is that German consumption of raw materials does not follow a growth trend in the considered time frame, even when taking RME of trade flows into account. Thus, no "externalization" of material consumption can be observed. On the other hand, the RME of exports have increased, which implies a different kind of dependence on raw materials for a heavy exporter such as Germany.

A comparison with data from the German Statistical Office and other sources revealed that differences exist mainly with respect to the amount of material contained in trade flows. Thus, the Statistical Office assumes slightly higher RME of imports and considerably higher RME of exports than the present analysis, specifically for metals and to a lesser extent fossil fuels. In contrast, the present analysis suggests higher RME of mineral imports and exports. The main reasons for the deviation in results was found to lie in the underlying data and methodologies used for the respective analyses. Regarding the latter, the MRIO approach used here relies on a consistent depiction of the global economy and associated material flows, though it is subject to the restrictions outlined in Section 2.3. In contrast, the national coefficient-based IO approach utilized by the Statistical Office may provide a more accurate depiction of the national economy but has to rely on external (and potentially inaccurate) data for material contained in trade flows. Other factors that potentially contribute to the deviation of results are the treatment of secondary material and double counting of trade flows.

A structural decomposition of past material use revealed that changes in final demand and the structure of the global economy had positive influences on Germany's RMC while the material intensity of material extracting sectors had a negative influence. These results point to a number of interesting conclusions. First, the reduction of material intensity implies a relative decoupling of material use from economic activity. In the case of German RMC, this change is mainly driven by a reduction of material coefficients in other countries, which materializes in reduced RME of imports. Second, and in contrast to the first conclusion, the positive influence of the changing structure of the global economy on German RMC implies that this decoupling trend is counteracted by shifts in domestic and global supply chains which make German consumption more material intensive. This effect is dominated by changes in domestic production. However, domestic production still relies on imported intermediate inputs, the change of which dominates the overall structural effect on the hypothetical German RMC increase. Third, the increase in final demand was expectedly found to contribute positively to German RMC. However, this effect is exclusively due to a change in the level of final demand and not due to changes in its composition. Contrary to the EKC hypothesis, the structure of German final demand therefore does not appear to have changed in such a way that would negatively influence RMC.

6 Prospective simulations of material flows and economic dynamics

This chapter presents the results of prospective simulations performed with ISI-Macro. In Section 6.1, the effects of an aggregate material efficiency scenario are analyzed. At first, results on the physical level are reported, followed by a description of the economic consequences of the simulated material efficiency measures. In order to account for feedbacks from the economic to the physical dimension, rebound effects are analyzed in the last part of this section. In Section 6.2, simulation results of efficiency scenarios within the German copper cycle are presented. Through the coupling of the copper flow and the macroeconomic model, stock and flow dynamics can be portrayed. This allows for conclusions on the availability of secondary copper and therefore the demand for primary material. Section 6.3 closes with conclusions on the two simulation analyses.

6.1 Economy-wide effects of material efficiency measures

6.1.1 Overview

The rationale and possible methodologies for analyzing macroeconomic effects of material efficiency measures were outlined in Chapter 3. This section presents an empirical application of these insights. To the best of the author's knowledge, no integrative material efficiency plan exists for Germany based on which a universally valid national material efficiency scenario could be defined. Therefore, a broad material efficiency scenario is compiled using data from two recent research programs of the German Ministry for Education and Research (BMBF), "Innovative Technologies for Resource Efficiency – Resource-Intensive Production Processes (r^2)" and "Innovative Technologies for Resource Efficiency – Strategic Metals and Minerals (r^3)". These programs only represent a fraction of all possible material efficiency measures and so the scenario is not intended to assess the overall potential effects of material efficiency in Germany. Instead, the main aim of the scenario is to analyze the macroeconomic and structural effects of representative material efficiency measures as portrayed by the two research programs. The insights gained from this analysis may then allow for more general conclusions on the effects of material efficiency measures. The individual projects within the r-research programs are summarized in Tables 6.2 and 6.3, respectively. Each program contains clusters which broadly group the individual projects according to their general technical approaches. The majority of r^2-projects address high volume resources and range from loss reductions in production processes to the recovery of valuable raw materials from waste fractions. The r^3-projects address strategic metals and minerals with lower overall volumes in the German production system. Though a number of projects are concerned with recycling of old and new scrap as well as substitution of strategic raw materials, the majority of the projects analyze measures to increase raw material supply through urban or landfill mining. Not all of the listed projects provided quantitative data, and for reasons of confidentiality, project-level data cannot be published. However, the aggregate impulses used for the modeling are summarized below.

6.1.2 Scenario definition[1]

Baseline scenario

In order to put the results of prospective simulations in perspective, a reference or baseline scenario must be defined. Such a scenario presumes a development of the economy and associated material flows based on historic trends and without interventions such as material efficiency measures. As described in Section 4.2, ISI-Macro is calibrated to match OECD long term projections of German GDP up to the year 2060 (OECD, 2014). Other economic aggregates roughly follow the growth trend of GDP, including final demand. According to the modeling logic, final demand is also the main driver of material consumption, while other factors are held constant, including the material intensity of production processes and the structural linkages within the economy (see Section 4.3). Thus, in the model, the increase in final demand of roughly 50% in the time frame from 2011 to 2050 leads to a similar increase in material consumption ("only FD change" in Figure 6.1).

In the logic of the decomposition performed in Section 5.2, material consumption in the baseline scenario therefore behaves as if it were just determined by one factor. The results of the decomposition can, however, also be used to illustrate the other potential developments of Germany's material consumption based on changes in the other decomposition factors. Assuming a continuation of the trends observed between 1995 and 2011 with respect to the change in material use coefficients and the structure of the global economy as expressed by the multi-regional Leontief inverse, Figure 6.1 additionally illustrates other hypothetical material consumption trajectories for the example of RMC. A continued structural change of the global economy would thus, ceteris paribus, lead to a lower increase of German RMC by 2050 than final demand changes alone. In contrast, a continuation of the material coefficient reduction alone would cause RMC to drop to roughly one quarter of its 2011 value by the year 2050. However, these results are simple continuations of historic trends for a fairly long time horizon. Especially in the case of the material coefficient reduction, the steep downward slope proves that trend extrapolations can lead to unrealistic results. As

[1] Part of this section has been published in an earlier version in Pfaff and Sartorius (2015).

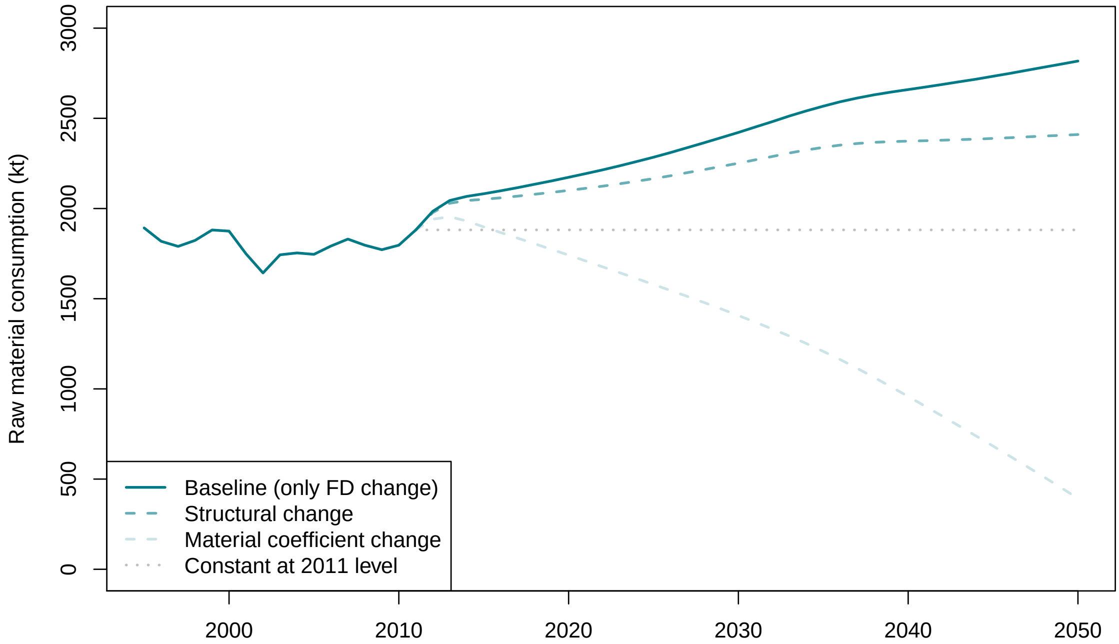


Figure 6.1: Possible RMC trajectories based on decomposition factors

discussed in Section 5.2.2, there are physical limits to material input reductions in production processes, rendering the sharp decline in RMC due to material coefficient changes implausible.

The development of material consumption in the baseline scenario proportional to final demand therefore appears to be a reasonable assumption without deeper knowledge of material intensity reduction trends or changes in the production structure of the economy. Potential reductions in the material intensity of production processes and structural shifts in the German production structure based on specific technologies are discussed in the following sub-section.

Material efficiency scenario

The material efficiency measures in the r-research programs allow for demand reductions for a number of raw materials. In order to generate model inputs, all material savings within the programs are aggregated according to the material categories defined in Section 4.3.1. Because it is assumed that the implementation of the efficiency measures unfolds gradually throughout the German economy, the savings also build up gradually in the form of an s-shaped diffusion curve. Section A.7.1 in the Appendix outlines the assumptions about the technology diffusion and discusses the implications for individual impulses. As can be seen in Table 6.1, by far the largest yearly reduction is possible in the category of minerals with about 40 Mt in 2050. This equates to a reduction of about 3.2% of the projected total minerals use in Germany. The second largest reduction is possible in the iron ores category with about 2 Mt in 2050, which equals approximately a 6.6% reduction of the projected iron ore use in Germany. The third largest absolute reduction in the area of fossil fuels of 1.3 Mt in 2050 is negligible with respect to the overall fossil fuel use. Likewise, the reductions of the other metals are negligible with respect to their respective overall uses in the German economy.

Table 6.1: Physical scenario inputs for macroeconomic Impact Assessment: reduction of material demand, in kt

Material	**2020**	**2030**	**2040**	**2050**
Iron ores	-72	-872	-1,921	-2,050
Copper ores	-0.2	-2.6	-5.7	-6
Nickel ores	0.0	-0.4	-0.9	-1
Bauxite and aluminium ores	-0.1	-1.0	-2.3	-2.4
Lead ores	0.0	-0.4	-0.8	-0.9
Tin ores	0.0	-0.2	-0.5	-0.5
Zinc ores	0.0	0.0	-0.1	-0.1
Other non-ferrous metal ores	-0.1	-0.7	-1.5	-1.6
Agricultural, industrial and construction minerals	-1,402	-16,770	-36,926	-39,407
Coal, oil and gas	-47	-567	-1,248	-1,332

These material savings do not accrue to the earliest stage of the supply chain but at a later point in different production processes or in the form of the recovery of secondary material from previously unused sources, as described in Tables 6.2 and 6.3. In the case where production processes actually reduce their material inputs, the reduction thus primarily pertains to the exchange between sectors and is thus best reflected in corresponding changes of the intermediate input coefficients, as described in Section 3.3.3 and Section A.7.2 in the Appendix.[2] Thus, a structural change of the economy equivalent to the historical structural change discussed in Section 5.2 is induced. For this, the absolute changes are fed into the input-output module where new coefficients are calculated for every year of the simulation (see Equation 4.19). However, as will be discussed in Section 6.2.1, the size of the coefficient change depends on the assumptions made about the cost of the efficiency measure as well as the market situation. Thus, the coefficients do not necessarily have to change by the full monetary amount corresponding to the physical reduction. The lower part of Table 6.4 lists the theoretical material savings accruing to the material delivering sectors if the physical

[2] The use of virtual material use coefficients as described in Section 4.3.1 complicates this slightly, since the distinction between material extracting and material using sectors collapses. The reduction of material inputs in one sector would thus also imply a change in its overall material intensity aside from that reflected in changed IO coefficients. However, for simplicity, this is left out.

Table 6.2: Projects in the r^2-research program

Cluster	Project
Improving energy and material efficiency in metal production	• Concentrating phosphorus: Optimized process control for resource-efficient production in the steel converting process • Copper slags: Avoiding metal losses in metallurgical slag based on the example of copper recovery • Increasing the energy and material efficiency of steel production in electric arc furnaces using optimized heat management and continuous dynamic process control • Optimized process control for resource-efficient production in the steel converting process • Resource-efficient shaping processes for titanium and highly heat-resistant alloys • Strip casting: Resource efficiency with the belt casting technology for the production of HSD steels
Recovery of valuable metal fractions from waste streams	• Dezincification of steel scrap • Extracting residues from mining waste: Recovery of metals and mineral products from old Kupferschiefer mine dumps, Mansfeld district, Central Germany • Lead metallurgy: Better resource use and lower primary energy consumption in lead metallurgy • Shredder sand: Recycling fine-grained non-ferrous metal phases from shredder sand • Zero-waste metallurgy: Auto thermal metal recovery from WEEE scrap using energy-optimized zero-waste metallurgy
Ceramics and Innovative Construction Materials	• Building aggregates: Increasing resource efficiency in the construction sector by developing innovative technologies to produce high-quality building aggregates from secondary raw materials based on heterogeneous construction and demolition waste • Celitement®: Development of sustainable cement • Dry control: Development of a resource-efficient drying technology for ceramic products
Catalytic Processes and Material Cycles	• Improving the efficiency of chlorine production • New, resource-conserving efficiency technology for closed-loop recycling of metals and process water in tin plate production

impulse fully translates into monetary savings. For the scenario simulations, it was assumed that such a full translation takes place and therefore the respective input-output coefficients are changed accordingly.

In the case where secondary material is recovered from previously unused sources, the material efficiency measures do not so much lead to a more efficient use of material but an increase in the supply of secondary material. This new supply could theoretically be used by all sectors using the respective material inputs. A precise allocation to intermediate input coefficients is therefore not possible (see Section 3.3.3).

Table 6.3: Projects in the r^3-research program

Cluster	Project
Recycling	• Bo2W: Global recycling of strategic metals • CaF_2: Recovery of CaF_2 as secondary material from waste fractions • InAccess: Development of a resource efficient and economic recycling process for LCD screens • Nickelrück: Resource efficient recovery of nickel from waste water of phosphating processes • PhotoRec: Recycling of thin-film (TF) solar cells • r^3-BECE: Recovery of tin and copper from tin stripper solutions in PCB production • UpGrade: Recovery of trace metals from electronic waste
Substitution	• EcoTan: Reduction of chrome use in leather tanning • Innodruck: Development of an innovative printing process for complex parts made from refractory metals • PitchER: Substitution of NdFeB magnets with electric transverse flux reluctance machines • SubITO: Development of a layering process that substitutes indium tin oxide with fluorine tin oxide for conductive transparent polymer foils • SubMag: Development of an alternative disulfurization method in metal casting
Urban Mining	• ATR: Recovery of metals from residues of thermal treatment processes • Grenzflächen: Demolition through microwave-induced surface failure • Kraftwerksasche: Chemical-biotechnological recovery of raw materials from power plant ashes • PhytoGerm: Germanium mining through concentration in phytomass • PRRIG: Identification of techno-economic potentials to recover raw materials from commercial and industrial buildings • Resource-App: Development of a mobile system for the identification and exploitation of resources in the building infrastructure and products • ReStrateGIS: Development of a GIS-based land register of mining waste tips and identification of recovery strategies • ROBEHA: Assessment of resource potentials in mining waste tips in the western Harz region, Germany • Rotschlamm: Dismantling of red mud landfills for the recovery of aluminium and gallium • SMSB: Recovery of minerals and metals from mining waste tips in Saxony, Germany • TönsLM: Recovery of raw materials from residential waste and sludge landfills • UrbanNickel: Recovery of nickel from neutralization sludges in steel production • VemRec: Loss minimized recovery of metals from incineration ashes • ZwiPhos: Development of a temporary storage concept for sewage sludge ashes with the aim of a later phosphorus recovery

The reduction of primary material implicit in these projects is thus modeled by subsequently reducing the overall demand for the respective materials when calculating the economy-wide material flow indicators.

As described in Section 3.1, the implementation of material efficiency technologies requires investments and subsequent Operation and Maintenance (O&M). The investments increase the demand in sectors which produce investment goods relevant in the context of material efficiency, i.e. electronics, machinery, other manufacturing and machinery services. O&M expenditures are implemented in the form of changes in intermediate demand for machinery services and business services by those sectors which install the material efficiency technologies. The yearly impulses are summarized for the reference years 2020, 2030, 2040 and 2050 in Table 6.4.

Table 6.4: Monetary scenario inputs for macroeconomic Impact Assessment, in M€

Variable	**Sector**		**2020**	**2030**	**2040**	**2050**
Investment	26	Electronics	7.0	50	12	0.7
	28	Machines	40	286	69	3.9
	31-32	Other manufacturing	4.7	33	8.0	0.5
	33	Machinery services	4.0	28	6.8	0.4
O&M	33	Machinery services	7.6	91	201	225
	80-82	Business services	2.5	30	67	75
Material demand	05	Coal	-10	-124	-274	-292
	07-09	Mining	-4.6	-55	-121	-129
	19	Coke	-0.6	-6.8	-15	-16
	20	Chemicals	-0.1	-1.6	-3.5	-3.8
	23.2-23.9	Ceramics	-0.1	-1.5	-3.3	-3.5
	24.1-24.3	Ferrous metals	-1.3	-16	-34	-36
	24.4	Non-ferrous metals	-7.8	-93	-205	-219
	35.1, 35.3	Electricity	8.5	101	223	238
	35.2	Gas	-6.6	-79	-174	-186
	36	Water	0.1	1.0	2.3	3.1
	37-39	Sewerage and waste	-11	-137	-300	-321
Differential			32.3	106.1	-540.7	-659.7

All inputs are dynamically implemented in the model as described in section 3.1. The technologies are assumed to follow the "slow diffusion" path (see Table A.5 in the Appendix) and to have fully diffused by 2050. The assumptions on possible technology diffusion paths are explained in more detail in Section A.7.1 in the Appendix. Note that the yearly investments follow a bell shape and thus appear relatively small. In order to provide a sense of the overall investment expenditures, the cumulative investments are summarized separately in Table 6.5. Due to the gradual unfolding of the material efficiency technologies, the yearly O&M impulses and yearly changes in material flows also follow an s-shaped diffusion curve and thus reach their maximum value at the end of the simulation period.

The cumulative investments, from which the yearly investment expenditures are derived, are based on the projected maximum investment levels. These projected investment levels are slightly reduced by assuming a generic cost degression, which is implemented by taking the original cumulative investment sums to the power of 0.85 (Ostertag et al., 2013; Dürkoop et al., 2016b; see also Argote and Epple, 1990 for an overview of the concept of learning curves in manufacturing). The cumulative investments follow an s-shaped diffusion trajectory and reach their maximum value of about 5.7 billion € at the end of the simulation period in 2050 (see Table 6.5). However, this amount is marginal compared the overall yearly investment volume in Germany of about 600 billion € in the year 2016 (Destatis, 2017c).

Table 6.5: Cumulative investment expenditures in the r-research programs, in M€

Sector		**2020**	**2030**	**2040**	**2050**
26	Electronics	25	304	670	715
28	Machines	146	1,748	3,849	4,108
31-32	Other manufacturing	17	203	447	468
33	Machinery services	14	173	381	406

As will be discussed in Section 6.2.1, the difference between the costs and the savings of efficiency measures also has to be taken into account when simulating their macroeconomic effects. The cost differential between investment and O&M expenditures on the one hand and material savings on the other hand determines the extent to which a positive or negative impulse additionally enters the economy. Thus, for each material efficiency project within the r-research program, a simple balance sheet can de devised, which allows for the calculation of a cost differential (see Table 6.6). Since the information from the projects is scaled up to the national level, this cost differential is denoted at the macroeconomic level and can thus be understood as an aggregate demand impulse. If the differential is negative, the savings from reduced material demand outweigh the necessary expenditures. This frees up financial resources which can be re-spent in other parts of the economy. Therefore, a negative cost differential leads to a positive final demand impulse. In contrast, if the differential is positive, the expenditures outweigh the savings. In this case, the ongoing savings cannot be used to cover the expenditures and thus final demand in other parts of the economy must be reduced. Therefore, a positive cost differential leads to a negative aggregate final demand impulse in the economy.

As can be seen in the bottom part of Table 6.4, this differential is at first positive and grows over the first half of the simulation period, implying that from a macroeconomic perspective, the increases in demand (in the form of investments, O&M and additional material) are higher than the decreases (in the form of material savings). If

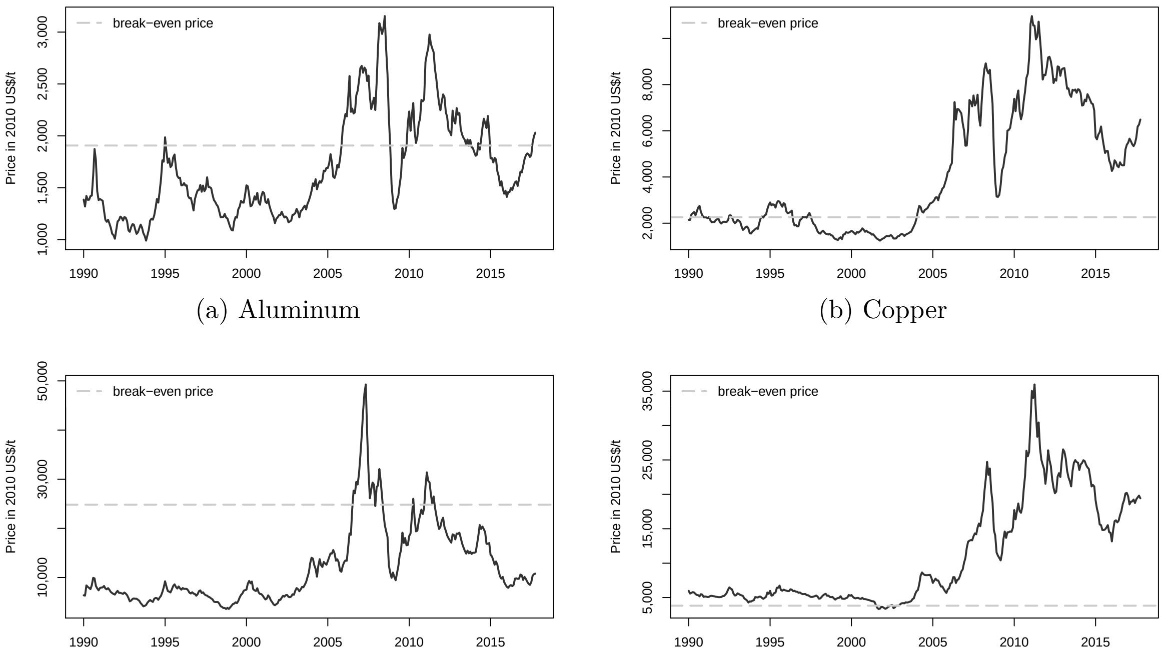
Table 6.6: Balance sheet for every project; savings are denoted in negative terms, expenditures in positive terms

	Monetary savings due to a demand reduction of material i for $i = \{1, \ldots, m\}$
+	Additional expenses due to an increased use of material j for $j = \{1, \ldots, n\}$
+	Capital investment
+	Operation and maintenance costs
	Cost differential

– in a neoclassical tradition – it is assumed that the economy operates at full capacity utilization, demand in other parts of the economy has to be reduced. In the second half of the simulation period, this relationship changes, and the demand decreases are higher than the demand increases. This change in the relationship between positive and negative demand changes happens on both sides: the positive demand first increases but then decreases again due to the temporal distribution of the investment impulse, which dominates the positive side. At the same time, the negative demand keeps increasing as it acts cumulatively (each year new actors adopt the efficiency technologies and thus overall demand is continually reduced). Together this leads to a situation in which the yearly demand increases start being outweighed by demand decreases. Viewed over the entire simulation period, cumulative investments and operation and maintenance costs of approximately 11.3 billion € stand against cumulative material savings of 18.8 billion €. All else being equal, the material savings continue beyond the simulation period, though operation and maintenance of the technologies must also continue. Investments, on the other hand, cease after the simulation period. Excluding replacement investments, the yearly differential is then at around -665 million €. This positive aggregate demand impulse is assumed to enter the economy according to historic shares of sectoral final demand.

The positive demand side is mainly determined by technology costs, which could theoretically decrease further over time, though it is difficult to predict the exact degression of individual technologies. As described above, the cumulative investment sums already include a generic cost degression. However, more detailed information could theoretically be used to substitute this generic assumption. On the negative demand side, raw material prices play the most important role. However, they have been rather volatile in recent years and are therefore also difficult to predict beyond the short term (cf. Glöser-Chahoud et al., 2017). In order to test the sentivity of the modeling results with respect to different price developments, a sensitivity analysis is conducted at the end of Section 6.1.3.

Figure 6.2 plots the prices of an exemplary set of raw materials which have been analyzed in the r^2- and r^3-research programs. For individual projects within the research programs, a so-called 'break-even price' of the respective target raw material was calculated under the assumption that all other factors are constant. Thus, in the four



(a) Aluminum (b) Copper

(c) Nickel (d) Tin

Figure 6.2: Time series of raw material prices and exemplary break-even prices, own calculation with price data from World Bank (2017) and Kelly and Matos (2014)

examples in Figure 6.2, a given raw material must at least have the break-even price in order for the project to save as much as it spends on the efficiency measure. For reasons of confidentiality, the individual projects cannot be described. The description of the break-even price thus only serves to illustrate that the analyzed material efficiency projects may move in or out of cost-effectiveness relatively easily if the respective raw material price is close to the break-even price. In the case of copper and tin, the break-even price appears to be sufficiently low for the two considered projects not to be in danger of sliding out of cost-effectiveness. For aluminum, the current price is just slightly above the break-even price, so a relatively small price decline could yield the project unviable. In the case of nickel, it appears that the considered project is far from cost-effectiveness with respect to nickel prices – unless a dramatic cost reduction can be achieved, for example through a lowering of technology costs. For simplicity, these cost dynamics have no influence on the selection of projects included in the aggregate material efficiency scenario. It is thus assumed that projects get scaled to their maximum potentials regardless of their profitability.[3] This also applies to the sensitivity analysis in the last part of Section 6.1.3.

[3]According to the logic of the scenario definition, unviable projects are accompanied by a negative aggregate final demand impulse. Hence, the scale-up of such projects can be conceived of as being

6.1.3 Simulation results

Results on the physical level

The primary aim of the efficiency measures is the reduction of (primary) material demand. To this end, the model results indicate that towards the end of the simulation period reductions of Raw Material Consumption (RMC) on the order of low single digit percentages are possible. Overall RMC can thus be reduced by about 1.6% by 2050. The more broadly defined indicator RMI also includes raw material exports and is thus not as interesting from a domestic resource consumption perspective. However, to put the results of the present analysis in perspective with the internal analysis of the r^2-research program, the effects on RMI are briefly summarized. The effects of the r^3-research program on aggregate material demand were not analyzed within the program because of the small overall volume of the material demand reduction.

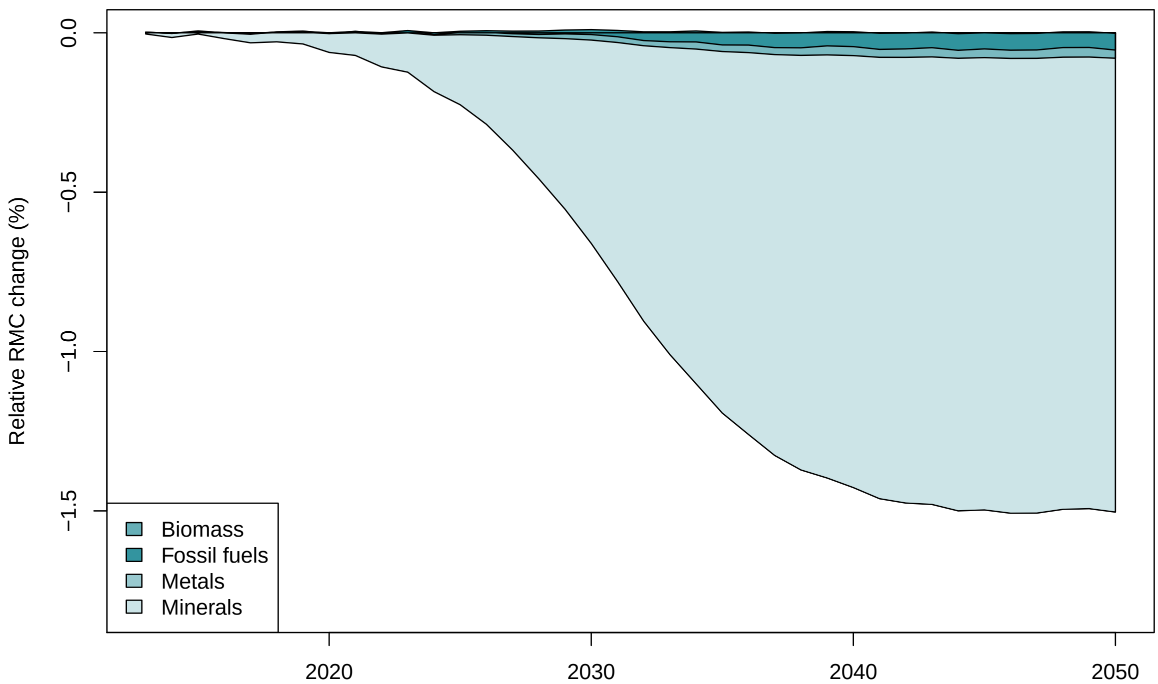


Figure 6.3: Cumulative relative change to RMC, model results

Due to RMI's larger size, the effect on it is comparatively smaller with −1.1%. This is a little more than a third of what Ostertag et al. (2013) find for the reduction of RMI in their comparative static analysis of the effects of the r^2-research program (−3.2%). However, due to the static nature of their analysis, Ostertag et al. (2013) only compare the yearly maximum reduction of the efficiency measures to the German

supported with external funds, which reduce the budget for other consumption purposes in the economy.

RMI of 2009. In the present dynamic analysis, a gradual unfolding of the efficiency measures is assumed. The maximum material demand reduction is thus only reached in 2050, and this value is compared to the projected baseline material use indicators of 2050. Thus, despite albeit small compounding effects in the simulation, the reference value for the calculation of the relative reduction is different, making the results not directly comparable.

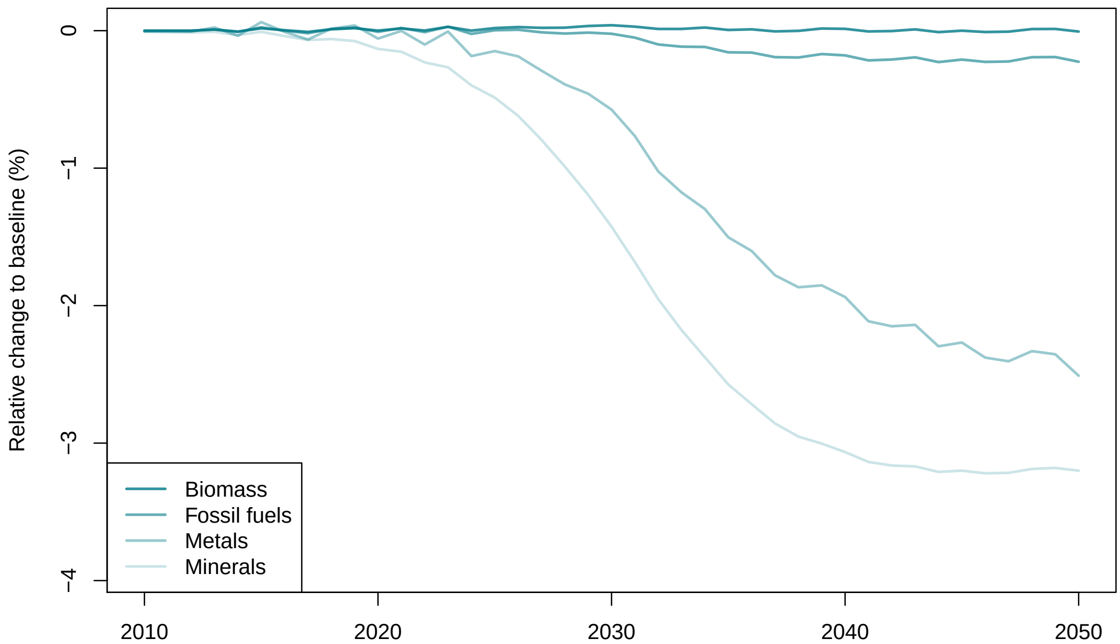


Figure 6.4: Relative change to the demand for the components of RMC, model results

As shown in Figure 6.3, by far the largest part of the simulated RMC reduction is due to a reduction in the demand for minerals (−1.5 percentage points). Metals and fossil fuels only contribute −0.08 and −0.05 percentage points, respectively, while there is no measurable decrease in biomass use. This is due to the fact that no quantitative information was provided by the projects within the r^2- and r^3-research programs that indicated a reduction of biomass use. The induced macroeconomic effects also do not lead to a reduction of biomass use. The time path in Figure 6.3 shows that the reduction largely follows the s-shape of the input data with only minor kinks. The induced macroeconomic dynamics resulting from the material efficiency inputs therefore appear not to have a large effect on the overall development of RMC.

Figure 6.4 plots the reductions of the individual RMC components relative to their individual use in the baseline scenario and not to overall RMC. These relative reductions of the components are distributed slightly differently. Minerals still display the largest reduction at the end of the simulation period (−3.2% in 2050). However, the reduction of metals relative to their individual use is much larger (−2.5% in 2050) than their contribution to the overall RMC reduction. At the same time, the metals curve has more kinks than the other curves. The reason for this appears to be that the scenario inputs for metals partly run counter to each other, i.e. reductions in metal use are countered by investment impulses which trigger additional metal use through demand for machinery. In addition, the induced macroeconomic effects have a larger relative effect on metals than on minerals due to the former's lower overall demand level (in physical terms). For fossil fuels and biomass, only minor reductions can be achieved through the efficiency measures of the r-research programs.

Results on the macroeconomic level

On the macroeconomic level, the scenarios do not lead to large changes in Gross Domestic Product (GDP) or employment. By 2050, GDP only changes by +0.01%, whereas employment in Full-Time Equivalents (FTEs) changes by +0.02%. The higher value for employment is mainly due to relatively higher gains in sectors with low labor productivity and relatively lower losses in sectors with high productivity. The model results suggest that the trade balance is not affected in a measurable way by the efficiency measures due to the small nature of the overall impulses.

Despite these small overall effects, some structural shifts in Gross Value Added (GVA) and employment between sectors take place. By 2050, these shifts amount to up to ±5% per sector. Figure 6.5 depicts these changes at their maximum level in 2050. In the case of employment, the occurrence of positive and negative employment effects implies that the amount of job shifts in 2050 is three times as high as the overall gain of +0.02%. The coal sector incurs the highest loss in both GVA and employment, mainly due to reductions in energy demand in the respective processes. A reduction in energy and heat demand is also reflected in the negative impacts in the gas sector. More material efficient processes also lead to a lower demand for sewage and waste treatment, leading to a negative impact on the corresponding sector. The reduction of demand for non-ferrous metals (especially copper, aluminum and nickel; see Table 6.1) materializes as a negative impact on the non-ferrous metals sector. Even though the technology investments also create a positive demand impulse in the non-ferrous metals sector, this is minor compared to the efficiency-induced demand reduction and therefore cannot compensate it.

The sectors which gain most strongly from the efficiency measures are the ferrous metals and the metal casting sectors. In both cases, the positive impacts on GVA and employment of about 1.5% are mainly due to a reduction of intermediate inputs in these sectors, which raises GVA and thus their demand for employment. In the case of the ceramics sector, which displays the third largest gain in GVA and employment, and the chemicals sector, which only experiences a small gain in GVA and employment (+0.3%), the positive effect is also mainly due to a reduction of intermediate inputs and a corresponding increase in GVA.

The machine repair and business services sectors are the only ones which benefit noticeably from the investment and/or O&M expenditures of the efficiency measures

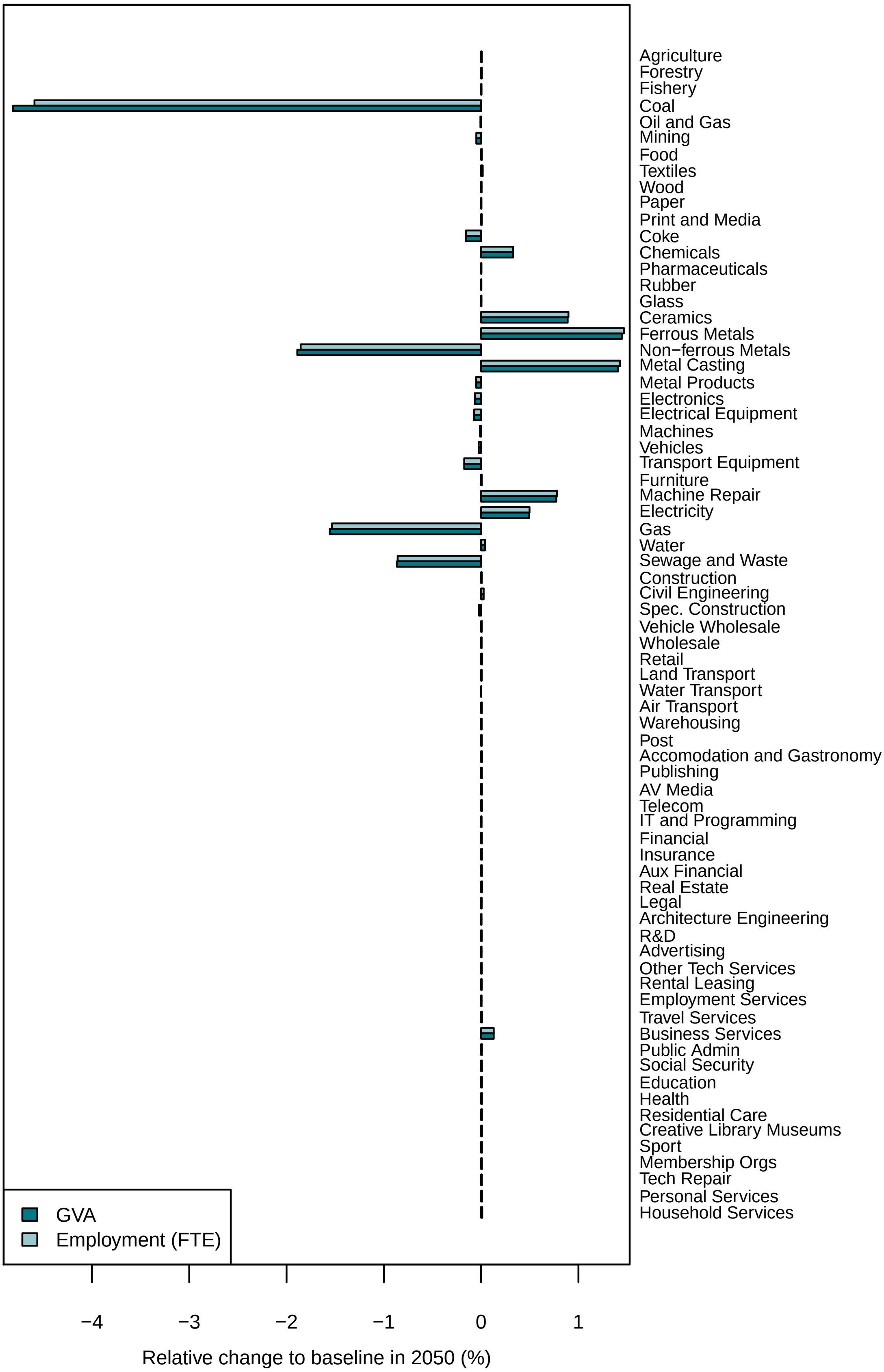


Figure 6.5: Relative changes to GVA and employment in FTE, model results

(and not solely from efficiency-induced intermediate input reductions). This is due to the relatively large size of the investment impulse in comparison to their respective GVAs. The manufacturing sectors which also benefit from the investment impulse, i.e. machinery and electronics, are larger than the machine repair and business services sectors. In relation to their size, the yearly investment demand for their products is thus low and does not have a strong effect on their GVA or employment. On the contrary, many manufacturing sectors display slightly negative total effects, which are mainly due to indirect supply chain effects of the material demand reductions. They are not compensated by the overall positive macroeconomic impulse described above. The positive impact on the electricity sector is due to an increase in electricity demand in some sectors induced by the new material efficiency technologies.

A look at the temporal distribution of the macroeconomic effects reveals that the majority of them happen in the period between 2020 and 2040. Figure 6.6 exemplarily shows the employment effects of the efficiency measures (the effects on GVA are almost identical in their temporal distribution). For most sectors, the middle two bars are largest, indicating that the effects until 2020 and again between 2040 and 2050 are small compared to the period between 2020 and 2040. This is mainly due to the design of the impulses, which experience the strongest acceleration in the latter period (see Section A.7.1 in the Appendix).

A clear outlier is the coal sector; here the largest part of the negative effect happens in the period between 2020 and 2030, and a smaller part from the beginning of the scenario until 2020. After 2030, the GVA and employment effects in the coal sector are negligibly small. This temporal distribution has two main reasons. The relatively larger effect in the first two periods is due to the small size of the coal sector within the German economy (only about 0.05% of total GVA in 2013, Destatis, 2016c). The negative demand impulse of the efficiency scenario thus has a strong impact even at an early stage of the simulation since it is relatively large compared to the coal sector's GVA. However, this effect is considerably reduced after 2030 because of a positive demand impulse from the electricity sector, which has a relatively high share of coal input for gross electricity generation. The reversal of the negative effect in the latter two periods is thus due to an increase in electricity demand. This demand increase is part of the material efficiency measures in some of the projects within the r-research programs as described above (see also Figure 6.5).

Over the simulation period, a number of sectors experience shifts from positive to negative GVA and employment effects, and vice versa. In many cases these are just small variations between both positive and negative effects resulting from indirect demand effects induced by positive developments in other sectors, and the aforementioned overall positive compensation impulse. However, for the ceramics and the machinery sector, there is a clear divide between the period until 2030 and the period from 2030 to 2050. The former period is characterized by positive effects on GVA and employment, whereas the latter is characterized by negative effects. In the case of the ceramics sector, the small positive GVA and thus employment effect outweighs an efficiency-measure induced demand reduction for ceramics until around 2030. After

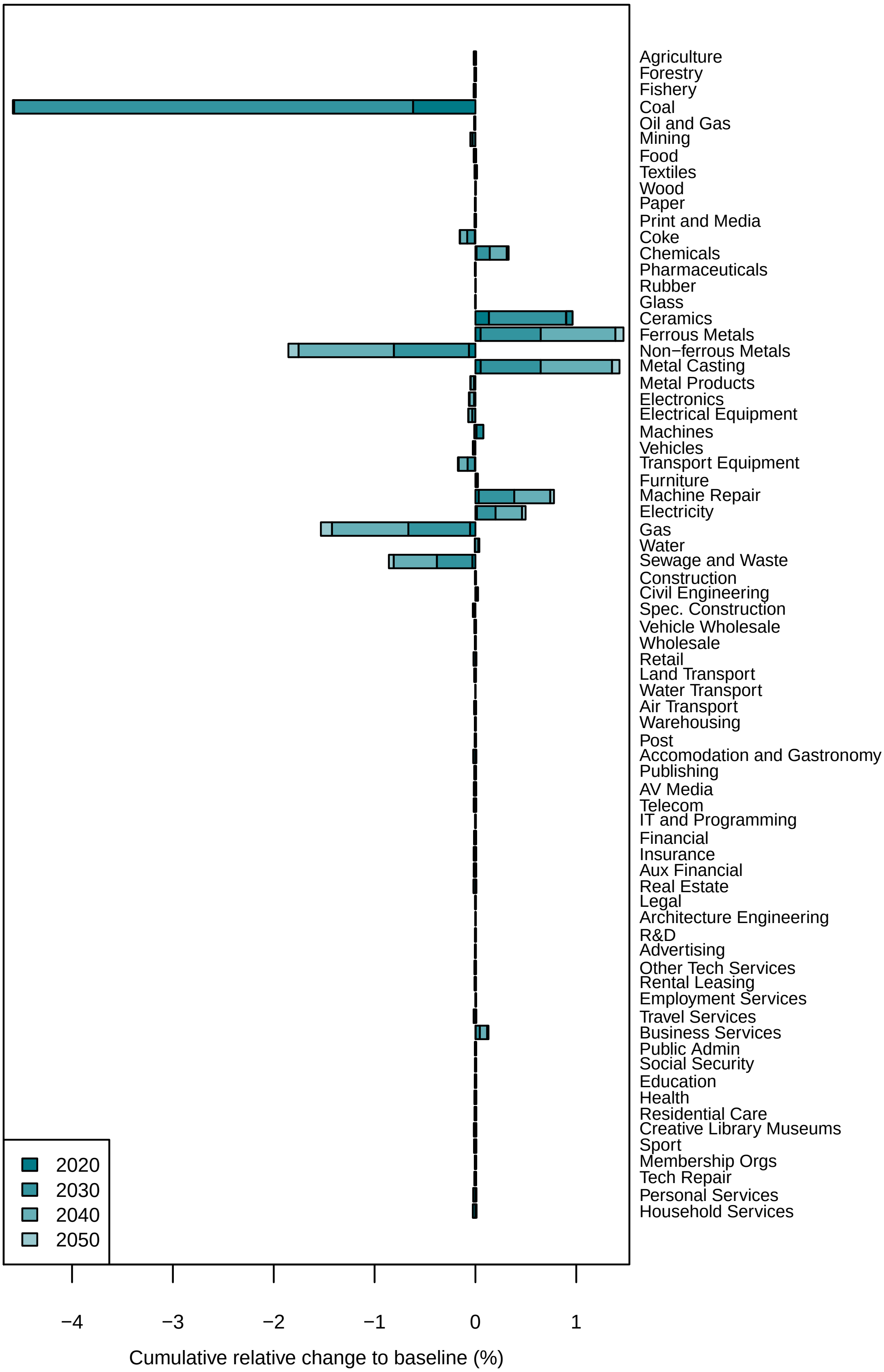


Figure 6.6: Cumulative relative changes to employment in FTE, model results

that, the reduction in ceramics demand compensates for this positive effect, rendering the GVA and employment effect in the latter part of the simulation period slightly negative. In the case of the machinery sector, the switch from positive to negative effect is due to the way the investment impulse unfolds, which resembles a bell-shape (see Section A.7.1 in the Appendix). The initial increase in the demand for machinery is thus gradually reduced again. Together with small negative supply chain effects, the machinery sector thus experiences a very small negative effect on GVA and employment in 2050. It therefore cannot sustain its initial positive trajectory induced by the efficiency measures.

Rebound effects

In order to perform a full analysis of the physical effects of material efficiency measures, it is necessary to take into account their macroeconomic effects. This is because the changes in material demand are not solely dependent on the technology-derived projections of material savings but also on the wider macroeconomic developments, which themselves also have an influence on material demand. While the results described in Section 6.1.3 already include these macroeconomic effects, they have not been isolated from the physical effects directly induced by the efficiency measures. This section therefore reports the effects on the physical side that can be attributed to direct and indirect changes on the economic side.

As described in Section 3.3.5, if the actual (or simulated) absolute material savings deviate from the potential material savings as defined in the scenarios, one can speak of rebound effects. The above described way of accounting for rebound effects can be located somewhere in between the economic and the industrial ecology approaches in the rebound literature (Thomas and Azevedo, 2013a; van den Bergh, 2011; Barker et al., 2009). The approach used in this thesis is similar to those of Guerra and Sancho (2010) and Saunders (2013b) in the way embodied material (in their case energy) is accounted for.

According to the simplest definition, the rebound effect is the relative difference between actual material savings (in this case the model results) and the potential material savings determined by the respective technology ("engineering estimate"). As Equation 3.2 illustrates, a positive relative rebound indicates smaller actual than potential savings, while a negative value indicates larger actual than potential savings (i.e. super conservation). A positive value above 1 indicates a backfire effect, as the savings are negative, i.e. material demand has actually increased as opposed to decreased.

As may be expected, the deviation of the actual material savings from the projected ones depends on the size and structure of the surrounding macroeconomic effects. Since the aggregate macroeconomic effects resulting from the r-research programs are very small, the overall feedback on material demand is also relatively small. However, it is still interesting to investigate the mechanisms determining the magnitude and direction of rebound effects. Two broad factors of this analysis can be identified which can cause rebound effects. One is the investment and O&M impulse of the material efficiency measures, which leads to demand increases in the sectors producing investment goods and providing O&M services. As described in Sections 3.3.1 and 3.3.2, these monetary demand increases in turn induce material demand. In the case of investments, the material demand mainly occurs directly in the form of machinery etc., whereas in the case of O&M, the material demand is mainly indirect through supply chain effects. The other factor which potentially causes rebound effects is the aggregate demand impulse resulting from the cost differential between material savings and necessary expenditures. In the present case, the overall savings are first lower but subsequently higher than the overall expenditures, leading to an initially negative but then positive aggregate demand impulse.

The positive investment, O&M and aggregate demand impulses and the negative supply chain effects from the material efficiency measures counteract each other. However, overall the results suggest that the negative effects dominate slightly. Thus, the simulated RMC is 0.3% lower than the projected value, yielding a −0.3% rebound (or 0.3% super conservation) on overall domestic raw material consumption. This overall effect is mainly driven by metals and fossil fuels since the difference between actual and potential savings is largest for these two material categories, even though the overall savings of metals and fossil fuels are small compared to their overall demand values. A number of rebound effects of individual material categories in 2050 are exemplarily summarized in Table 6.7.[4] The relatively small potential changes in the demand for metals and fossil fuels makes them susceptible to large rebound effects, so the individual results should be treated with caution. Small economic impulses can thus easily lead to relatively large demand changes for metals and fossil fuels and therefore theoretically yield large rebound effects. For example, this appears to be the case for copper, nickel and aluminum, as can be seen in Table 6.7.

In the aggregate, minerals display no significant positive or negative rebound effect. However, on the level of individual mineral categories, positive rebound effects can be observed. For instance, this is the case for limestone and the combined category clays and kaolin. The positive rebound for limestone mainly results from the positive economic developments in the ceramics and ferrous metals sectors. Another positive impulse comes from the three construction-related sectors: construction, civil engineering and special construction activities. In this case the monetary impulse is small, but the limestone demand per Euro output in these sectors is relatively high, leading to a relatively high physical effect. For clays and kaolin, the positive rebound effect is also mainly due to a demand increase in the ceramics and non-ferrous metals sectors as well as the construction sectors. However, other positive impulses also come from the chemicals, machine repair and electricity sectors. In sum, these impulses lead to positive rebound effects of the two mineral categories and thus play a role in overall de-

[4]Note that the numbers for potential savings may not add up to the scenario inputs presented in Table 6.1 since only a selection is presented here. In the case of minerals, the negative potential savings of limestone and clays and kaolin are counterbalanced by potential demand increases in other categories.

Table 6.7: Potential and actual savings of individual material categories in 2050 (kt) and corresponding rebound effects; RE = rebound, SC = super conservation

Material	Iron	Copper	Nickel	Aluminum	Limestone	Clays and kaolin
Potential savings	−2,050	−6.1	−1.0	−2.4	−32,266	−34,908
Actual savings	−2,054	−18.9	−2.1	−4.3	−32,161	−34,794
Rebound	−0.21%	−208%	−102%	−78%	0.32%	0.33%
Type	SC	SC	SC	SC	RE	RE

mand for these minerals. Even though the rebound effect is small, this shows that it is important to take demand changes resulting from macroeconomic effects into account. Depending on the relationship between the potential saving and the magnitude of the macroeconomic effects associated with the material efficiency measures, considerable differences can occur between potential and actual material reductions.

Sensitivity analysis

In order to assess whether model results would change considerably in response to variations in key input parameters, a sensitivity analysis is performed. The aggregate model results are generally robust with respect to variations in input parameters. However, certain structural results display significant variations when related input parameters are changed. For instance, in the case of sectoral changes in GVA and employment, some results were found to respond sensitively to changes in raw material prices.

After some initial tests in which prices were varied randomly between the minimum and maximum values in the period from 1990 to 2017 (see Figure 6.2), a more systematic approach is chosen for variations of the most important raw material prices in the efficiency scenario defined above. It is difficult to project material prices into the future due to a multitude of influencing factors as well as relatively fast demand responses (if technologically feasible) to price changes but only delayed supply adjustments. There are certain possibilities for modeling these dynamics for individual raw materials, for instance with the help of complex SD models with accurate representations of raw material supply capacity (Glöser-Chahoud et al., 2017). However, such an approach is infeasible if a variety of materials is to be analyzed. In this case, statistical methods can provide realistic approximations of the range of potential price developments without aiming for exact price forecasts.

One suitable statistical method for projecting future developments of variables which have shown relatively erratic behavior in the past is the so-called Wiener process. It is named after the mathematician Norbert Wiener, who formalized an observation originally made by the botanist Robert Brown on the movement of plant pollen suspended in water (therefore it is also referred to as Brownian motion). The Wiener process is a continuous stochastic process with stationary, independent increments that are normally distributed. Formally, over the interval $[0, T]$, the variable $W(t)$ depends continuously on $t \in [0, T]$. Each increment $W(t) - W(s)$ is random and normally distributed with variance $t - s$ (Higham, 2001, pp.526):

$$W(t) - W(s) \sim \sqrt{t-s}N(0,1) \quad \text{for} \quad 0 \leq s < t \leq T \tag{6.1}$$

Where $N(0, 1)$ denotes a randomly distributed variable with zero mean and unit variance. The rate of change of W is thus determined stochastically within the bounds of a normal distribution. The independence of the increments ensures that there is no path dependency in time series generated with the Wiener process.

Future price time series can thus be constructed by integrating the descriptive statistics of (linearly de-trended) historic price data with the standard Wiener process. The resulting distribution of future prices can then be added to the extrapolated historic trend. Such a use of the Wiener process can be understood as providing a statistically derived limit to a random walk with drift (Lalley, 2013). The Wiener process is applied to the respective price time series of the non-ferrous metals aluminum, copper, tin, nickel and zinc, which play important roles in the aggregate material efficiency scenarios. In each case, the normal distribution is scaled to the variance of the respective de-trended time series (by multiplying it with the standard deviation σ), and 1000 simulations are run to get a representative sample of potential price trajectories. The standard deviations of the historic price time series, the linearly extrapolated 2050 prices and the spread of 2050 prices resulting from the price projections are summarized in Table 6.8.

Table 6.8: Standard deviation σ of de-trended price time series, 2050 prices and spread of price projections in 2050 (2010 USD/t), own calculation with price data from World Bank (2017)

	Aluminum	Copper	Nickel	Tin	Zinc
Standard deviation σ of historic prices	392	1,777	6,780	4,757	544
Price in 2050 (linear trend)	9,980	14,350	18,760	27,430	11,050
Spread in 2050	2,010	9,360	35,450	23,840	2,730
Weight (monetary) in efficiency scenario	43%	24%	2%	2%	29%

To illustrate the different trajectories the metal prices can take according to the Wiener process, Figure 6.7 exemplarily shows the results for copper. Next to the historic time series, the left side displays the plume of all 1000 runs, which reaches up to 20,000 and down to about 4000 USD/t. The 1000 simulations result in a probability distribution for future copper prices as illustrated on the right side of Figure 6.7. The gray area is defined as $\mu \pm 2.576\sigma$, where μ is the extrapolated trend of the historic time series. The area thus covers 99% of the results for each time step. As can be seen, the distribution widens over time with a final spread of almost 10,000 USD/t.

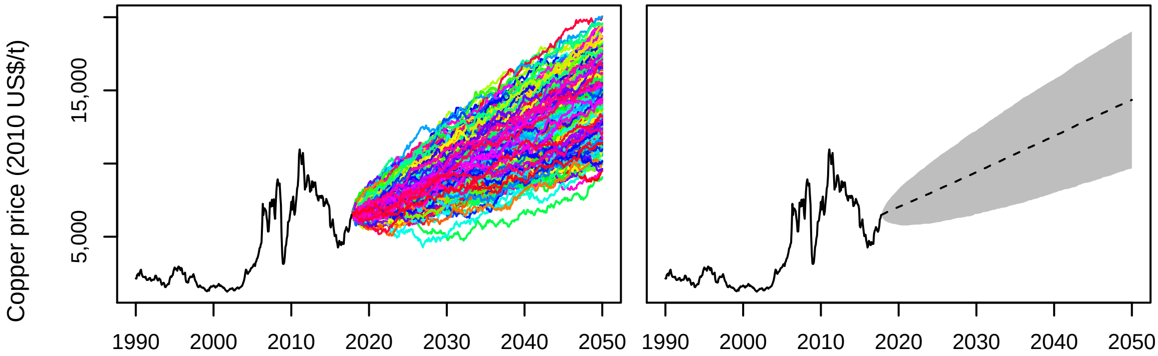


Figure 6.7: Time series of copper price and forecast based on the Wiener process; left: results of 1000 simulations, right: resulting probability distribution; own calculation with price data from World Bank (2017)

These price variations are separately applied to the scenario impulses for the aggregated non-ferrous metals sector as outlined in Table 6.4. The results of the sensitivity analysis are therefore weighted averages of the results of the individual price changes. However, since for the baseline simulation no trend is assumed for raw material prices, the actual values of the non-ferrous metal price projections used for the sensitivity analysis are the de-trended versions.[5]

Of the 72 sectors portrayed in the model, only few are noticeably affected by the price variations in the form of changes to GVA in comparison to the baseline. These sectors are directly connected to non-ferrous metals either as suppliers or users, the former of which experience losses while the latter benefit from reduced input demands. Since no significant GVA reactions to the non-ferrous metal price variations can be observed for other sectors, it appears that the variations are not large enough to cause significant indirect or induced effects. The results for the most strongly affected sectors are shown in Figure 6.8. The funnels represent the percentiles of the distributions of GVA changes based on the 1000 simulations run with the price projections described above. 50% of all results are thus located in the yellow area, another 25% in the green area, and so forth. The black line represents the GVA results for unchanged 2013 prices of the non-ferrous metals listed above.

[5]The results would be equivalent if both the baseline and the efficiency scenario contained linear price trends, so for simplicity they are left out.

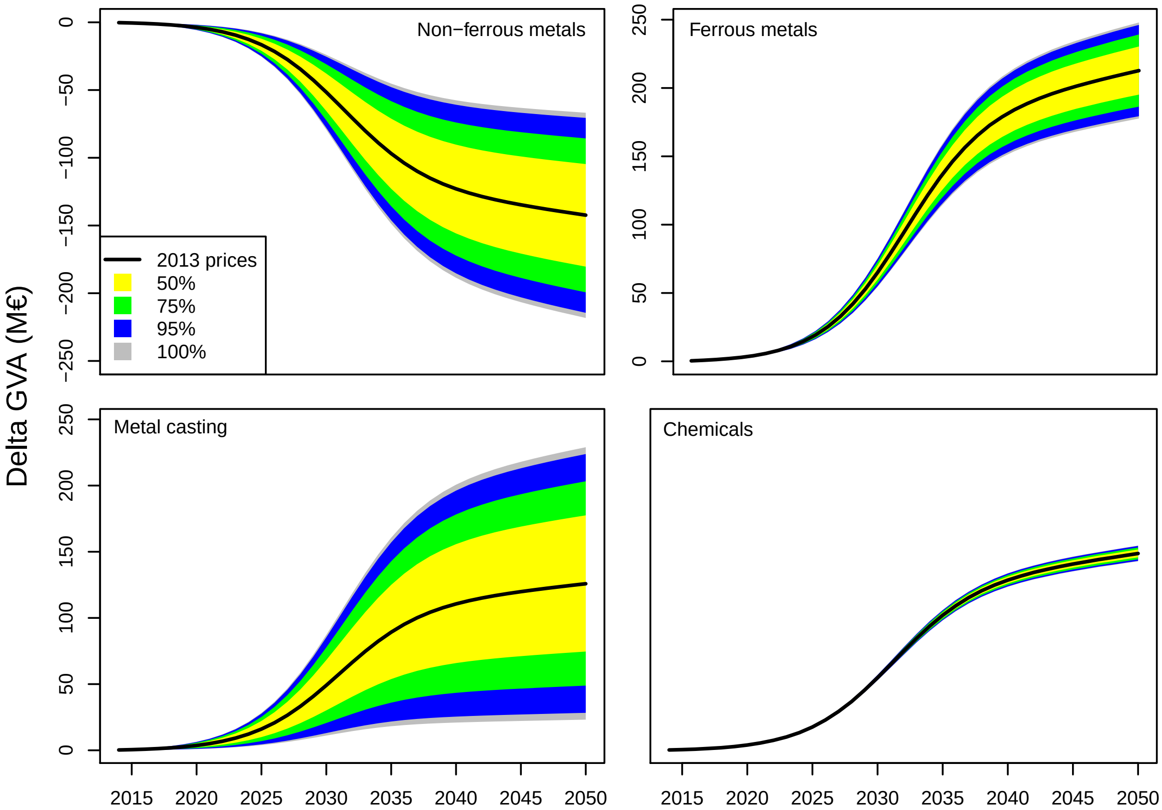


Figure 6.8: Sensitivity analysis for price changes of non-ferrous metals, model results

All funnels depicted in Figure 6.8 are distributed relatively evenly around the results for constant 2013 prices as indicated by the black lines. This is a result of the Wiener process, which indicates that no systematic bias is introduced by this method. The largest absolute spread for GVA changes can be observed for the metal casting sector, which is a direct user of non-ferrous metals and displays a reduced input of these metals through the efficiency measures. The highest GVA delta is almost twice as high as in the case of constant 2013 prices, while the lowest GVA delta is close to zero. The GVA change thus ranges between about 2.6% and 0.3%, with a value of about 1.4% for 2013 non-ferrous metal prices. For the non-ferrous metals sector, the change in GVA is negative since it experiences a demand decrease. It displays the second highest absolute spread of results. The relative differences are, however, not as large as those in the case of the metal casting sector. The lowest reduction is at approximately −60 M€, which equals a GVA reduction of about 0.8%, while the highest is at close to −220 M€, which equals about −2.9%. Smaller absolute spreads of GVA deltas can be observed for the ferrous metals and the chemicals sectors, both of which also reduced their non-ferrous metal inputs. The GVA changes in the chemicals sector are only minimally affected by the price variations due to the relatively small non-ferrous metal input reduction in this sector. While the ferrous metals sector experiences a relative GVA increase very close to that of the metal casting sector for constant 2013 prices (+1.5%), the relative spread only ranges from +1.2% to +1.7%. The leveraging effect of higher prices is thus not as large in the ferrous metals sector as in the smaller metal casting sector.

Overall, the sensitivity analysis illustrates that partial model results can be considerably influenced by changes in relevant input parameters. For instance, statistically derived non-ferrous metal price projections can lead to GVA (and in turn employment) deltas in related sectors almost twice as high as in the case of constant prices. The breadth of the ranges varies between sectors and depends on the extent to which the respective sector depends on non-ferrous metals as inputs or outputs. Therefore, some sectors are only marginally affected by the price variations while others display no change in their GVA or employment results. The non-ferrous price variations also have no noticeable effect on aggregate GVA or employment.

6.2 Stock and flow dynamics within the copper cycle[6]

6.2.1 Scenario definition

In this section, the effects of different material efficiency strategies on the stock and flow dynamics of the German copper cycle are analyzed. The analysis reaches beyond the aggregate scenario in the previous section in that the flow perspective is complemented by an explicit accounting of material stocks. As outlined above, the temporary nature of anthropogenic material stocks makes them future flows of secondary material, which can make up a considerable share of material supply. A holistic portrayal of material demand scenarios therefore rests on an adequate depiction of material stocks and the corresponding stock and flow interaction.

A number of measures can be envisioned that have the potential to reduce copper demand in Germany. These measures can be broadly sorted into changes in stock dynamics and demand side changes. The first category includes product lifetime extensions,[7] increases in EoL collection rates and measures to recover copper contained in unused anthropogenic stocks, for example through landfill mining. The second category includes changes in the copper intensity of products, increases in fabrication efficiencies of end-use products and absolute demand reductions, i.e. what is sometimes summarized under the concept of “sufficiency”.

Unlike the aggregate material efficiency scenario in the previous section, no information is available on specific technologies that can be used to achieve large reductions

[6]Part of this section has been published in an earlier version in Pfaff et al. (2018).

[7]Product lifetime extensions can be conceived of as technical measures in the production phase which increase the useful lifetime of products, or as consumer based measures such as re-use, repair and refurbishment (Box, 1983). Of course, technical product improvements only lead to lifetime extensions if consumers actually keep the products longer in use. The implications of each variant are briefly discussed in the detailed scenario description below.

Table 6.9: Summary of copper reduction scenarios

Scenario	**Parameter change**
Changes in stock dynamics	
Product lifetime extension	10 % increase for all product categories
Increase in scrap collection rate	10 % increase of overall EoL scrap collection
Increase in availability of secondary copper, e.g. through urban mining	10 % increase of yearly amount of secondary material from EoL scrap
Demand side changes	
Reduction of copper intensity of products	10 % decrease of all copper coefficients
Fabrication efficiency	10 % increase for all product categories
Absolute demand reduction	10 % decrease in demand for copper containing goods

in copper demand. Therefore, a number of generic scenarios have to be defined. These scenarios are summarized in Table 6.9 and explained in more detail below. As in the case of the aggregate material efficiency scenario, a baseline scenario has to be defined against which the scenario results can be compared. In the baseline scenario, copper use is solely driven by the projected economic development as described in Sections 4.2 and 4.3.2. Analogous to the case of RMC described in Section 6.1.2, the copper baseline scenario thus behaves as if it was driven just by one decomposition factor, namely final demand, without changes in the copper intensity or the structure of the economy. The trajectories of other potential baseline scenarios of total copper demand derived solely from changes in copper intensity or the structure of the economy would therefore look similar to Figure 6.1, though with the limitations outlined in Section 6.1.2.

In all six efficiency scenarios, a 10 % change is assumed relative to the baseline. With the exception of the sufficiency scenario, the 10 % change applies to physical copper flows, making the scenarios comparable. However, it should be noted that the reference figures differ in absolute terms, which implies that the theoretical absolute changes of copper flows differ between scenarios. The sufficiency scenario serves to illustrate that unspecific demand reductions necessarily have smaller effects on copper use than targeted efforts. The rationales for why these scenarios could get implemented are outlined in the individual scenario descriptions below.

Since it is unlikely that the changes described in the scenarios happen instantaneously, the implementation of the measures follows a diffusion trajectory as discussed in Section A.7.1 in the Appendix. Analogous to the economy-wide material efficiency scenarios above, in all technology scenarios except for the lifetime extension scenario (see below), the technologies are assumed to follow the “slow diffusion” path (see Table A.5 in the Appendix) and to have fully diffused by 2050. Likewise, the absolute demand reduction in the sufficiency scenario is modeled as a gradual lifestyle change that also evolves according to an s-shaped diffusion path.

The measures in all scenarios but the final demand reduction would likely require technology or infrastructure investments. However, due to the heterogeneity of the measures it is difficult to determine the investment sums and attribute them correctly to the relevant economic sectors. To get a rough estimate, data from the two aforementioned German research programs, “Innovative Technologies for Resource Efficiency – Resource-Intensive Production Processes (r^2)” and “Innovative Technologies for Resource Efficiency – Strategic Metals and Minerals (r^3)”, is used (see Section 6.1.2). Across all of the technical projects, specific investment expenditures per saved ton of copper were calculated. These investment expenditures have a fairly wide range from approximately 60 € per ton of saved copper to 3000 €/t.

None of the analyzed technologies have by themselves the potential to achieve the 10% changes defined in the scenarios in this thesis. The investment expenditures can thus only be used as a rough indicator of the technology investments necessary to achieve concrete reductions of copper use. However, even if all efficiency technologies were fully deployed, the cumulative investment sum would be low compared to the overall investment volume in Germany. It would not surpass approximately 1 billion € even if the high price of 3000 €/t was used. In light of about 600 billion € of total yearly investments in Germany in 2016 (Destatis, 2017c), the macroeconomic and consequently physical effects on copper demand can be expected to be negligible.

Nevertheless, the technology investments are implemented in the model and it is worth briefly outlining their theoretical effects on the economy and thus on copper demand. The investments increase final demand in those sectors which produce investment goods. As in the case of the efficiency technologies described in Section 6.1.2, this mainly accrues to the electronics, machinery, machinery installation/repair and other manufacturing sectors. The increase in final demand for these sectors is accompanied by a direct but small increase in copper demand (since the investment goods themselves contain copper) as well as an indirect positive effect on overall economic activity, which implies a further small increase in copper demand. The capital goods created through the investments also have to be operated and maintained, which implies additional macroeconomic impulses. In this case, the sectors implementing the efficiency technologies receive additional inputs from the machinery installation/repair and business service sectors.

The monetary investment and O&M impulses may be accompanied by further macroeconomic demand impulses. Depending on which underlying economic theory is adhered to, it must either be assumed that investments, which would have otherwise been made, get replaced (crowding out), or the new technology investments can be modeled as a standalone positive demand impulse that need not be balanced through other impulses (see Section 3.2). In the present case, it is assumed that a negative aggregate demand impulse balances the positive investment impulse. However, as stated above, considering the size of the investments and the monetary copper savings, these impulses are likely to have a negligible effect on the overall economy. The physical dimension as well as other economic aspects of the individual scenarios are described in more detail in the following sub-sections.

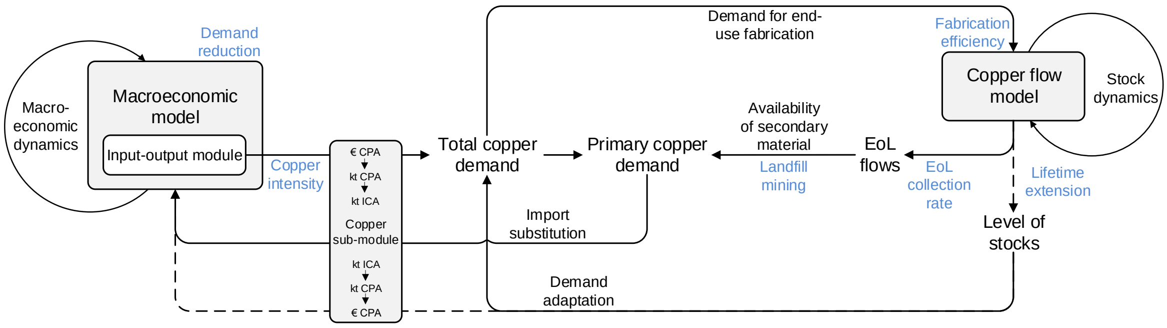


Figure 4.17: Illustration of model coupling, scenarios in blue (repeated from page 84)

Lifetime extension scenario

In the context of accelerating innovation cycles and planned obsolescence, lifetime extensions are seen as a viable strategy to reduce raw material demand (Bakker et al., 2014). While the longer use of existing products decreases the need for new products, they are also fixated longer in the anthropogenic in-use stock and thus only become available for recycling at a later point in time. The lifetime extension scenario intends to elucidate this trade-off. It simulates a relative increase in the lifetimes of all end-use products. It does not explicitly model the way lifetime extensions are brought about, though it implicitly assumes a technical improvement which only accrues to new product vintages. For this, some adaptations to the aging chain of the copper flow model have to be made because the introduction of new products with longer lifetimes only affects new vintages and not existing ones. In order not to change existing vintages in the model, the lifetime extension has to be sequentially applied to the entire aging chain. Thus, in year 1, only new products (age 0) are assigned a longer lifetime. In year 2, these products will have moved into the vintage of 1 year old products, at which point the lifetime of these products has to be changed. In year 3, the lifetime of 2 year old products has to be changed, and so on. Formally, this can be done by changing the failure rate h of each vintage n with variable delay times:

$$h_{t,n} = \begin{cases} h^0_{t,n} & \text{for } t < \tau + (n-1) \\ h^*_{t,n} & \text{for } t \geq \tau + (n-1) \end{cases} \tag{6.2}$$

where h^0 is the original distribution of failure rates, h^* is the failure rate distribution including the lifetime extension, and τ is the point in time at which the lifetime extension is introduced. The upper part of Equation 6.2 ensures that the lifetime distributions of current products in use do not change, whereas the lower part sequentially introduces the lifetime extension to the aging stock of products produced at time τ or after.

By design, the lifetime extension serves the purpose of keeping products longer in use and thereby, ceteris paribus, reducing the demand for new goods[8]. One way of accounting for this in the model is by adopting a stock-driven perspective as suggested by Müller (2006). According to this perspective, the services demanded by society are provided by stocks (as opposed to flows) and thus stocks determine the demand for new goods as represented by flows. However, stocks have to be maintained or replaced through flows, thus reversing the logic of economic approaches where flows (e.g. investment) determine the development of stocks (e.g. fixed capital). Lifetime extensions keep the stocks longer at the desired level, so the demand for inflows can be reduced. The level of this reduction can be calculated by comparing the difference between the stock of products with extended lifetimes to a hypothetical stock without the lifetime extension. The new inflow $I^*_{t,1}$ into the first vintage n of the product stock at each point in time t thus has to be reduced according to the following formula:

$$I^*_{t,1} = I^0_{t,1} - (S^*_{t,1} - S^0_{t,1}) \tag{6.3}$$

where $I^0_{t,1}$ is the inflow solely based on total production of copper containing goods, $S^*_{t,1}$ is the stock with extended lifetimes and $S^0_{t,1}$ is the hypothetical stock without a lifetime extension. As described by Equation 4.3, the inflows of the following vintages are then based on the outflows of preceding vintages. The original product lifetimes and the corresponding demand for replacements are therefore implicit in the baseline scenario. The lifetime extension induced demand changes are based on a recursive logic in which consumers adapt their demand to current stocks in each year.

In order to account for further reaching macroeconomic effects, the theoretical physical reduction could first be transformed into an economic impulse for the macroeconomic model (dashed line labeled “demand adaptation” in Figure 4.17). Within the macroeconomic model, a number of effects would ensue due to the demand impulse, including changes in sectoral production, value added and, accordingly, employment. Translating these impulses back into physical copper use, these effects would thus also be portrayed on the physical side. However, in order to model the scenario in this way some assumptions have to be made in such a modeling (i.e. non-equilibrium) setup. As outlined above, for a realistic portrayal of economic dynamics, the relationship between expenditures and savings of efficiency measures has to be taken into account.

For instance, lifetime extensions through product improvement constitute a special case as the expenditures are (at least initially) on the side of the manufacturers whereas the savings accrue to consumers. It thus appears reasonable to assume that producers would not voluntarily extend the lifetimes of their products unless this can be marketed

[8]This may not always be the most environmentally effective strategy if the use phase is taken into account. For instance, early replacement of appliances with more energy efficient ones may lead to lower overall energy consumption over the entire life cycle than extending the lifetimes of less efficient appliances (Bakker and Schuit, 2017; Wieser et al., 2015). However, in the case of copper, the use phase consumption is negligible compared to production.

as a premium feature for which higher prices can be charged. In fact, as a rigorous measure producers could calculate the amount of foregone sales due to the lifetime extensions and adapt prices so as to fully recover the reduced turnover. Overall this would result in a unchanged situation from a monetary perspective.

In contrast, lifetime extensions through changed user behavior in the form of re-use, repair, refurbishment etc. would, ceteris paribus, result in a monetary demand reduction. This could in turn be countered by producers with lower prices, which may lead to a re-increase of sales and thus alleviate the demand reduction. If it is despite these price reductions still assumed that consumer induced lifetime extensions are less costly than purchases of new products, the freed up financial resources could be spent elsewhere (see Section 3.3.5). However, the motivation behind engaging in more repair etc. could also be of a purely environmental nature and so consumers may not benefit financially or even end up spending more money than they would have in the case of new purchases.

Due to the difficulty in determining the exact economic forces at play in this scenario, only the demand reduction on the physical side is modeled in the form of reduced inflows into the copper in-use stock (solid line labeled “demand adaptation” in Figure 4.17). Indirect and induced effects resulting from the demand reduction are therefore not portrayed in this scenario.

EoL collection rate scenario

The EoL collection rate scenario simulates an increase in the overall rate of EoL scrap collection. On the physical side, this increase leads to a higher recovery rate of secondary material from EoL products, which reduces the demand for primary material. On the economic side, the change in primary demand results in a substitution of primary copper imports with domestic secondary production. This can be modeled as a reduction of imports from the metal ore and mineral mining sector and a concurrent demand increase in the waste and recycling sector. Regarding the historical development of the EoL collection rate (see Figure 4.3a), a 10% increase would lead to a nearly complete collection of EoL copper scrap. This is obviously an idealized scenario, but some studies suggest that there is a certain potential to increase the EoL collection especially of consumer goods which remain in households after their service lifetimes (cf. Oswald and Reller, 2011; Suckling and Lee, 2015; Wilson et al., 2017). In such a case, two broad types of measures are conceivable to either address consumers directly or shift the burden to producers. The first consists of (economic) incentives for consumers to more readily recycle unused products, for instance in the form of deposit return schemes or recycling awards, such as the car allowance rebate systems introduced in some countries. The costs of such measures range from mere administrative costs in the case of deposit schemes to increases in government spending for awards. The second type of measure consists of new business models in which not the products themselves but the services they provide are sold to customers. Within so-called use oriented Product Service Systems (PSS), the ownership of the products thus remains with producers (Beuren et al., 2013) and therefore high EoL recycling rates are more likely. The introduction of PSS may involve additional costs for producers, though they would likely also benefit from the returned products. Such measures would, however, not address the EoL copper scrap contained in obsolete infrastructure, which is often not collected because of the difficulties in accessing it, such as copper contained in subterranean power grids (cf. Krook et al., 2011). Such a recovery of unused copper, among other things, is addressed in the scenario below.

Increase in secondary copper scenario

The increase in the availability of secondary copper has similar effects as the EoL collection rate scenario. The measures to recover copper contained in unused anthropogenic stocks, such as mining waste tips, ashes from waste incineration or obsolete infrastructure, also lead to an increase in the availability of secondary copper and a corresponding reduction of demand for primary material. The effects on the economic side are the same as in the recycling efficiency scenario. Depending on which type of unused stock is considered, different measures may need to be taken in order to induce urban mining. In some examples involving the recovery of residue materials from waste tips or streams, new technologies or simply better information on industrial waste flows proved to economically incentivize producers to recover unused material (cf. Dürkoop et al., 2016a; Woidasky et al., 2013). In the case of obsolete infrastructure that is difficult to access, the profitable recovery of materials can for example be achieved by integrating it with existing processes, such as regular maintenance (Krook et al., 2011).

Reduction of copper intensity

Reducing the copper intensity of domestically produced goods has the effect of an absolute reduction of copper demand per sectoral production. This in turn leads to a reduction of the copper stock compared to the baseline. Depending on the technical nature of this reduction, other materials may need to substitute for copper and/or components may be more complex and thus potentially more expensive. These aspects can be modeled on the economic side. The demand for other materials would imply an increase in the respective input coefficients of the input-output table (see Section A.7.2 in the Appendix). Likewise, the decrease in copper intensity may result in a change of input-output coefficients if the physical reduction directly translates into an economic reduction, for example because copper can be saved without having to use more expensive components (e.g. through lightweighting). In fact, two extremes can be identified: a change of the monetary input-output coefficients that corresponds fully to the physical copper reduction implies a costless[9] reduction of the copper in-

[9]Costless in this means that there are no additional running costs, e.g. in the form of more expensive components but a simple reduction of physical input. As discussed above, technology investments may nevertheless be necessary.

tensity. However, since these changes concern the flows of semi-finished goods, the prices corresponding to a 10% reduction would have to be known for each receiving sector (since semis are not as homogenous as refined copper, which has a fairly uniform price). No change in the input-output coefficients implies that the decrease in copper intensity costs as much as the value of the saved copper semis (assuming that the suppliers of the less copper intensive parts are the same as before). It is also conceivable that the reduction of copper intensity is more costly than the value of the saved copper, e.g. because it is mandated by regulation. In the simulation of this scenario, it is for simplicity assumed that the copper intensity reduction costs as much as the value of the saved copper, for example due to a newly discovered technology out of ongoing R&D, which implies no change in the input-output coefficients.

The logic of this scenario is somewhat different from the material coefficient change covered in Chapter 5. In the latter case, the material intensity as expressed by material coefficients referred to the earliest stage of the supply chain, while here the material coefficients refer to the copper input of semis manufacturers, who are further down the supply chain (see Section 4.3.2). Thus the division between material intensity and structure of the production system is not as strict as in Chapter 5. The reduction of material intensity as depicted here is therefore more appropriately labeled as a general increase in the material efficiency of copper semis use.

Fabrication efficiency scenario

The fabrication of copper containing goods produces a certain amount of copper scrap, which is usually returned to semis manufacturers as new scrap. This new scrap is recycled and enters the production process as secondary material. Therefore, assuming steady demand and no changes in production technologies and product composition, a constant amount of copper cycles through the production system. If a technology that increases the fabrication efficiency (i.e. reduces new scrap) is introduced in a given year (at time t_3 in Figure 6.10), the demand for semis decreases initially since the same amount of final products can be produced with less total copper input (semis + new scrap). However, because the increase in the fabrication efficiency at the same time reduces the amount of new scrap, the demand for semis must go up again in the following period (at time t_4 in Figure 6.10) to fulfill the unchanged copper content of the products. Eventually, the increase in fabrication efficiency only reduces the amount of new scrap which cycles through the system but not the overall demand for semis.

While this increase in the fabrication efficiency has no lasting effect on physical copper demand, there is a small change on the economic side. In their deliveries to end-use manufacturers, the semis producers usually include a surcharge for the remelting of new scrap. In German, this is called the “Schmelzaufschlag”. This surcharge decreases if the amount of new scrap that cycles between semis and end-use producers is reduced. The decrease in the surcharge can be modeled through a reduction of

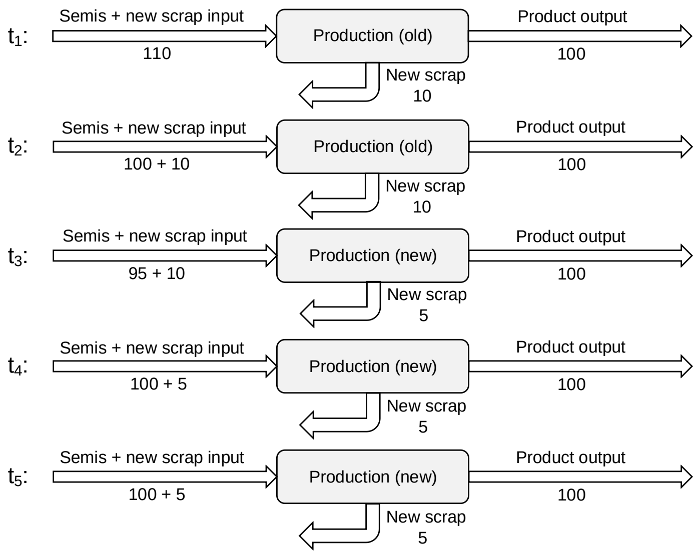


Figure 6.10: Illustration of effect of increase in fabrication efficiency

the deliveries from the non-ferrous metals sector to the sectors that produce end-use goods.

Absolute demand reduction

The absolute demand reduction scenario is the only scenario in which a generic reduction of monetary final demand is implemented. It is therefore not directly comparable to the other scenarios which explicitly address physical flows of copper. However, it is part of the broader approaches typically discussed under the heading "sufficiency" in the context of material efficiency and other sustainability policies.

6.2.2 Simulation results

Individual simulations are run for the six material efficiency scenarios described above, a combination of all of these scenarios, and a baseline scenario in which no actions to reduce copper use are taken. The efficiency scenarios are assumed to start in the year 2013 and unfold until 2050. The measures depicted in the scenarios have varying effects on different variables in the German copper cycle. In the following sub-sections, the effects on total copper demand for the domestic production of end-use goods, the amount of EoL copper scrap and total primary copper demand from imports will be discussed.

Total copper demand for domestic end-use goods production

In the case of total copper demand for domestic end-use goods production, the simulation results suggest that only the lifetime extension and the coefficient change scenarios have noticeable effects. As may be expected, the absolute reduction (−10% in 2050) of the coefficient change scenario mirrors the scenario assumption. The lifetime extension scenario leads to a similar absolute reduction, though a slight oscillation can be observed (see Figure 6.11). The most likely cause for this are the changed replacement periods of the in-use stocks due to the changed lifetime distributions, where the period of the oscillation roughly corresponds to the average lifetime across all product categories. As illustrated above, the fabrication efficiency scenario was expected to have no significant long term effect on domestic production. This was confirmed by the simulation results. The recycling and landfill mining scenarios do not quantitatively affect domestic production of end-use goods; they simply increase the fraction of secondary material used in production. Therefore, no reduction of total copper demand for end-use goods production can be observed. The differences in the effects of the scenarios on different parts of the copper cycle are explained in more detail below. The final scenario, the overall change in final demand, is too small to significantly affect domestic production of end-use goods. The curves for the latter three scenarios in Figure 6.11 are thus mostly concealed by the baseline curve.

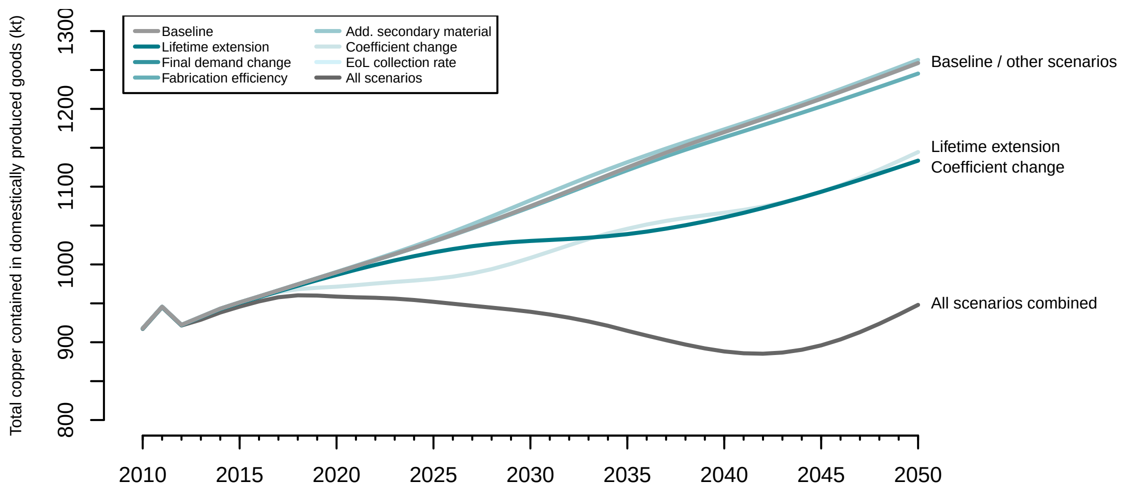


Figure 6.11: Total copper input to domestic production of finished goods, model results

The simultaneous simulation of all scenarios yields the highest demand reduction for copper input in domestic end-use goods production. This reduction amounts to almost 25% in 2050, which is more than the sum of all individual reductions (which only add up to about −20%). The two scenarios with the highest impact on copper demand for domestic production therefore reinforce each other through a positive feedback loop. Since total copper input to domestic production does not distinguish between primary and secondary copper, it is not affected by the negative influence of the lifetime extension on the availability of secondary copper. Thus, the lifetime extension positively reinforces the coefficient reduction, leading to a combined effect that is larger than the sum of the individual effects.

End-of-Life copper scrap

In the case of EoL copper scrap, the lifetime extension scenario leads to a considerable reduction which gradually unfolds and peaks at −12.4% in 2044. In contrast, the increase in the EoL collection rate leads to a corresponding increase in the amount of collected EoL scrap, which peaks at the end of the simulation period at +13.8%. Figure 6.12 also shows the trajectories of the other scenarios which have, however, no considerable impact on EoL scrap collection. For some scenarios, this may be expected since they have no conceivable influence on Germany's technical EoL collection rate. This is for instance the case for the landfill mining scenario, in which only copper in so far unused scrap stocks is recovered. Likewise, the fabrication efficiency scenario does not directly influence EoL collection capabilities and thus has a negligible effect on EoL collection.

It is more surprising that the coefficient reduction scenario does not decrease EoL collection more visibly. In absolute terms, less copper is used in the products of all end-use categories, so less copper should be available for EoL recycling. However, this change only applies to the domestic production system, leaving the copper intensity of imported end-use goods unchanged. The potential effect on EoL collection and thus recycling is thus considerably reduced. The overall reduction of final demand applies to both domestic production and imports of end-use goods. However, as mentioned above, it does not proportionally translate into an equivalent decrease in copper demand and therefore also leaves the amount of collected EoL scrap virtually unchanged.

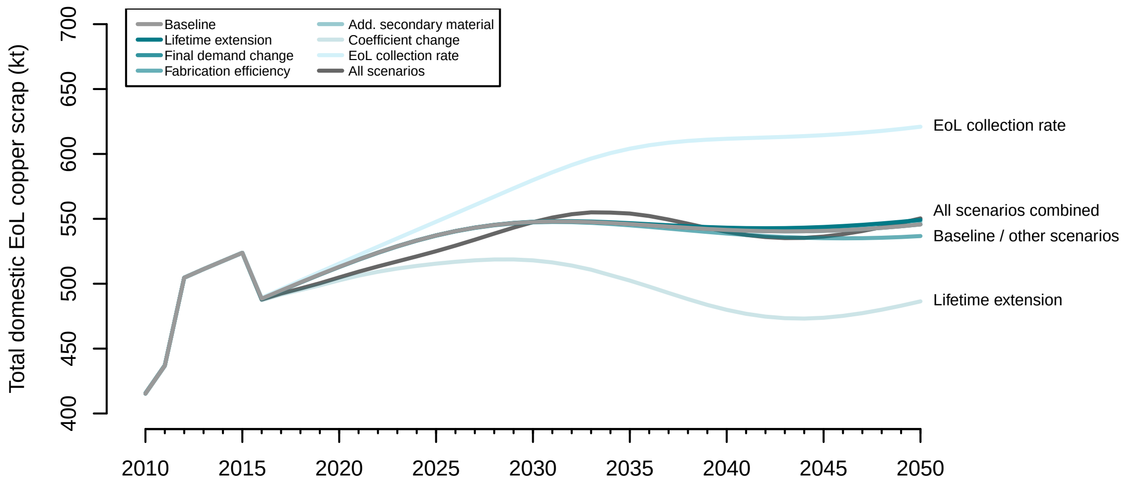


Figure 6.12: Total collected domestic EoL copper scrap, model results

The combination of all scenarios leads to a partial leveling of opposing effects from individual scenarios. Thus, while the lifetime extension scenario reduces the availability of total EoL copper scrap, the EoL collection rate scenario increases it. All other scenarios only have marginal effects and so the combined effect of all scenarios leaves EoL copper scrap at approximately the baseline level in 2050.

Primary copper demand

Figure 6.13 shows the effects of the efficiency measures on the demand for primary copper, which is exclusively imported since Germany has no domestic copper deposits. This is the entirety of primary copper that goes into German production processes, regardless of whether it is imported in the form of concentrates, blisters or semi-finished products. Primary material contained in finished goods is excluded under this perspective since the measures do not apply to foreign production.

The strongest decrease in the demand for primary copper results from a reduction of the copper intensity of German products (coefficient change scenario). In 2050, this reduction amounts to −18%. The coefficient reduction reduces the overall demand for copper input while at the same time leaving the amount copper scrap at approximately the baseline levels (see Figure 6.12). Together, this explains the disproportionately high reduction of primary copper demand in this scenario.

The lifetime extension scenario causes the largest reduction in the first years of the simulation. However, the oscillatory behavior of the extended lifetimes has a strong effect on primary demand, causing a relative re-increase between the late 2020s and the late 2030s and thus leading to a lower relative reduction towards the end of the simulation period (−8%). As can be seen through a comparison between Figures 6.12 and 6.13, the development of the EoL scrap collection is inversely related to the development of primary copper demand in the lifetime extension scenario. This reduction is very close to that of the landfill mining scenario in the last decade of the simulation. A slightly larger reduction of primary copper demand (−10.6% by 2050) can be achieved through an increase in the EoL collection rate. The final demand reduction and fabrication efficiency scenarios have no noticeable effect on primary copper demand.

Overall, the results indicate a relatively wide range of potential primary copper demand reductions across the scenarios. They suggest that the most effective efficiency measures allow for disproportionately high reductions in primary copper demand, whereas other measures have no noticeable effect. This is especially the case for the fabrication efficiency scenario, which only leads to a reduction of new scrap that cycles through the economy but does not have a lasting effect on primary copper demand. Furthermore, trade-offs can be observed between reductions in primary copper demand and the later availability of secondary material for re-use, which is especially the case for the lifetime extension. Since the technical measures only concern the German production system, overall copper demand may not change to a large extent as the copper contained in end-use products may not decrease similarly or even

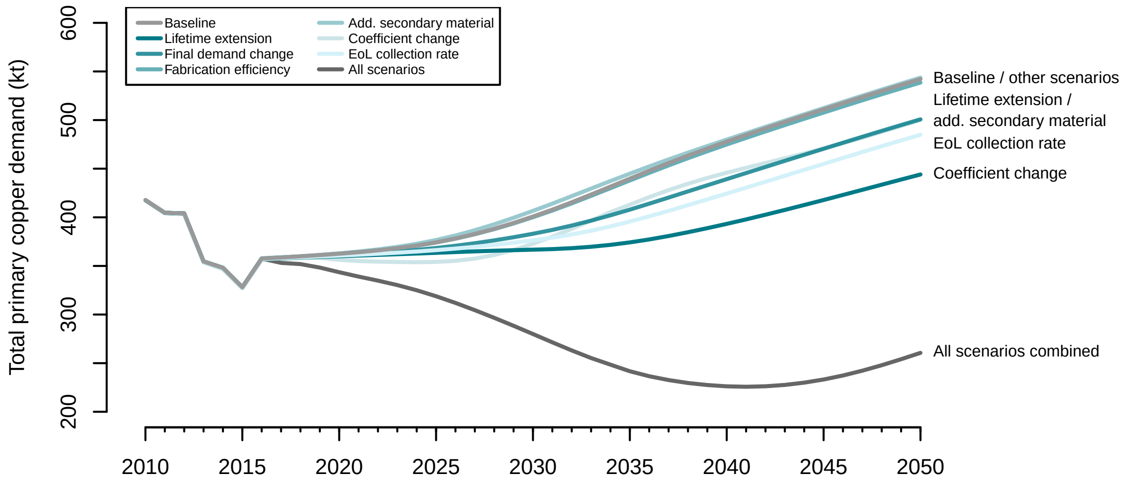


Figure 6.13: Primary copper input to domestic production of finished goods, model results

increase (i.e. the potential for an “externalization” of resource use is not addressed with this analysis). However, as the historical analysis of aggregate material use in Section 5.1 has shown, this does not appear to be happening so far.

The combination of all scenarios yields a similarly large overall effect on primary copper demand as in the case of total demand for end-use goods production. Thus, close to 50% of primary copper could be saved through a combination of the considered measures. This is slightly more than the sum of the individual scenarios, which would amount to a reduction of about 45%. Hence, a positive feedback between the scenarios can also be observed in the case of primary copper demand. While the effect is not as strong in relative terms as in the case of total copper demand for domestic production, it nevertheless indicates that the mutual reinforcement of the scenarios can also lead to disproportionately high reductions of primary copper demand.

6.3 Conclusions

6.3.1 Aggregate material efficiency measures

In the first part of this chapter, the macroeconomic effects of a broad material efficiency scenario were analyzed. This scenario was based on technical information from two recent research programs and therefore contains real-life examples of efficiency technologies, but does not represent the overall efficiency potential of the German economy. The estimated technical efficiency potentials were translated into a diffusion trajectory until the year 2050. On the physical level, these measures can lead to a reduction of RMC of about 1.6% and RMI of about 1.1% by the end of the simulation period. The majority of these reductions is due to decreases in mineral demand, while metals, fossil fuels and biomass only make small contributions. On the macroeconomic level, the aggregate effects on GDP and employment are very small. The combination of reduced material demands, investment and O&M expenditures does not induce large developments within the overall economy. However, on the sectoral level, considerable shifts of up to ±5% in GVA and employment can be observed. The largest losses in GVA and employment accrue to coal and gas sectors due to reductions in energy demand, and to the non-ferrous metals sector due to reduced inputs of copper, aluminum, nickel and other non-ferrous metals. The largest gains are experienced by the ferrous metals, metal casting and ceramics sectors, as well as the machine repair sector. In the former three cases, these gains are due to reductions of material inputs in these sectors, which raises their respective GVA and employment. The machine repair sector, in contrast, is one of the few sectors which directly benefit from the investment impulse. The negative effects accruing to some sectors are mainly due to indirect supply chain effects of the efficiency reductions, which are not compensated by the overall positive (albeit small) demand impulse.

The altered material demands partly deviate from the material demand reductions defined in the scenario because macroeconomic dynamics can either weaken or amplify the reductions of the impulses. The former case can be broadly labeled as rebound effect, while the latter case is called super conservation. Since macroeconomic effects of the scenario are very small, the overall feedback on material demand is also relatively small. The positive rebound potential of the investment and O&M impulses is counteracted by the negative supply chain effects of the material efficiency measures so that overall a 0.3% super conservation can be observed for RMC. On a sectoral level, the results are more diverse, though they should be treated with caution due to the relatively small reduction potentials to which the simulated material demand reductions are compared.

A sensitivity analysis was conducted by varying non-ferrous metal prices, since they were found to have a large influence on sectoral GVA and employment results. With the help of a statistically bound stochastic process, a random walk with drift was devised for time series of the most relevant non-ferrous metals, which lead to probability distributions of future prices. Utilizing these price distributions, 1000 simulations were run. The price variations caused no noticeable effect on overall GVA or employment. Only the sectors directly connected to the use or provision of non-ferrous metals are affected by the price variations, indicating that indirect effects from changing prices are negligible. However, the direct effects caused the GVA results to almost double or drop towards zero in the case of the metal casting sector, which is a direct user of non-ferrous metals.

6.3.2 Stock and flow dynamics within the copper cycle

For the simulation of stock and flow dynamics in the German copper cycle, six generic scenarios were defined, which can be summarized under the categories of stock dynamics and demand side changes. The first category includes product lifetime extensions, increases in EoL collection rates and measures to recover copper contained in unused anthropogenic stocks, for example through landfill mining. The second category includes changes in the copper intensity of products, increases in fabrication efficiencies of end-use products and absolute demand reductions. In all scenarios, a 10% change of the respective variables compared to a baseline scenario was assumed. Where possible, auxiliary impulses, such as investment expenditures, were also implemented, though mostly in the form of rough estimates. The main interest of these scenarios lied thus in the interaction between copper stocks and flows in response to different efficiency measures. In order to accurately portray these dynamics, some adaptations had to be made to the copper flow and the macroeconomic model.

Three indicators were used to gauge the effectiveness of the six individual measures as well as a combination of all measures. These are the total copper demand for the domestic production of end-use goods, the amount of EoL copper scrap available for use as secondary material, and total primary copper demand, which is exclusively supplied by imports. In the case of total copper demand for domestic goods production, the lifetime extension and the intensity reduction scenario generate the largest reductions. The time path of the lifetime extension induced demand reduction displays oscillatory behavior, which indicates a trade-off between reduced material demand and later availability of secondary material. All scenarios combined lead to a disproportionately large reduction of copper demand, which is due to a positive feedback between the lifetime extension and the intensity reduction scenario.

The availability of EoL copper scrap can be most effectively increased through an increase in the EoL collection rate. In contrast, the lifetime extension scenario leads to a reduction of EoL copper scrap since copper is fixated in anthropogenic stocks for a longer period of time. Since the other scenarios have no noticeable effect on the amount of EoL scrap, the two scenarios more or less cancel each other out in the combined simulation of all scenarios.

In the case of primary copper demand, the reduction of the copper intensity of German end-use goods production leads to the largest reduction. It is followed by an increase in the EoL collection rate and the lifetime extension and urban mining scenarios, the latter two of which display approximately the same reductions. Since primary copper demand is a fraction of total copper demand, the overall magnitude of the effects is the largest. The combination of all scenarios thus allows for a reduction of primary copper demand of almost 50%, which is higher than the sum of the individual scenarios. Hence, feedbacks between the scenarios are also present in this case.

However, the scenarios have some limitations. Only generic technology investment sums were used to portray the expenditure side of the scenarios. These expenditures may not be a realistic representation of the actual costs and associated macroeconomic effects. As described in Section 6.2.1, even if the height of the investments is accurate, the macroeconomic effects depend on assumptions regarding the sources of funds and the relationship between monetary savings and expenditures. In addition, certain feedbacks which are theoretically possible within the model structure have not been utilized due to data limitations. For instance, the lifetime extension scenario would be more holistically described if the reduction would fully pass through the macroeconomic model, since this would trigger further reaching macroeconomic effects (see Section 6.2.1). Even though these effects are likely to be small, this would provide a fuller picture of the economic (and in turn indirect physical) effects of lifetime extensions. Finally, the induced macroeconomic effects are generally small due to the relatively small size of the monetary impulses. The results may change noticeably if the object of investigation and spatial scope change.

7 Summary and conclusions

7.1 Summary of results

7.1.1 Past material flows in Germany

The analysis of Germany's past raw material use revealed a positive trend for input-based indicators (RMI and TMR) in the period from 1995 to 2011. This trend has been identified as being mainly driven by exports, a situation which can be viewed from two contrasting perspectives. On the one hand, exports contribute to the generation of gross value added. In fact, Germany's industrial performance depends heavily on exports, which accounted for almost 40% of German GDP in 2016 (Destatis, 2017a,c). On the other hand, from a consumption-based perspective of material use, which is a closer reflection of Germany's own investment and consumption needs, exports are not considered. From this point of view, imports are the more important trade flow, since they are demanded by the domestic market. The consumption-based perspective is in addition favored by some because it can be used additively as a global indicator (i.e. the sum of all countries' RMCs is global raw material consumption). In contrast, input-based indicators cannot be used additively since countries' exports would be double counted as other countries' imports.

The consumption-based indicators (RMC and TMC) show no strong upward or downward trend in the period from 1995 to 2011. TMC decreased by 7%, mainly due to a reduction in fossil fuel use, while consumption in the other categories remained more or less constant. In the case of RMC, despite no clear overall trend (a 1% reduction), internal shifts between material categories took place, so that the consumption of metals and biomass increased while that of fossil fuels decreased. Since raw material consumption measures the worldwide direct and indirect material extraction induced by domestic consumption, no clear upward trend also refutes the suspicion that an externalization of material extraction has taken place. Therefore, the claim that material consumption has not decreased alongside domestic extraction because foreign materials are embodied in imported products does not appear to hold.

A Structural Decomposition Analysis revealed that different factors have contributed differently to the development of raw material consumption in Germany. While the overall level of RMC in 2011 was close to that in 1995, changes in the factors contributing to RMC had diverging influences. Thus, changes in the production structure of the global economy as well as the level of German final demand would by themselves have led to an increase of German RMC. In contrast, the change in the material intensity of extracting sectors, as expressed by material use coefficients, would by itself have led to a noticeable decrease in RMC. The relationship between material intensity and global production structure yielded the interesting insight that while at the first stage of the supply chain less material is used per Euro of output, the intermediate delivery structure of the economy in fact requires more embodied material due to different product compositions. The reduction of the material use coefficients therefore does not equate to a general dematerialization of the economy.

The results differ between the components of RMC, where the largest effects can be observed for fossil fuels and the smallest for metals. Different decomposition variants also lead to considerably different contributions of the three decomposition factors material intensity, economic structure and final demand. This highlights the importance of taking the full set of decomposition variants into account. A number of sub-decompositions were additionally carried out. They showed that the level of final demand exclusively determines the contribution to raw material consumption changes in Germany, while its structure plays no role. Contrary to the EKC hypothesis, structural change of final demand in Germany has not contributed to a reduction of raw material consumption as one form of environmental pressure. In the case of the material intensity of sectoral production, a sub-decomposition revealed that the larger part of the RMC change is due to changes in foreign material use coefficients, while only a small fraction is due to domestic coefficient changes. A further sub-decomposition has been carried out for the structural linkages of the global economy. Thus, a change in Germany's domestic production structure (including imported intermediate inputs) would only have accounted for about three quarters of the overall production structure induced RMC change. If only the change in domestically produced intermediate inputs were taken into account, German RMC would have decreased by about 5% whereas it would have increased by 25% if only the change of intermediate inputs from the rest of the world to Germany were taken into account. These results illustrated the considerable influence of the global economic structure on domestic raw material consumption.

In sum, the analysis revealed that multiple factors determine Germany's raw material consumption. In the period between 1995 and 2011, these factors have interacted in such a way that Germany's RMC remained relatively steady. This state is not guaranteed to last forever, especially considering that some of these factors, such as the composition of international value chains, are outside of Germany's control.

7.1.2 Economy-wide effects of material efficiency measures

The simulation of economy-wide effects of aggregate material efficiency measures as defined in the underlying scenario showed that Germany's RMC could potentially be reduced by about 1.6% and RMI by about 1.1% until 2050 based on the modeled technology implementation. This reduction is mainly achieved through a reduction in the use of minerals, followed by minor contributions from metals and fossil fuels, which is mainly due to the dominance of mineral saving technologies in the analyzed scenarios. The small contributions from the metals and fossil fuel categories are on the one hand due to relatively small scenario impulses and on the other hand due to small macroeconomic effects, which do not induce large indirect physical effects. Some effects also counteract each other. For instance, reductions in metal demand are countered by increases in the demand for metals from sectors producing the efficiency technologies in the form of machinery etc., and from those sectors that maintain them.

The macroeconomic effects of the material efficiency scenarios are negligibly small with an overall GDP increase of 0.01% and an employment increase of 0.02% in 2050. The investment and O&M as well as the intermediate delivery impulses are too small compared to the overall size of the economy to cause more profound macroeconomic effects. It is unclear whether the relationship between material use reductions and economic effects would be the same if these impulses were larger, since feedback effects may create non-linearities. More interesting economic developments can be observed in the form of shifts between sectors, which can reach up to ±5% per sector. Negative effects both in terms of GVA and employment mainly occur to sectors providing raw materials or fossil fuels, most notably the coal sector but to a lesser extent also the non-ferrous metals sector. In contrast, the sectors which benefit the most are on the one hand those sectors in which the implementation of a specific material efficiency technology takes place and which therefore have lower input demands and thus higher GVA. The affected sectors include the ferrous metals and the metal casting sectors. On the other hand, a few sectors benefit from the positive investment and O&M impulse, though generally this plays a minor role. The only sectors affected by this impulse are the machine repair and business services sectors. In the analysis, it was assumed that these adjustments take place without any frictions. However, in reality, labor markets may be sticky with respect to geographical mobility or qualification levels. Therefore, it can be assumed that in reality some of these shifts would not take place.

The largest macroeconomic effects were found to happen in the period from 2020 to 2040, which is mainly due to the way the scenario impulses were modeled to unfold. In that period, the impulses experience the strongest acceleration. However, the temporal distribution of the results is also partially determined by overlapping effects which do not strictly follow the development of the scenario inputs. This is especially the case for sectors which on the one hand experience demand reductions but indirectly also benefit from the material efficiency measures. For instance, the machinery sector on the one hand benefits from investments in material efficiency technologies, which gradually build up but also decline again (see Section 6.1.2). On the other hand, negative supply chain effects unfold until 2050 and eventually overcompensate the positive demand effect in this sector.

As may be expected, the small macroeconomic effects do not induce considerable overall rebound effects. A number of factors have been identified as potential causes of rebound effects within individual material categories, including the investment and O&M impulses, which have embodied material requirements, as well as the positive aggregate demand effect. However, negative supply chain effects from the material efficiency measures appear to counteract these positive impulses, leading to an overall

RMC reduction that is 0.3% lower than the projected value. Thus, slightly larger material savings were achieved according to the simulation than expected from the scenario inputs, i.e. a small amount of super conservation can be observed. Especially some metals and fossil fuels contribute to this overall result. However, it is likely that the results are determined by small potential savings and comparatively large overlapping macroeconomic effects relative to the sizes of the affected sectors.

Finally, a sensitivity analysis was carried out for stochastic variations of non-ferrous metal prices. While the overall effect on GVA and employment was negligible, sectors directly connected to the use or provision of non-ferrous metals were considerably affected. These include the non-ferrous metals sector, the ferrous metals sector and the metal casting sector. The latter displayed GVA variations of close to ±100% of the original GVA and employment deltas from the baseline. Indirect effects, on the other hand, played no significant role, leaving other sectors unaffected by the price variations.

7.1.3 Stock and flow dynamics within the copper cycle

Stock and flow dynamics within the German copper cycle resulting from different efficiency measures were analyzed within different generic scenarios, which either constitute changes in the demand for copper or in the dynamics of the anthropogenic copper stock. The model results suggest a relatively wide range of possible trajectories for three analyzed variables: 1) total copper use in domestic production processes (regardless of the source), 2) the amount of EoL copper scrap and 3) the demand for imported primary copper. In the case of total copper input in domestic production processes, the 10% reduction of the material intensity of copper processing sectors within the macroeconomic model is reflected in an almost equivalently lowered copper demand. A similar reduction could be observed for the lifetime extension scenario, though the development of total copper input displays oscillatory behavior in this scenario. The reason for this was assumed to lie in the changed replacement periods of the in-use stocks due to the changed lifetime distributions. The other scenarios were not found to have considerable effects on copper use in domestic production processes, including the fabrication efficiency scenario, which was found to only change the amount of copper that cycles between end-use goods and semis manufacturers. Due to positive feedback effects between the lifetime extension and the intensity reduction scenario, the combined simulation of all scenarios led to an overall decrease in total copper demand for domestic production processes larger than the sum of the individual scenarios.

In the case of the availability of EoL copper scrap, the lifetime extension scenario led to reductions of over 12% in 2050. In this scenario, the trade-off between reduced copper demand and subsequent decrease in the availability of secondary material was also visible in the form of oscillatory behavior of the projected EoL scrap amount. As expected, an increase of the EoL collection rate was found to raise the amount of collected scrap. The other scenarios were not found to have significant effects on the availability of EoL scrap. Interestingly, this includes the coefficient reduction scenario, which was assumed to eventually also reduce the amount of copper scrap. However, the availability of copper scrap is largely determined by copper embodied in imported end-use goods, so the change in the domestic production system only had a minor impact. The simultaneous simulation of all scenarios caused EoL copper scrap to remain close to the baseline levels, since the scrap collection and the lifetime extension scenario largely canceled each other out.

In the case of imported primary copper input in the domestic production of end-use goods, the largest decreases could be observed in the intensity reduction scenario (−18% in 2050). The reason for this disproportionally high reduction was found to lie in the overall demand decrease, combined with close to no impact on EoL scrap availability. The increase of the EoL collection rate was found to cause the second largest reduction in primary copper demand, while the smallest reduction was observed in the case of the lifetime extension and the landfill mining scenarios (−8% in 2050). The other scenarios caused no noticeable reduction. However, a combination of all scenarios led to a disproportionately high reduction, which was mainly driven by positive feedback effects between the individual scenarios.

The most interesting dynamics arose from the lifetime extension scenario since it entails a trade-off between a demand reduction for primary copper and a longer fixation of copper in end-use stocks. This led to oscillatory behavior in the results for all indicators. A likely reason for this behavior are the changed replacement periods of the end-use stocks due to changed lifetime distributions. In contrast, as suspected the fabrication efficiency scenario only led to onetime reductions of copper demand, which quickly returned to preexisting levels. Contrary to some accounts, an increase in the fabrication efficiency of copper products therefore does not appear to have a lasting effect on copper demand.

7.2 Conclusions

7.2.1 Methodological reflection

The analysis of past material consumption in Germany was carried out with an MRIO approach, which has the advantage of being transparent and encompassing the entirety of global production interlinkages, but is subject to the limitations of IO approaches in general, as outlined in Section 2.3. The results were critically compared to those of studies utilizing a coefficient-based approach, which may be partially more accurate in a national context but has to rely on external and possibly faulty data on the RME of trade flows. Assuming that the global inter-industry flows and the material use coefficients are accurately portrayed by EXIOBASE, the MRIO approach thus appears to have more explanatory power than coefficient-based approaches.

The macroeconomic simulation model developed in this thesis, ISI-Macro, is centered around a detailed IO module with 72 sectors based on national accounting principles. The model's demand orientation is well suited for the analysis of material efficiency measures since the most important effects happen on the demand side of the economy. Supply side effects, such as changes to the production potential of the economy, do not play a large role in the context of material efficiency. The model relies on a number of simplifying assumptions, which make it somewhat predictable on the one hand but rather linear on the other hand. This especially pertains to the exclusion of supply-demand feedback loops, which would introduce non-linearity, and the utilization of fixed split factors in the calculation of some sectoral variables. ISI-Macro can therefore be interpreted as a partially closed macroeconomic accounting model, which portrays well the structural relationships in the economy but does not endogenously account for supply-driven structural change. Therefore, an explicit portrayal of the supply side and supply-demand interactions could be beneficial for analyses of more long term effects of material efficiency.

MRIO data from EXIOBASE was also used to develop an aggregate environmental extension for ISI-Macro, which covers the national level. This data is used for the detailed depiction of material extraction and trade, as well as other environmental indicators. However, being integrated in a national model, much of the information is condensed into national material use and trade coefficients, losing flexibility with respect to multi-regional dynamics. Due to the lower resolution of the IO module of the national model, the material use coefficients could not be directly extracted from EXIOBASE. Instead, virtual material use coefficients were calculated based on total sectoral material demands that result from the composition of final demand in the latest year portrayed in EXIOBASE, 2011. These coefficients therefore do not represent the material intensity of the extractive sectors but the cumulative material intensity of all sectors. Changes to these coefficients therefore cannot be interpreted in the same way as the recorded coefficient changes within the standard tables of EXIOBASE.

A specific environmental extension of ISI-Macro was built with the help of detailed copper flow data. In contrast to the logic used by EXIOBASE or the aggregate environmental extension, copper use is not attributed to the earliest stage of the supply chain or conceived as the total copper intensity of sectors. Instead, copper use is attributed to the distribution of copper semi-finished goods across end-use goods producing sectors. This allows for a more accurate distribution of copper in the economy since the divergence between monetary flows as portrayed by the IO table and physical flows of copper is largest at this stage of the supply chain. However, as above, this complicates the comparison with other implementations of material flows in a macroeconomic context, including EXIOBASE and the aggregate environmental extension.

The methodological suitability of the general structure of the copper flow model to portray metal cycles has been documented elsewhere (Glöser et al., 2013; Soulier et al., 2018a,b). The German version has been augmented in its structure and coupled with the macroeconomic simulation model in order to be able to portray the effects of different efficiency measures. The coupling of the two models undertaken in this thesis is key to portraying the interaction between economically and technologically induced copper demand and life cycle determined supply of secondary copper. Therefore, material stock dynamics are integrated into a flow-based logic of economic modeling. On the one hand, this allows for a more holistic depiction of the role of economic (sectoral) flows in driving material demand. On the other hand, the concurrent dependence of economic flows on physical stocks can be portrayed. The demand for primary copper can thus be calculated based on realistic measures of available secondary copper.

7.2.2 Conclusions and outlook

In light of the dramatic impacts raw material extraction has on the world's ecosystem, it is vital to understand the drivers of raw material consumption and to assess the means of reducing it. Even though industrialized countries such as Germany are only part of the problem, they can act as forerunners in using raw materials more sustainably. The first aim of this thesis was therefore to analyze past patterns of raw material use in Germany in order to identify the main drivers and draw conclusions on potential areas in which reductions can be achieved. A positive conclusion to be drawn from the retrospective analysis is that Germany's RMC has remained relatively steady in the period from 1995 to 2011, refuting the suspicion that an externalization of its material footprint is taking place. However, Germany relies heavily on exports, and the RME of its exports have been increasing in the same period, leading to an increase of RMI of close to 20%. Thus, while from a consumption perspective Germany has experienced relative decoupling between material use and economic growth, this growth has been fueled to some degree by the value added generated from increased exports with a corresponding material footprint. Germany's trade surplus is therefore not only problematic from an economic but also from an ecological perspective.

The analysis of the drivers of Germany's raw material consumption has revealed that changes in consumption and investment preferences in Germany have not had a significant impact on RMC. Therefore, increased environmental awareness, which is usually attributed to more affluent countries, has not translated into a reduction of those consumption and investment activities that are especially material intensive. Future research could look into the reasons for this. One possible explanation for this is that the material dimension of consumption is not as apparent as, for example, the associated GHG emissions, since many consumption activities do not have large direct material requirements but instead considerable indirect requirements. This issue could be addressed, for instance, by creating more transparency and traceability of the material footprints of different consumption activities and by moving away from selective accounts of material consumption with a strong public appeal to a broader and standardized accounting of complete material footprints.

Effective measures to reduce material demand cannot be conceived in isolation of the wider socio-economic system. The second aim of this thesis was therefore to assess a set of technological material efficiency measures with respect to their macroeconomic impacts. For this, an aggregate material efficiency scenario was built around a set of efficiency technologies. While this set is non-representative, the structural shifts observed through the modeling of their economy-wide implementation are indicative of the likely effects of technical material efficiency measures in general. The pattern of the simulation results is close to that of the scenario inputs and the modeling assumptions, implying that the implementation of these technologies did not induce large macroeconomic feedback effects. The most affected sectors are those which either demand less material inputs and thus increase their GVA and employment or those which deliver less material and therefore experience losses. The manufacturers of investment goods or providers of O&M services are only slightly affected. This distribution of effects implies a certain degree of import substitution, induced by the demand reduction for raw materials and the demand increase for technical goods and services, though the overall effect is comparatively low for the considered scenario. Correspondingly, the overall value added and employment effect is also relatively low. However, the simulation results do indicate that under the given modeling assumptions, mildly positive value added and employment effects can be expected from material efficiency measures of this kind.

At the outset of this thesis it was argued that the full extent of material savings can only be determined once macroeconomic effects are taken into account, which could theoretically dampen or amplify the material savings. On an aggregate level, the small negative rebound effect (or super conservation) of 0.3% is indicative of the small macroeconomic response to the efficiency measures. On the level of individual sectors, different cases can be observed, indicating different sectoral dynamics. In the case of some metals, small potential savings stand against relatively large demand increases caused by supply chain effects or aggregate impulses of the underlying scenario, leading to large relative measures of rebound effects. Only reporting rebound effects in relative terms may thus lead to the misinterpretation that small material savings are responsible for relatively larger macroeconomic effects causing demand re-increases. However, the bigger portion of these demand re-increases may not be causally linked to the material savings. In other cases, mainly concerning minerals, relatively large savings are counterbalanced by small demand increases resulting from the aggregate demand impulse, leading to small positive rebound effects. Rebound effects portrayed in this way should in any case be understood as the potential of re-increases in material demand due to macroeconomic adaptation mechanisms, rather than a micro-founded consumption reaction to specific efficiency measures, which was already outlined by Pfaff and Sartorius (2015). It is therefore also difficult to empirically measure macroeconomic rebound effects in the sense that an efficiency measure with a known savings potential is the definite cause of an observed re-increase in material demand, since individual causes and effects are difficult to isolate in such a setting. A more promising way to consider this type of rebound effect is thus a comparison of aggregate savings potentials with potential macroeconomic effects based on different assumptions regarding the macroeconomic setting. Future research could look into feasible means of quantifying this potential.

A holistic portrayal of the effects of material efficiency measures requires a consideration of material stocks since their development ultimately determines the amounts of available secondary material. The third aim of this thesis was therefore to shed light on the interaction between material stocks and flows in the German copper cycle in response to different efficiency measures. While the defined scenarios are generic in their overall design, some interesting insights arose from the stock and flow dynamics resulting from the depicted measures. Considerable reductions in total as well as primary copper demand could be achieved with some measures and a combination of these measures could lead to disproportionately high reductions.

While product lifetime extensions proved to have noticeable effects on overall and specifically primary copper demand, a trade-off could be observed due to a longer fixation of copper in anthropogenic stocks. However, the lifetime extension scenario did not address the issue of product hibernation, which describes a situation in which products remain in households after their service lives without being discarded (and eventually recycled). Future research could address the issue of product hibernation in conjunction with different means to achieve product lifetime extensions. A first step in this direction was taken by Glöser-Chahoud et al. (2019). In this context, the role of different types of recycling could be investigated, ranging from the product to the substance level.

The simulations of the copper cycle also showed that, contrary to some accounts, an increase in the fabrication efficiency of copper containing end-use products has no noticeable effect on primary copper demand. Thus, while energy savings are theoretically possible through an increase in fabrication efficiency, it does not affect the material dimension of copper. Copper is a special case since the infrastructure to re-melt new scrap is well established and the scrap quality is sufficient to substitute primary material. This is not the case for all materials, and so the conclusion is not universally applicable. However, it indicates that assessments of the effectiveness of increases in fabrication efficiencies have to be conducted with regard to the treatment of new scrap.

Despite these insights, the measures analyzed in the scenarios only addressed the domestic production system. However, much of the copper contained in end-use goods is imported in this form and therefore cannot be addressed through technical measures domestically. This was illustrated by the small effect of the intensity reduction scenario on the amount of available EoL copper scrap. Further reaching decreases of primary copper demand will thus also depend on measures addressing the copper that went into end-use products in foreign production systems. Next to technical measures, economic measures such as supply chain management will hence have to play a role in the future.

Bibliography

Acquaye, A. A., Wiedmann, T., Feng, K., Crawford, R. H., Barrett, J., Kuylenstierna, J., Duffy, A. P., Koh, S. C. Lenny, and McQueen-Mason, S. (2011). Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis. *Environmental Science & Technology*, 45(6):2471–2478.

Adelle, C. and Weiland, S. (2012). Policy assessment: The state of the art. *Impact Assessment and Project Appraisal*, 30(1):25–33.

Aghion, P. and Howitt, P. (1992). A Model of Growth Through Creative Destruction. *Econometrica*, 60(2):323.

Albrecht, S., Bollhöfer, E., Brandstetter, P., Fröhling, M., Mattes, K., Ostertag, K., Peuckert, J., Seitz, R., Trippe, F., and Woidasky, J. (2012). Ressourceneffizienzpotenziale von Innovationen in rohstoffnahen Produktionsprozessen. *Chemie Ingenieur Technik*, 84(10):1651–1665.

Alexandri, E., Boonekamp, P., Chewpreecha, U., de Rose, A., Drost, R., Estourgie, L., Farhangi, C., Funcke, D., Markkanen, S., Moret, G., Pollitt, H., Rodenburg, C., Suerkemper, F., Tensen, S., Theillard, P., Thema, J., Vethman, P., Vondung, F., and Voogt, M. (2016). The Macroeconomic and Other Benefits of Energy Efficiency. Final Report prepared for the European Commission.

Argote, L. and Epple, D. (1990). Learning curves in manufacturing. *Science*, 247(4945):920–924.

Arto, I., Rueda-Cantuche, J. M., Amores, A. F., Dietzenbacher, E., Sousa, N., Montinari, L., and Markandya, A. (2015). EU Exports to the World: Effects on Employment and Income. Technical report, Publications Office of the European Union, Luxembourg.

Ayres, R. U. (1997). Metals recycling: Economic and environmental implications. *Resources, Conservation and Recycling*, 21(3):145–173.

Ayres, R. U. and Kneese, A. V. (1969). Production, consumption, and externalities. *The American Economic Review*, 59(3):282–297.

Bacharach, M. (1965). Estimating Nonnegative Matrices from Marginal Data. *International Economic Review*, 6(3):294.

Bailey, R., Allen, J. K., and Bras, B. (2004a). Applying Ecological Input-Output Flow Analysis to Material Flows in Industrial Systems: Part I: Tracing Flows. *Journal of Industrial Ecology*, 8(1-2):45–68.

Bailey, R., Bras, B., and Allen, J. K. (2004b). Applying Ecological Input-Output Flow Analysis to Material Flows in Industrial Systems: Part II: Flow Metrics. *Journal of Industrial Ecology*, 8(1-2):69–91.

Baiocchi, G. and Minx, J. C. (2010). Understanding Changes in the UK's CO2 Emissions: A Global Perspective. *Environmental Science & Technology*, 44(4):1177–1184.

Bakker, C., Wang, F., Huisman, J., and den Hollander, M. (2014). Products that go round: Exploring product life extension through design. *Journal of Cleaner Production*, 69:10–16.

Bakker, C. A. and Schuit, C. S. (2017). The Long View. Exploring Product Lifetime Extension.

Barker, T., Alexandri, E., Mercure, J.-F., Ogawa, Y., and Pollitt, H. (2015). GDP and employment effects of policies to close the 2020 emissions gap. *Climate Policy*, 16(4):393–414.

Barker, T., Dagoumas, A., and Rubin, J. (2009). The macroeconomic rebound effect and the world economy. *Energy Efficiency*, 2(4):411–427.

Barker, T., Pollitt, H., Chewpreecha, U., Alexandri, E., Gonzalez-Martinez, A., Higson, A., and Billington, S. (2014). E3ME Technical Manual, Version 6.0.

Bass, F. M. (1969). A new product growth for model consumer durables. *Management Science*, 15(5):215–227.

Bassi, A. M., Tan, Z., and Mbi, A. (2012). Estimating the impact of investing in a resource efficient, resilient global energy-intensive manufacturing industry. *Technological Forecasting and Social Change*, 79(1):69–84.

Berkhout, P. H., Muskens, J. C., and W. Velthuijsen, J. (2000). Defining the rebound effect. *Energy Policy*, 28(6-7):425–432.

Beuren, F. H., Gomes Ferreira, M. G., and Cauchick Miguel, P. A. (2013). Product-service systems: A literature review on integrated products and services. *Journal of Cleaner Production*, 47:222–231.

Beylot, A. and Villeneuve, J. (2015). Assessing the national economic importance of metals: An Input–Output approach to the case of copper in France. *Resources Policy*, 44:161–165.

Blazejczak, J., Braun, F. G., Edler, D., and Schill, W.-P. (2014). Economic effects of renewable energy expansion: A model-based analysis for Germany. *Renewable and Sustainable Energy Reviews*, 40:1070–1080.

Bleischwitz, R. (2003). Cognitive and institutional perspectives of eco-efficiency. *Ecological Economics*, 46(3):453–467.

Böhringer, C., Keller, A., and van der Werf, E. (2013). Are green hopes too rosy? Employment and welfare impacts of renewable energy promotion. *Energy Economics*, 36:277–285.

Borenstein, S. (2013). A Microeconomic Framework for Evaluating Energy Efficiency Rebound And Some Implications: Energy Institute at Haas (EI @ Haas) Working Paper Series.

Bornhöft, N. A., Nowack, B., and Hilty, L. M. (2013). Material Flow Modelling for Environmental Exposure Assessment – A Critical Review of Four Approaches Using the Comparative Implementation of an Idealized Example. In *Proceedings of the 27th EnviroInfo Conference 2013, Hamburg, Germany.*

Bouwmeester, M. C. and Oosterhaven, J. (2013). Specification and Aggregation Errors in Environmentally Extended Input–Output Models. *Environmental and Resource Economics*, 56(3):307–335.

Box, J. M. (1983). Extending Product Lifetime: Prospects and Opportunities. *European Journal of Marketing*, 17(4):34–49.

Bréchet, T. and Jouvet, P.-A. (2009). Why environmental management may yield no-regret pollution abatement options. *Ecological Economics*, 68(6):1770–1777.

Breitschopf, B., Nathani, C., and Resch, G. (2013). Employment Impact Assessment Studies – Is There a Best Approach to Assess Employment Impacts of RET Deployment. *Renewable Energy Law and Policy Review*, 2:93–104.

Bringezu, S. (1997). Introduction. In Bringezu, S., Fischer-Kowalski, M., Kleijn, R., and Palm, V., editors, *Regional and national material flow accounting*, pages 12–15.

Bringezu, S. and Moriguchi, Y. (2002). Material flow analysis. In Ayres, R. U. and Ayres, L., editors, *A handbook of industrial ecology*, pages 79–90. Edward Elgar Pub, Cheltenham, UK and Northampton, MA.

Brunner, P. H. and Ma, H.-W. (2009). Substance Flow Analysis. *Journal of Industrial Ecology*, 13(1):11–14.

Brunner, P. H. and Rechberger, H. (2004). *Practical handbook of material flow analysis*, volume 1 of *Advanced methods in resource and waste management.* CRC/Lewis, Boca Raton, FL.

Brunot, A., Hovestad, A., Hummen, T., Joce, C., Pena Garay, I., Smuk, L., Tercero Espinoza, L. A., Todorovic, J., van der Eijk, Casper, and Velte, D. (2013). *Substitution of Critical Raw Materials: CRM_InnoNet Deliverable D 3.3*. Raw Materials Profiles.

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (2016). German Resource Efficiency Programme II.

Bundesministerium für Wirtschaft und Technologie (2010). Rohstoffstrategie der Bundesregierung.

Bundesregierung (2002). Perspektiven für Deutschland. Unsere Strategie für eine nachhaltige Entwicklung.

Bundesregierung (2012). Nationale Nachhaltigkeitsstrategie: Fortschrittsbericht 2012.

Bundesregierung (2016). Deutsche Nachhaltigkeitsstrategie: Neuauflage 2016.

Buyny, S., Klink, S., and Lauber, U. (2009). Verbesserung von Rohstoffproduktivität und Ressourcenschonung – Weiterentwicklung des direkten Materialinputindikators. Technical report, Statistisches Bundesamt, Wiesbaden.

Calvo, G., Mudd, G., Valero, A., and Valero, A. (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? *Resources*, 5(4):36.

Capros, P., van Regemorter, D., Paroussos, L., and Karkatsoulis, P. (2017). GEM-E3 Manual.

Carnall, M., Dale, L., and Lekov, A. (2016). The economic effect of efficiency programs on energy consumers and producers. *Energy Efficiency*, 9(3):647–662.

Chen, W.-Q. and Graedel, T. E. (2012). Anthropogenic cycles of the elements: a critical review. *Environmental Science & Technology*, 46(16):8574–8586.

Ciacci, L., Vassura, I., and Passarini, F. (2017). Urban Mines of Copper: Size and Potential for Recycling in the EU. *Resources*, 6(1):6.

Ciscar, J.-C. and Dowling, P. (2014). Integrated assessment of climate impacts and adaptation in the energy sector. *Energy Economics*, 46:531–538.

Cooper, S., Skelton, A. C., Owen, A., Densley-Tingley, D., and Allwood, J. M. (2016). A multi-method approach for analysing the potential employment impacts of material efficiency. *Resources, Conservation and Recycling*, 109:54–66.

Croucher, M. (2012). What is important when modeling the economic impact of energy efficiency standards? *Utilities Policy*, 22:50–57.

Crutzen, P. J. and Stoermer, E. F. (2000). The 'Anthropocene'. *IGBP Newsletter*, 41:17–18.

Daniels, P. L. and Moore, S. (2001). Approaches for Quantifying the Metabolism of Physical Economies: Part I: Methodological Overview. *Journal of Industrial Ecology*, 5(4):69–93.

Davidson, P. (2011). *Post Keynesian macroeconomic theory: A foundation for successful economic policies for the twenty-first century.* Edward Elgar, Cheltenham, U.K. and Northamptom, Mass., 2nd edition.

de Haan, M. (2010). A Structural Decomposition Analysis of Pollution in the Netherlands. *Economic Systems Research*, 13(2):181–196.

de Haan, P., Peters, A., and Scholz, R. W. (2007). Reducing energy consumption in road transport through hybrid vehicles: investigation of rebound effects, and possible effects of tax rebates. *Journal of Cleaner Production*, 15(11–12):1076–1084.

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.

de Ridder, W., Turnpenny, J., Nilsson, M., and von Raggamby, A. (2007). A framework for tool selection and use in integrated assessment for sustainable development. *Journal of Environmental Assessment Policy and Management*, 09(04):423–441.

Destatis (2006). Volkswirtschaftliche Gesamtrechnung: Input-Output-Rechnung 2000.

Destatis (2008). Klassifikation der Wirtschaftszweige 2008: Mit Erläuterungen.

Destatis (2010a). Rohstoffeffizienz: Wirtschaft entlasten, Umwelt schonen: Ergebnisse der Umweltökonomischen Gesamtrechnungen 2010.

Destatis (2010b). Volkswirtschaftliche Gesamtrechnung: Input-Output-Rechnung 1995-2007.

Destatis (2011). Umweltökonomische Gesamtrechnung. Sonderauswertung. DMI in Rohstoffäquivalenten 2000-2010.

Destatis (2012). Einkommens- und Verbrauchsstichprobe 2008. Special Evaluation.

Destatis (2014a). Volkswirtschaftliche Gesamtrechnung: Input-Output-Rechnung 1995-2012.

Destatis (2014b). Volkswirtschaftliche Gesamtrechnung: Input-Output-Rechnung 2000.

Destatis (2014c). Volkswirtschaftliche Gesamtrechnung: Input-Output-Rechnung 2012.

Destatis (2015). Bevölkerung Deutschlands bis 2060. 13. koordinierte Bevölkerungsvorausberechnung.

Destatis (2016a). Einkommens- und Verbrauchsstichprobe 2013.

Destatis (2016b). Volkswirtschaftliche Gesamtrechnung: Inlandsproduktberechnung - Lange Reihen ab 1970.

Destatis (2016c). Volkswirtschaftliche Gesamtrechnung: Input-Output-Rechnung 2013.

Destatis (2017a). Außenhandel: Zusammenfassende Übersichten für den Außenhandel.

Destatis (2017b). Umweltnutzung und Gesamtwirtschaft: Bericht zu den Umweltökonomischen Gesamtrechnungen.

Destatis (2017c). Volkswirtschaftliche Gesamtrechnung: Inlandsproduktberechnung - Vierteljahresergebnisse.

Destatis (2018). Umweltökonomische Gesamtrechnungen. Aufkommen und Verwendung in Rohstoffäquivalenten. Lange Reihen 2000 bis 2014.

Dietzenbacher, E. and Los, B. (1998). Structural Decomposition Techniques: Sense and Sensitivity. *Economic Systems Research*, 10(4):307–324.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., and de Vries, G. (2013). The Construction of World Input–Output Tables in the WIOD Project. *Economic Systems Research*, 25(1):71–98.

Dimitropoulos, J. (2007). Energy productivity improvements and the rebound effect: An overview of the state of knowledge. *Energy Policy*, 35(12):6354–6363.

Dittrich, M. (2011). *Physical Trade Data Base*. Heidelberg.

Dittrich, M., Giljum, S., Lutter, S., and Polzin, C. (2013). Aktualisierung von nationalen und internationalen Ressourcenkennzahlen.

Domar, E. D. (1947). Expansion and Employment. *The American Economic Review*, 37(1):34–55.

Duchin, F. (1992). Industrial input-output analysis: Implications for industrial ecology. *Proceedings of the National Academy of Sciences*, 89(3):851–855.

Dürkoop, A., Brandstetter, C. P., Gräbe, G., and Rentsch, L., editors (2016a). *Innovative Technologien für Ressourceneffizienz - Strategische Metalle und Mineralien: Ergebnisse der r3-Fördermaßnahme*. Fraunhofer Verlag, Stuttgart.

Dürkoop, A., Büttner, P., Albrecht, S., Brandstetter, C. P., Erdmann, M., Gräbe, G., Moller, B., Höck, M., Kleeberg, K., Rentsch, L., Schneider, K., Ostertag, K., Pfaff, M., Sartorius, C., Tercero Espinoza, L. A., Szurlies, M., and Wilken, H. (2016b). INTRA r^3+ – Integration und Transfer der r^3-Fördermaßnahme. In Dürkoop, A., Brandstetter, C. P., Gräbe, G., and Rentsch, L., editors, *Innovative Technologien für Ressourceneffizienz - Strategische Metalle und Mineralien*, pages 419–451. Fraunhofer Verlag, Stuttgart.

Duscha, V., Fougeyrollas, A., Nathani, C., Pfaff, M., Ragwitz, M., Resch, G., Schade, W., Breitschopf, B., and Walz, R. (2016). Renewable energy deployment in Europe up to 2030 and the aim of a triple dividend. *Energy Policy*, 95:314–323.

Duscha, V., Ragwitz, M., Breitschopf, B., Schade, W., Walz, R., Pfaff, M., de Visser, E., Resch, G., Nathani, C., Zagamé, P., Fougeyrollas, A., and Boitier, B. (2014). Employment and growth effects of sustainable energies in the European Union: Contract no. ENER/C1/428-2012. Final report on behalf of the European Commission, DG Energy, Fraunhofer ISI, Karlsruhe, Germany.

Elshkaki, A. and Graedel, T. E. (2013). Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *Journal of Cleaner Production*, 59:260–273.

Elshkaki, A., Graedel, T. E., Ciacci, L., and Reck, B. (2016). Copper demand, supply, and associated energy use to 2050. *Global Environmental Change*, 39:305–315.

European Commission (2001). 264 Communication "A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development".

European Commission (2002). 276 Communication "Impact Assessment".

European Commission (2008). 699 Communication "The raw materials initiative - meeting our critical needs for growth and jobs in Europe".

European Commission (2009). Impact Assessment Guidelines SEC(2009) 92.

European Commission (2011). 571 Communication "Roadmap to a Resource Efficient Europe".

European Commission (2015). 614 Communication "Closing the loop - An EU action plan for the Circular Economy".

European Environment Agency (2016). More from less — material resource efficiency in Europe.

European Union (2011). Regulation (EU) No 691/2011 of the European Parliament and of the Council of 6 July 2011 on European environmental economic accounts.

Eurostat (2001). *Economy-wide material flow accounts and derived indicators: A methodological guide.* Eurostat Theme 2, Economy and finance. Office for Official Publ. of the Europ. Communities, Luxembourg, 2000 edition.

Eurostat (2008a). Eurostat Manual of Supply, Use and Input-Output Tables: Methodologies and Working Papers.

Eurostat (2008b). NACE Rev. 2: Statistical classification of economic activities in the European Community: Methodologies and Working Papers.

Eurostat (2013). Glossary: Statistical classification of products by activity (CPA).

Eurostat (2015a). European Union Labour Force Survey (EU LFS): Special Evaluation.

Eurostat (2015b). Glossary: PRODCOM.

Fischer, H., Lichtblau, K., Meyer, B., and Scheelhaase, J. (2004). Wachstums und Beschäftigungsimpulse rentabler Materialeinsparungen. *Wirtschaftsdienst*, 4:247–254.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., and Weisz, H. (2011). Methodology and Indicators of Economy-wide Material Flow Accounting. *Journal of Industrial Ecology*, 15(6):855–876.

Fleissner, P., Böhme, W., Brautzsch, H.-U., Höhne, J., Siassi, J., and Stark, K. (1993). *Input-Output-Analyse: Eine Einführung in Theorie und Anwendungen.* Springers Kurzlehrbücher der Wirtschaftswissenschaften. Springer-Verlag, Wien.

Fontana, G. and Sawyer, M. (2016). Towards post-Keynesian ecological macroeconomics. *Ecological Economics*, 121:186–195.

Forrester, J. W. (1956). Dynamic models of economic systems and industrial organizations. Note to the Faculty Research Seminar, MIT System Dynamics Group D-Memo 0 (5 November). Reprinted as Forrester, J. W. 2003. *System Dynamics Review*, 19(4):331–345.

Forrester, J. W. (1971). *World dynamics.* Pegasus Communications Inc., Waltham.

Forrester, J. W. (1982). The system dynamics natonal model: Macrobehavior from microstructure: Working Paper D-4020. The MIT System Dynamics Group.

Forrester, J. W. (2013 (©1961)). *Industrial Dynamics.* Martino and MIT Press, Mansfield Centre, CT and Cambridge, MA.

Fragkos, P., Tasios, N., Paroussos, L., Capros, P., and Tsani, S. (2017). Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. *Energy Policy*, 100:216–226.

Frenzel, M., Kullik, J., Reuter, M. A., and Gutzmer, J. (2017). Raw material 'criticality'—sense or nonsense? *Journal of Physics D: Applied Physics*, 50(12):123002.

Gandenberger, C., Glöser, S., Marscheider-Weidemann, F., Ostertag, K., and Walz, R. (2012). *Die Versorgung der Deutschen Wirtschaft mit Roh- und Werkstoffen für Hochtechnologien - Präzisierung und Weiterentwicklung der Rohstoffstrategie: TAB Arbeitsbericht Nr. 150: Innovationsreport.*

Geng, Y., Zhao, H., Liu, Z., Xue, B., Fujita, T., and Xi, F. (2013). Exploring driving factors of energy-related CO2 emissions in Chinese provinces: A case of Liaoning. *Energy Policy*, 60:820–826.

George, C. and Kirkpatrick, C. (2007). Impact assessment and sustainable development: an introduction. In George, C. and Kirkpatrick, C., editors, *Impact assessment and sustainable development*, Evaluating sustainable development series, pages 1–12. Edward Elgar, Cheltenham.

Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process.* Harvard University Press, Cambridge, MA.

Geroski, P. A. (2000). Models of technology diffusion. *Research Policy*, 29:603–625.

Giegrich, J., Liebich, A., Lauwigi, C., and Reinhardt, J. (2012). Indikatoren / Kennzahlen für den Rohstoffverbrauch im Rahmen der Nachhaltigkeitsdiskussion: Texte Nr. 01/2012. Technical report, Umweltbundesamt, Dessau-Roßlau.

Giljum, S., Dittrich, M., Lieber, M., and Lutter, S. (2014). Global Patterns of Material Flows and their Socio-Economic and Environmental Implications: A MFA Study on All Countries World-Wide from 1980 to 2009. *Resources*, 3(1):319–339.

Glöser, S., Pfaff, M., and Soulier, M. (2016). Modeling material flows, cumulative material demand and market dynamics of industrial metals within a system dynamics framework. In *Proceedings of the 34th International Conference of the System Dynamics Society, Delft, The Netherlands.*

Glöser, S., Soulier, M., and Tercero Espinoza, L. A. (2013). Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation. *Environmental Science & Technology*, 47(12):6564–6572.

Glöser-Chahoud, S., Hartwig, J., Wheat, D., and Faulstich, M. (2017). The cobweb theorem and delays in adjusting supply in metals' markets. *System Dynamics Review*, 32(3-4):279–308.

Glöser-Chahoud, S., Pfaff, M., Walz, R., and Schultmann, F. (2019). Simulating the service lifetimes and storage phases of consumer electronics in Europe with a cascade stock and flow model. *Journal of Cleaner Production*, 213:1313–1321.

Gordon, R. B., Bertram, M., and Graedel, T. E. (2006). Metal stocks and sustainability. *Proceedings of the National Academy of Sciences*, 103(5):1209–1214.

Goulder, L. H. and Schneider, S. H. (1999). Induced technological change and the attractiveness of CO2 abatement policies. *Resource and Energy Economics*, 21(3-4):211–253.

Graedel, T. E. and Allenby, B. R. (2003). *Industrial ecology*. Prentice-Hall international series in industrial and systems engineering. Prentice Hall, Upper Saddle River, N.J., 2nd ed. edition.

Graedel, T. E., Allwood, J., Birat, J.-P., Buchert, M., Hagel?ken, C., Reck, B. K., Sibley, S. F., and Sonnemann, G. (2011). What Do We Know About Metal Recycling Rates? *Journal of Industrial Ecology*, 15(3):355–366.

Graedel, T. E., Bertram, M., Fuse, K., Gordon, R., Lifset, R. J., Rechberger, H., and Spatari, S. (2002). The contemporary European copper cycle: The characterization of technological copper cycles. *Ecological Economics*, 42(1-2):9–26.

Graedel, T. E., Harper, E. M., Nassar, N. T., and Reck, B. K. (2013). On the materials basis of modern society. *Proceedings of the National Academy of Sciences*, 112(20):6295–6300.

Gravgård Pedersen, O. and de Haan, M. (2006). The System of Environmental and Economic Accounts–2003 and the Economic Relevance of Physical Flow Accounting. *Journal of Industrial Ecology*, 10(1-2):19–42.

Grossman, G. and Krueger, A. (1991). Environmental Impacts of a North American Free Trade Agreement. NBER Working Paper No. 3914. Cambridge, MA.

Grubb, M., Hourcade, J.-C., and Neuhoff, K. (2014). *Planetary economics: Energy, climate change and the three domains of sustainable development*. Routledge, New York.

Guan, D., Hubacek, K., Weber, C. L., Peters, G. P., and Reiner, D. M. (2008). The drivers of Chinese CO2 emissions from 1980 to 2030. *Global Environmental Change*, 18(4):626–634.

Guerra, A.-I. and Sancho, F. (2010). Rethinking economy-wide rebound measures: An unbiased proposal. *Energy Policy*, 38(11):6684–6694.

Haes, H. U. d. (2002). Industrial ecology and life cycle assessment. In Ayres, R. U. and Ayres, L., editors, *A handbook of industrial ecology*, pages 138–148. Edward Elgar Pub, Cheltenham, UK and Northampton, MA.

Haes, H. U. d., van der Voet, E., and Kleijn, R. (1997). Substance Flow Analysis (SFA), an analytical tool for integrated chain management. In Bringezu, S., Fischer-Kowalski, M., Kleijn, R., and Palm, V., editors, *Regional and national material flow accounting*, pages 32–42.

Harrod, R. F. (1948). *Towards a Dynamic Economics*. Macmillan, London.

Hatfield-Dodds, S., Schandl, H., Newth, D., Obersteiner, M., Cai, Y., Baynes, T., West, J., and Havlik, P. (2017). Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies. *Journal of Cleaner Production*, 144:403–414.

Hellweg, S. and Mila i Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science*, 344(6188):1109–1113.

Hibbard, K., Crutzen, P. J., and Lambin, E. (2006). Decadal interactions of humans and the environment. In Constanza, R., Graumlich, L., and Steffen, W., editors, *Integrated History and Future of People on Earth. Dahlem Workshop Report 96.*, pages 341–375.

Higham, D. J. (2001). An Algorithmic Introduction to Numerical Simulation of Stochastic Differential Equations. *SIAM Review*, 43(3):525–546.

Hoekstra, R. and van den Bergh, J. C. (2002). Structural Decomposition Analysis of Physical Flows in the Economy. *Environmental and Resource Economics*, 23(3):357–378.

Hoekstra, R. and van den Bergh, J. C. J. M. (2006). Constructing physical input–output tables for environmental modeling and accounting: Framework and illustrations. *Ecological Economics*, 59(3):375–393.

Horowitz, K. J. and Planting, M. A. (2009). Concepts and Methods of the Input-Output Accounts. Bureau of Economic Analysis. U.S. Department of Commerce.

International Organization for Standardization (2006a). ISO 14040: Environmental management - Life cycle assessment - Principles and framework.

International Organization for Standardization (2006b). ISO 14044: Environmental management - Life cycle assessment - Requirements and guideline.

Jacob, K., Hertin, J., and Volkery, A. (2007). Considering environmental aspects in integrated impact assessment: lessons learned and challenges ahead. In George, C. and Kirkpatrick, C., editors, *Impact assessment and sustainable development*, Evaluating sustainable development series, pages 90–105. Edward Elgar, Cheltenham.

Joshi, S. (2000). Product Environmental Life-Cycle Assessment Using Input-Output Techniques. *Journal of Industrial Ecology*, 3(2&3):95–120.

Kaldor, N. (1957). A Model of Economic Growth. *Economic Journal*, 67:591–624.

Kaumanns, S. C. and Lauber, U. (2016). Rohstoffe für Deutschland: Bedarfsanalyse für Konsum, Investition und Export auf Makro- und Mesoebene: Texte Nr. 62/2016. Technical report, Umweltbundesamt, Dessau-Roßlau.

Kelly, T. D. and Matos, G. R. (2014). Historical statistics for mineral and material commodities in the United States (2016 version): U.S. Geological Survey Data Series 140.

Kleijn, R., van der Voet, E., Kramer, G. J., van Oers, L., and van der Giesen, C. (2011). Metal requirements of low-carbon power generation. *Energy*, 36(9):5640–5648.

Kok, R., Benders, R. M. J., and Moll, H. C. (2006). Measuring the environmental load of household consumption using some methods based on input–output energy analysis: A comparison of methods and a discussion of results. *Energy Policy*, 34:2744–2761.

Konijn, P., de Boer, S., and van Dalen, J. (1997). Input-output analysis of material flows with application to iron, steel and zinc. *Structural Change and Economic Dynamics*, 8(1):129–153.

Koopman, R., Wang, Z., and Wei, S.-J. (2014). Tracing Value-Added and Double Counting in Gross Exports. *American Economic Review*, 104(2):459–494.

Kosmol, J., Kanthak, J., Herrmann, F., Golde, M., Alsleben, C., Penn-Bressel, G., Schmitz, S., and Gromke, U. (2012). Glossar zum Ressourcenschutz. Umweltbundesamt. Dessau-Roßlau.

Krail, M. (2009). *System-Based Analysis of Income Distribution Impacts on Mobility Behaviour*. NOMOS, Baden-Baden.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., and Fischer-Kowalski, M. (2009). Growth in global materials use, GDP and population during the 20th century. *Ecological Economics*, 68(10):2696–2705.

Krook, J., Carlsson, A., Eklund, M., Frändegård, P., and Svensson, N. (2011). Urban mining: Hibernating copper stocks in local power grids. *Journal of Cleaner Production*, 19(9-10):1052–1056.

Kuhn, A. (2010). Input-Output-Rechnung im Überblick. Statistisches Bundesamt, Wiesbaden.

Kytzia, S., Faist, M., and Baccini, P. (2004). Economically extended—MFA: A material flow approach for a better understanding of food production chain. *Journal of Cleaner Production*, 12(8-10):877–889.

Lalley, S. (2013). Brownian Motion. Stochastic Processes II. Statistics 313 lecture notes. University of Chicago.

Lansche, J., Lübs, H., Giegrich, J., and Liebich, A. (2007). Ermittlung und Bereitstellung von Koeffizienten zum Rohstoffeinsatz bei Importgütern.

Lee, K., Pesaran, M. H., and Pierse, R. G. (1990). Aggregation bias in labour demand equations for the UK economy. In Barker, T. and Pesaran, M. H., editors, *Disaggregation in econometric modelling*, pages 113–149. Routledge, London and New York.

Lehr, U., Lutz, C., and Edler, D. (2012). Green jobs? Economic impacts of renewable energy in Germany. *Energy Policy*, 47:358–364.

Lenzen, M. (2002). A guide for compiling inventories in hybrid life-cycle assessments: Some Australian results. *Journal of Cleaner Production*, 10(6):545–572.

Lenzen, M., Moran, D. D., Kanemoto, K., and Geschke, A. (2013). Building EORA: a global multi-region input-output database at high country and sector resolution. *Economic Systems Research*, 25(1):20–49.

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics*, 52(3):262.

Leontief, W. (1986). *Input-output economics*. Oxford University Press, New York and Oxford, 2nd ed. edition.

Leontief, W. W. (1936). Quantitative Input and Output Relations in the Economic Systems of the United States. *The Review of Economics and Statistics*, 18(3):105.

Leontief, W. W. (1987). Input-Output Analysis. In Eatwell, J., Milgate, M., and Newman, P., editors, *The New Palgrave. A dictionary of economics*, volume 2, pages 860–864. Macmillan and Stockton Press and Maruzen, London and New York and Tokyo.

Lindner, S. and Guan, D. (2014). A Hybrid-Unit Energy Input-Output Model to Evaluate Embodied Energy and Life Cycle Emissions for China's Economy. *Journal of Industrial Ecology*, 18(2):201–211.

Liu, C.-H., Lenzen, M., and Murray, J. (2012). A disaggregated emissions inventory for Taiwan with uses in hybrid input-output life cycle analysis (IO-LCA). *Natural Resources Forum*, 36(2):123–141.

Löschel, A. (2002). Technological change in economic models of environmental policy: a survey. *Ecological Economics*, 43(2-3):105–126.

Lossin, A. (2003). Copper. In Bohnet, M. and Ullmann, F., editors, *Ullmann's encyclopedia of industrial chemistry*, volume Vol 10, pages 1–66. Wiley-VCH, Weinheim.

Lutter, S., Giljum, S., and Bruckner, M. (2016a). A review and comparative assessment of existing approaches to calculate material footprints. *Ecological Economics*, 127:1–10.

Lutter, S., Giljum, S., Lieber, M., and Manstein, C. (2016b). The Use of Natural Resources: Report For Germany 2016. Technical report, Umweltbundesamt, Dessau-Roßlau.

Manhart, A. (2007). Key Social Impacts of Electronics Production and WEEE-Recycling in China. Technical report, Öko-Institut e.V.

Mansfield, E. (1961). Technical Change and the Rate of Imitation. *Econometrica*, 29(4):741–766.

Maung, K. N., Hashimoto, S., Mizukami, M., Morozumi, M., and Lwin, C. M. (2017). Assessment of the Secondary Copper Reserves of Nations. *Environmental Science & Technology*, 51(7):3824–3832.

Maxwell, D. and McAndrew, L. (2011). Addressing the Rebound Effect: Final Report to the European Commission DG ENV.

Meade, N. and Islam, T. (2006). Modelling and forecasting the diffusion of innovation – A 25-year review. *International Journal of Forecasting*, 22(3):519–545.

Meadows, D. H., Meadows, D. L., Randers, J., and Behrens, W. W. (1972). *The limits to growth: A report for the Club of Rome's Project on the Predicament of Mankind.* Universe Books, New York.

Mercure, J.-F., Knobloch, F., Pollitt, H., Lewney, R., Rademakers, K., Eichler, L., van der Laan, J., and Paroussos, L. (2016). Policy-induced energy technological innovation and finance for low-carbon economic growth. Deliverable D2. Study on the Macroeconomics of Energy and Climate Policies for the European Commission.

Meyer, B., Distelkamp, M., and Wolter, M. I. (2007). Material efficiency and economic-environmental sustainability. Results of simulations for Germany with the model PANTA RHEI. *Ecological Economics*, 63(1):192–200.

Meyer, B., Meyer, M., and Distelkamp, M. (2012). Modeling green growth and resource efficiency: new results. *Mineral Economics*, 24(2-3):145–154.

Miller, R. E. and Blair, P. D. (2009). *Input-output analysis: Foundations and extensions*. Cambridge University Press, Cambridge [England] and New York, 2nd ed. edition.

Mirasgedis, S., Tourkolias, C., Pavlakis, E., and Diakoulaki, D. (2014). A methodological framework for assessing the employment effects associated with energy efficiency interventions in buildings. *Energy and Buildings*, 82:275–286.

Mizobuchi, K. (2008). An empirical study on the rebound effect considering capital costs. *Energy Economics*, 30(5):2486–2516.

Modis, T. (2007). Strengths and weaknesses of S-curves. *Technological Forecasting and Social Change*, 74(6):866–872.

Müller, D. B. (2006). Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. *Ecological Economics*, 59(1):142–156.

Müller, E., Hilty, L. M., Widmer, R., Schluep, M., and Faulstich, M. (2014). Modeling metal stocks and flows: a review of dynamic material flow analysis methods. *Environmental Science & Technology*, 48(4):2102–2113.

Müller, F., Kosmol, J., Keßler, H., Angrick, M., and Rechenberg, B. (2016). Aller Dinge Maß: Materialflussindikatoren allein liefern keine hinreichende Orientierung für Strategien zur Ressourcenschonung. *ReSource*, 4.

Nakamura, S. and Nakajima, K. (2005). Waste Input-Output Material Flow Analysis of Metals in the Japanese Economy. *MATERIALS TRANSACTIONS*, 46(12):2550–2553.

Nathani, C. (2003). *Modellierung des Strukturwandels beim Übergang zu einer materialeffizienten Kreislaufwirtschaft: Kopplung eines Input-Output-Modells mit einem Stoffstrommodell am Beispiel der Wertschöpfungskette "Papier"*, volume 51 of *Technik, Wirtschaft und Politik*. Physica-Verl., Heidelberg.

Norgate, T. and Haque, N. (2010). Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production*, 18(3):266–274.

Nuss, P. and Eckelman, M. J. (2014). Life cycle assessment of metals: a scientific synthesis. *PloS one*, 9(7):e101298.

OECD (2005). Glossary of Statistical Terms - NACE / CLIO Definition.

OECD (2014). Long-term baseline projections, No. 95 (Edition 2014): OECD Economic Outlook: Statistics and Projections.

Olivier, J., Saadé-Sbeih, M., Shaked, S., Jolliet, A., and Crettaz, P. (2016). *Environmental life cycle assessment*. CRC Press, Boca Raton.

Onat, N. C., Kucukvar, M., and Tatari, O. (2014). Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input–output hybrid life cycle assessment approach. *Building and Environment*, 72:53–62.

Ostertag, K. (2003). *No-regret Potentials in Energy Conservation: An Analysis of Their Relevance, Size and Determinants*, volume 15 of *Technology, Innovation and Policy, Series of the Fraunhofer Institute for Systems and Innovation Research ISI*. Physica-Verlag, Heidelberg.

Ostertag, K. and Dreher, C. (2002). Cooperative procurement: Market transformation for energy-efficient products. In Clinch, P., Schlegelmilch, K., Sprenger, R.-U., and Triebswetter, U., editors, *Greening the budget*, pages 314–332. Edward Elgar, Cheltenham, Northampton.

Ostertag, K., Marscheider-Weidemann, F., Niederste-Holleberg, J., Paitz, P., Sartorius, C., Walz, R., Moller, B., Seitz, R., Woidasky, J., Stier, C., Albrecht, S., Brandstetter, C. P., Fröhling, M., Trippe, F., Müller, J., Mayer, W. A., and Faulstich, M. (2013). Ergebnisse der r2-Begleitforschung: Potenziale von Innovationen in rohstoffintensiven Produktionsprozessen. In Woidasky, J., Ostertag, K., and Stier, C., editors, *Innovative Technologien für Ressourceneffizienz in rohstoffintensiven Produktionsprozessen*, pages 356–390. Fraunhofer Verlag, Stuttgart.

Oswald, I. and Reller, A. (2011). E-Waste: A Story of Trashing, Trading, and Valuable Resources. *GAIA - Ecological Perspectives for Science and Society*, 20(1):41–47.

Palley, T. I. (1996). Old wine for new bottles: putting old growth theory back into the new. *Australian Economic Papers*, 35(67):250–262.

Palley, T. I. (2002). Keynesian macroeconomics and the theory of economic growth: putting aggregate demand back in the picture. In Setterfield, M., editor, *The economics of demand-led growth*, pages 19–40. Edward Elgar, Cheltenham, U.K, Northampton, Mass.

Pauliuk, S., Kondo, Y., Nakamura, S., and Nakajima, K. (2017). Regional distribution and losses of end-of-life steel throughout multiple product life cycles-Insights from the global multiregional MaTrace model. *Resources, conservation, and recycling*, 116:84–93.

Pauliuk, S., Wang, T., and Müller, D. B. (2013). Steel all over the world: Estimating in-use stocks of iron for 200 countries. *Resources, Conservation and Recycling*, 71:22–30.

Pauliuk, S., Wood, R., and Hertwich, E. (2015). Dynamic Models of Fixed Capital Stocks and Their Application in Industrial Ecology. *Journal of Industrial Ecology*, 19(1):104–116.

Peters, G., Andrew, R. M., and Lennox, J. (2011). Constructing an environmentally-extended multi-regional Input–Output table using the GTAP Database. *Economic Systems Research*, 23(2):131–152.

Peters, G. P., Weber, C. L., Guan, D., and Hubacek, K. (2007). China's Growing CO 2 Emissions – A Race between Increasing Consumption and Efficiency Gains. *Environmental Science & Technology*, 41(17):5939–5944.

Pfaff, M., Glöser-Chahoud, S., Chrubasik, L., and Walz, R. (2018). Resource efficiency in the German copper cycle: Analysis of stock and flow dynamics resulting from different efficiency measures. *Resources, Conservation and Recycling*, 139:205–218.

Pfaff, M. and Sartorius, C. (2015). Economy-wide rebound effects for non-energetic raw materials. *Ecological Economics*, 118:132–139.

Plank, B., Eisenmenger, N., Schaffartzik, A., and Wiedenhofer, D. (2018). International Trade Drives Global Resource Use: A Structural Decomposition Analysis of Raw Material Consumption from 1990-2010. *Environmental Science & Technology*, 52(7):4190–4198.

Pollitt, H. and Mercure, J.-F. (2017). The role of money and the financial sector in energy-economy models used for assessing climate and energy policy. *Climate Policy*, 4(1):1–14.

Pothen, F. (2017). A structural decomposition of global Raw Material Consumption. *Ecological Economics*, 141:154–165.

Pothen, F. and Schymura, M. (2015). Bigger cakes with fewer ingredients? A comparison of material use of the world economy. *Ecological Economics*, 109:109–121.

Radzicki, M. J. (2011). System Dynamics and Its Contribution to Economics and Economic Modeling. In Meyers, R. A., editor, *Complex systems in finance and econometrics*, pages 727–737. Springer Science + Business Media, New York.

Rankin, J. (2012). Energy Use in Metal Production. Technical report, High Temperature Processing Symposium, Australia.

Rivers, N. and Jaccard, M. (2006). Useful models for simulating policies to induce technological change. *Energy Policy*, 34(15):2038–2047.

Rodríguez-Alloza, A. M., Malik, A., Lenzen, M., and Gallego, J. (2015). Hybrid input–output life cycle assessment of warm mix asphalt mixtures. *Journal of Cleaner Production*, 90:171–182.

Rogers, E. M. (1962). *Diffusion of innovations*. Free Press, New York.

Romer, P. M. (1990). Endogenous Technological Change. *Journal of Political Economy*, 98(5):S71–102.

Rothengatter, W., Schade, W., Kuchenbecker, K., Schade, B., Martino, A., Roda, M., Maffi, S., Davies, S., Devereux, L., Williams, I., McWilliams, D., Bryant, P., Coutts, F., Greenaway, E., and Clark, J. (2000). Assessment of Transport Strategies. Final Report ST-97-SC.1049. Institut für Wirtschaftspolitik und Wirtschaftsforschung (IWW), Universität Karlsruhe, Germany, Transporti e Territorio Srl, Milano, Italy, Marcial Echenique & Partners Ltd, Cambridge, United Kingdom, Centre for Economics and Business Research Ltd, London, United Kingdom.

Rothengatter, W. and Schaffer, A. (2006). *Makro kompakt: Grundzüge der Makroökonomik; mit 13 Tabellen*. Physica-Lehrbuch. Physica-Verlag Heidelberg, Heidelberg.

Ruhrberg, M. (2006). Assessing the recycling efficiency of copper from end-of-life products in Western Europe. *Resources, Conservation and Recycling*, 48(2):141–165.

Saunders, H. D. (2000). A view from the macro side: rebound, backfire, and Khazzoom–Brookes. *Energy Policy*, 28(6–7):439–449.

Saunders, H. D. (2013a). Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts. *Technological Forecasting and Social Change*, 80(7):1317–1330.

Saunders, H. D. (2013b). Is what we think of as “rebound” really just income effects in disguise? *Energy Policy*, 57:308–317.

Saunders, H. D. (2014). Toward a neoclassical theory of sustainable consumption: Eight golden age propositions. *Ecological Economics*, 105:220–232.

Schade, B. (2005). *Volkswirtschaftliche Bewertung von Szenarien mit System Dynamics: Bewertung von nachhaltigen Verkehrsszenarien mit ESCOT (Economic assessment of Sustainability poliCies Of Transport)*. PhD Thesis, Universität Karlsruhe.

Schade, W. (2004). *Strategic Sustainability Analysis: Concept and Application for the Assessment of European Transport Policy*. NOMOS, Baden-Baden.

Schaffartzik, A., Eisenmenger, N., Krausmann, F., and Weisz, H. (2014a). Consumption-based Material Flow Accounting. *Journal of Industrial Ecology*, 18(1):102–112.

Schaffartzik, A., Mayer, A., Eisenmenger, N., and Krausmann, F. (2016). Global patterns of metal extractivism, 1950–2010: Providing the bones for the industrial society's skeleton. *Ecological Economics*, 122:101–110.

Schaffartzik, A., Mayer, A., Gingrich, S., Eisenmenger, N., Loy, C., and Krausmann, F. (2014b). The global metabolic transition: Regional patterns and trends of global material flows, 1950-2010. *Global Environmental Change*, 26:87–97.

Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., Krausmann, F., Gierlinger, S., Hosking, K., Lenzen, M., Tanikawa, H., Miatto, A., and Fishman, T. (2017). Global Material Flows and Resource Productivity: Forty Years of Evidence. *Journal of Industrial Ecology*, 46(1):61.

Schoer, K., Weinzettel, J., Kovanda, J., Giegrich, J., and Lauwigi, C. (2012). Raw material consumption of the European Union–concept, calculation method, and results. *Environmental Science & Technology*, 46(16):8903–8909.

Schoer, K., Wood, R., Arto, I., and Weinzettel, J. (2013). Estimating raw material equivalents on a macro-level: comparison of multi-regional input-output analysis and hybrid LCI-IO. *Environmental Science & Technology*, 47(24):14282–14289.

Schütz, H. and Bringezu, S. (2008). Ressourcenverbrauch von Deutschland – aktuelle Kennzahlen und Begriffsbestimmungen: Erstellung eines Glossars zum „Ressourcenbegriff“ und Berechnung von fehlenden Kennzahlen des Ressourcenverbrauchs für die weitere politische Analyse. Technical report, Umweltbundesamt, Dessau-Roßlau.

Scott, M. F. (1989). *A new view of economic growth.* Clarendon Press and Oxford University Press, Oxford [England] and New York.

Seetzen, J. (1979). Die Abbildung von technischen Veränderungen in Produktionsfunktionen und Input-Output-Modellen. In Seetzen, J., Krengel, R., and von Kortzfleisch, G., editors, *Makroökonomische Input-Output-Analysen und dynamische Modelle zur Erfassung technischer Entwicklungen*, Interdisziplinäre Systemforschung, pages 1–26. Birkhäuser, Basel.

Sievers, L. (2019). *Regionale Verteilungswirkung der Energiewende.* PhD Thesis. Forthcoming., Universität der Bundeswehr, München.

Sievers, L., Breitschopf, B., Pfaff, M., and Schaffer, A. (2019). Macroeconomic impact of the German energy transition and its distribution by sectors and regions. *Ecological Economics*, 160:191–204.

Solow, R. M. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics*, 70(1):65–94.

Solow, R. M. (1957). Technical Change and the Aggregate Production Function. *The Review of Economics and Statistics*, 39(3):312–320.

Sommer, M. (1981). *System Dynamics und Makroökonometrie: Dynamische makroökonomische Modellierung in multimethodologischer Sicht*. Haupt, Bern and Stuttgart.

Sommer, M. (1984). On the applicability of econometric methods to system dynamics models. *Dynamica*, 10(2).

Sorrell, S. (2009). Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. *Energy Policy*, 37(4):1456–1469.

Sorrell, S. and Dimitropoulos, J. (2008). The rebound effect: Microeconomic definitions, limitations and extensions. *Ecological Economics*, 65(3):636–649.

Soulier, M., Glöser-Chahoud, S., Goldmann, D., and Tercero Espinoza, L. A. (2018a). Dynamic analysis of European copper flows. *Resources, Conservation and Recycling*, 129:143–152.

Soulier, M., Pfaff, M., Goldmann, D., Walz, R., Geng, Y., Zhang, L., and Tercero Espinoza, L. A. (2018b). The Chinese copper cycle: Tracing copper through the economy with dynamic substance flow and input-output analysis. *Journal of Cleaner Production*, 195:435–447.

Spatari, S., Bertram, M., Gordon, R. B., Henderson, K., and Graedel, T. E. (2005). Twentieth century copper stocks and flows in North America: A dynamic analysis. *Ecological Economics*, 54(1):37–51.

Sprecher, B., Daigo, I., Murakami, S., Kleijn, R., Vos, M., and Kramer, G. J. (2015). Framework for resilience in material supply chains, with a case study from the 2010 Rare Earth Crisis. *Environmental Science & Technology*, 49(11):6740–6750.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., de Koning, A., and Tukker, A. (2018). EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology*, 45(3):539.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., and Ludwig, C. (2015). The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review*, 2(1):81–98.

Steffen, W., Crutzen, P. J., and McNeill, J. R. (2007). The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature. *AMBIO: A Journal of the Human Environment*, 36(8):614–621.

Steffen, W., Jäger, J., Matson, P., Moore, B., Oldfield, F., Richardson, K., Sanderson, A., Schellnhuber, H. J., Turner, B. L., Tyson, P., and Wasson, R. J. (2005). *Global Change and the Earth System: A Planet Under Pressure.* Global Change — The IGBP Series. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg.

Stengel, J. (2014). *Akteursbasierte Simulation der energetischen Modernisierung des Wohngebäudebestands in Deutschland.* Doctoral thesis, Karlsruhe Institute of Technology, Karlsruhe.

Sterman, J. D. (1986). The economic long wave: Theory and evidence. *System Dynamics Review*, 2(2):87–125.

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world.* Irwin/McGraw-Hill, Boston.

Stone, R. and Brown, A. (1962). *A computable model of economic growth, Part 1.* Chapman and Hall, London.

Su, B. and Ang, B. W. (2013). Input–output analysis of CO2 emissions embodied in trade: Competitive versus non-competitive imports. *Energy Policy*, 56:83–87.

Suckling, J. and Lee, J. (2015). Redefining scope: The true environmental impact of smartphones? *The International Journal of Life Cycle Assessment*, 20(8):1181–1196.

Suh, S. (2004). Functions, commodities and environmental impacts in an ecological–economic model. *Ecological Economics*, 48(4):451–467.

Suh, S. (2006). *Handbook on Input-Output Economics in Industrial Ecology*, volume Vol. 23 of *Eco-Efficiency in Industry and Science.* Springer, Berlin, 1 edition.

Suh, S. and Kagawa, S. (2005). Industrial ecology and input-output economics: An introduction. *Economic Systems Research*, 17(4):349–364.

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., and Norris, G. (2004). System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environmental Science & Technology*, 38(3):657–664.

System Dynamics Society (2017). Introduction to System Dynamics: http://www.systemdynamics.org/what-is-s/.

Takase, K., Kondo, Y., and Washizu, A. (2005). An Analysis of Sustainable Consumption by the Waste Input-Output Model. *Journal of Industrial Ecology*, 9(1-2):201–219.

ten Raa, T. and Rueda-Cantuche, J. M. (2007). A Generalized Expression for the Commodity and the Industry Technology Models in Input–Output Analysis. *Economic Systems Research*, 19(1):99–104.

Tercero Espinoza, L. A. and Soulier, M. (2016). An examination of copper contained in international trade flows. *Mineral Economics*, 29(2-3):47–56.

Thomas, B. A. and Azevedo, I. L. (2013a). Estimating direct and indirect rebound effects for U.S. households with input–output analysis Part 1: Theoretical framework. *Ecological Economics*, 86:199–210.

Thomas, B. A. and Azevedo, I. L. (2013b). Estimating direct and indirect rebound effects for U.S. households with input–output analysis. Part 2: Simulation. *Ecological Economics*, 86:188–198.

Train, K. E. (2009). *Discrete Choice Methods with Simulation*. Cambridge University Press, New York.

Treloar, G. J., Love, P. E. D., Faniran, O. O., and Iyer-Raniga, U. (2000). A hybrid life cycle assessment method for construction. *Construction Management and Economics*, 18(1):5–9.

Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J., Rueda-Cantuche, J. M., Bouwmeester, M. C., Oosterhaven, J., Drosdowski, T., and Kuenen, J. (2013a). EXIOPOL – Development and illustrative analyses of a detailed global MR EE SUT/IOT. *Economic Systems Research*, 25(1):50–70.

Tukker, A., de Koning, A., Wood, R., Moll, S., and Bouwmeester, M. C. (2013b). Price corrected domestic technology assumption – a method to assess pollution embodied in trade using primary official statistics only. With a case on CO2 emissions embodied in imports to Europe. *Environmental Science & Technology*, 47(4):1775–1783.

Tukker, A., Huppes, G., Guinée, J. B., Heijungs, R., de Koning, A., von Oers, L., Suh, S., Geerken, T., van Holderbeke, M., Jansen, B., and Nielsen, P. (2006a). Environmental Impacts of Products (EIPRO): Analysis of the life cycle environmental impacts related to the final consumption of the EU-25. Technical Report EUR 22284 EN, European Commission, Joint Research Centre, Institute for Prospective Technological Studies and European Science and Technology Observatory.

Tukker, A., Huppes, G., van Oers, L., and Heijungs, R. (2006b). Environmentally extended input-output tables and models for Europe. Technical Report EUR 22194 EN, European Commission, Joint Research Centre, Institute for Prospective Technological Studies.

Tukker, A. and Jansen, B. (2006). Environmental Impacts of Products: A Detailed Review of Studies. *Journal of Industrial Ecology*, 10(3):159–182.

Tukker, A., Poliakov, E., Heijungs, R., Hawkins, T., Neuwahl, F., Rueda-Cantuche, J. M., Giljum, S., Moll, S., Oosterhaven, J., and Bouwmeester, M. C. (2009). Towards a global multi-regional environmentally extended input–output database. *Ecological Economics*, 68(7):1928–1937.

Turner, K. (2009). Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. *Energy Economics*, 31(5):648–666.

UKERC (2007). Review of Evidence for the Rebound Effect.

UN International Resource Panel (2017). Global Material Flows Database.

United Nations (2014). *System of environmental-economic accounting 2012: Central framework*. United Nations, New York, NY.

United Nations (2015). Resolution 70/1 of the United Nations General Assembly: Transforming our world: the 2030 Agenda for Sustainable Development.

United Nations (2017). UN Commodity Trade Statistics Database (UN Comtrade). https://comtrade.un.org/.

van den Bergh, J. C. J. M. (2011). Energy Conservation More Effective With Rebound Policy. *Environmental and Resource Economics*, 48(1):43–58.

van der Voet, E. (1996). *Substances from cradle to grave : development of a methodology for the analysis of substances flows through the economy and the environment of a region: with case studies on cadmium and nitrogen compounds*. PhD Thesis, Leiden University, Leiden, Netherlands.

van der Voet, E. (2002). Substance flow analysis methodology. In Ayres, R. U. and Ayres, L., editors, *A handbook of industrial ecology*, pages 91–101. Edward Elgar Pub, Cheltenham, UK and Northampton, MA.

van der Voet, E., Oers, L., and Nikolic, I. (2004). Dematerialization: Not Just a Matter of Weight. *Journal of Industrial Ecology*, 8(4):121–137.

van der Voet, E., van Oers, L., Verboon, M., and Kuipers, K. (2018). Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. *Journal of Industrial Ecology*, 13(5):718.

Varian, H. R. (2006). *Intermediate microeconomics: A modern approach*. W. W. Norton & Company, New York and London, 7. ed. edition.

Victor, P. A. and Rosenbluth, G. (2007). Managing without growth. *Ecological Economics*, 61(2-3):492–504.

Walz, R. (2011). Employment and structural impacts of material efficiency strategies: results from five case studies. *Journal of Cleaner Production*, 19(8):805–815.

Walz, R. and Schleich, J. (2009). *The economics of climate change policies: Macroeconomic effects, structural adjustments and technological change*. Sustainability and innovation. Physica-Verlag, Heidelberg.

Watanabe, M. D. B., Chagas, M. F., Cavalett, O., Guilhoto, J. J. M., Griffin, W. M., Cunha, M. P., and Bonomi, A. (2016). Hybrid Input-Output Life Cycle Assessment of First- and Second-Generation Ethanol Production Technologies in Brazil. *Journal of Industrial Ecology*, 20(4):764–774.

Wei, M., Patadia, S., and Kammen, D. M. (2010). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, 38(2):919–931.

Weinzettel, J. and Kovanda, J. (2011). Structural Decomposition Analysis of Raw Material Consumption: The Case of the Czech Republic. *Journal of Industrial Ecology*, 15(6):893–907.

Weisz, H. and Duchin, F. (2006). Physical and monetary input–output analysis: What makes the difference? *Ecological Economics*, 57(3):534–541.

Wheat, D. (2016). Endogenous Money. In *Proceedings of the 34th International Conference of the System Dynamics Society, Delft, The Netherlands*.

Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., and Krausmann, F. (2019). Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting: Concepts, Modelling, and Global Application for 1900–2050. *Ecological Economics*, 156:121–133.

Wiedmann, T., Suh, S., Feng, K., Lenzen, M., Acquaye, A. A., Scott, K., and Barrett, J. R. (2011). Application of Hybrid Life Cycle Approaches to Emerging Energy Technologies – The Case of Wind Power in the UK. *Environmental Science & Technology*, 45(13):5900–5907.

Wieser, H., Tröger, N., and Hübner, R. (2015). *Die Nutzungsdauer und Obsoleszenz von Gebrauchtsgütern im Zeitalter der Beschleunigung: Eine empirische Untersuchung in österreichischen Haushalten*. AK Wien, Wien.

Wilson, D. and Swisher, J. (1993). Exploring the gap: top-down versus bottom-up analyses of the cost of mitigating global warming. *Energy Policy*, 21(3):249–263.

Wilson, G. T., Smalley, G., Suckling, J. R., Lilley, D., Lee, J., and Mawle, R. (2017). The hibernating mobile phone: Dead storage as a barrier to efficient electronic waste recovery. *Waste management (New York, N.Y.)*, 60:521–533.

WirtschaftsVereinigung Metalle (1998-2015). Metallstatistik 1998 - 2015.

Wittmer, D. (2006). *Kupfer im regionalen Ressourcenhaushalt: Ein methodischer Beitrag zur Exploration urbaner Lagerstätten*. Doctoral Thesis Nr. 16325, Eidgenössische Technische Hochschule ETH, Zürich.

Wittmer, D. and Lichtensteiger, T. (2007). Exploration of urban deposits: Long-term prospects for resource and waste management. *Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA*, 25(3):220–226.

Woidasky, J., Ostertag, K., and Stier, C., editors (2013). *Innovative Technologien für Ressourceneffizienz in rohstoffintensiven Produktionsprozessen: Ergebnisse der Fördermaßnahme* r^2. Fraunhofer Verlag, Stuttgart.

Wood, R., Hawkins, T. R., Hertwich, E. G., and Tukker, A. (2014). Harmonising National Input-Output Tables for Consumption-Based Accounting – Experiences from EXIOPOL. *Economic Systems Research*, 26(4):387–409.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J., Merciai, S., and Tukker, A. (2015). Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. *Sustainability*, 7(1):138–163.

World Bank (2017). Commodities Price Data (The Pink Sheet).

Yamaguchi, K. (2014). *Money and Macroeconomic Dynamics: Accounting System Dynamics Approach*. Japan Futures Research Center, Awaji Island, Japan, 1.1 edition.

Yamaguchi, K. and Yamaguchi, Y. (2016). The Heads and Tails of Money Creation and its System Design Failures – Toward the Alternative System Design. In *Proceedings of the 34th International Conference of the System Dynamics Society, Delft, The Netherlands*.

Ziemann, S. and Schebek, L. (2010). Substitution knapper Metalle - ein Ausweg aus der Rohstoffknappheit? *Chemie Ingenieur Technik*, 82(11):1965–1975.

A Appendix

A.1 Additional information on System Dynamics

This section provides some additional information about System Dynamics as a modeling methodology. SD distinguishes between two main types of variables – stocks (or levels) and flows – as well as auxiliary variables, which can fulfill a number of functions, such as suppliers of exogenous data, or constants. Stocks are determined by their in- and outflows, the rate of change of the stock being the difference between in- and outflow (cf. Forrester, 1961; Sommer, 1981; Sterman, 2000). The representation of variables in System Dynamics is also derived from feedback control theory. Similar to process flow charts, flow variables are represented by arrows which are normally accompanied by valve and cloud-like symbols. The cloud-like symbols represent sources and sinks of the flows, which are generally considered to lie outside the purview of the model. Inside the model are the decision functions (or rate equations) which determine the rate of flows; they are represented by valve symbols. Stock variables are represented by boxes and auxiliary variables were originally conceived as circles (Forrester, 1961, pp.81). However, the simulation software Vensim®, which is used in this thesis, does not use any dedicated symbol for them. Functional relationships between variables are indicated through arrows (see Figure A.1). As a simple illustration of the interaction between stocks and flows, the example of a bathtub is often used, where the water fill level represents the stock, which depends on an inflow from the tap and an outflow through the drain (Sterman, 2000).

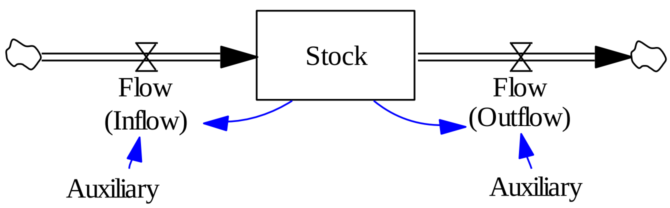
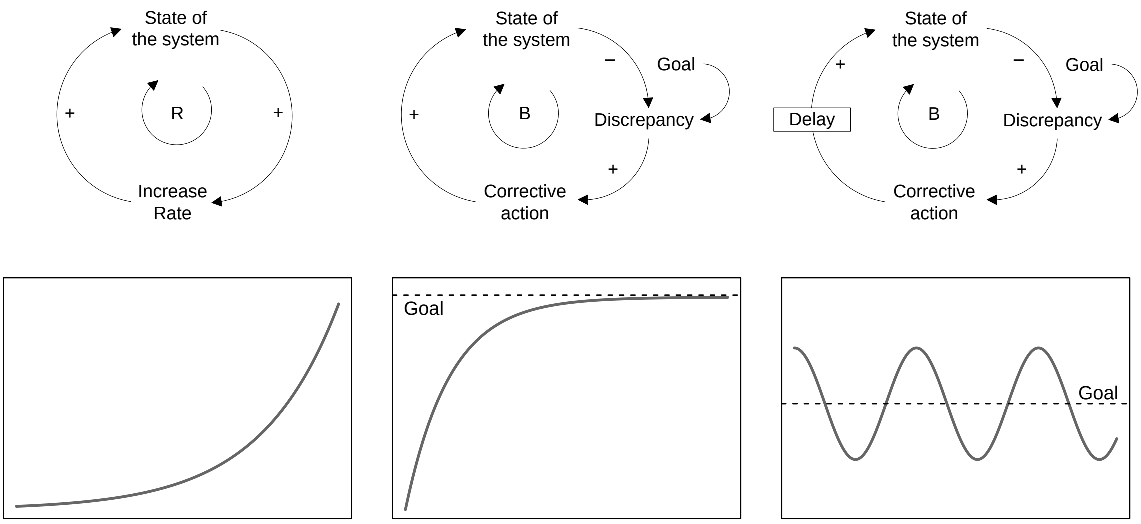


Figure A.1: Illustration of stock and flow variables in SD

Complex dynamics of systems emerge through feedback loops and time delays. As Sterman (2000, p.12) notes, “the most complex behaviors usually arise from the interactions (feedbacks) among the components of the system, not from the complexity of the components themselves.” Feedback loops occur if the rate of change of a stock depends on the stock itself. Two broad types of feedback loops can be distinguished: positive (reinforcing) and negative (balancing) loops. Positive feedback loops self-reinforce and therefore lead to growth or contractionary processes (see Figure A.2a). In contrast, negative feedback loops are self-correcting and therefore generally lead to goal-seeking behavior. In this case, the current state of the system is compared to a predetermined goal and depending on the discrepancy between the two, corrective action is taken, which brings the system closer to the goal (Figure A.2b). In the presence of time delays, for instance due to a delayed reaction of the system to the corrective action, the goal-seeking behavior of the system can result in oscillatory behavior. In this case, the delay causes the corrective action to exceed the goal, which then causes corrective action in the other direction and so on, leading to an oscillation around the goal (Figure A.2c). These are the three archetypes of dynamic behavior (Sterman, 2000, pp.114; see also Rothengatter and Schaffer, 2006, pp.169).



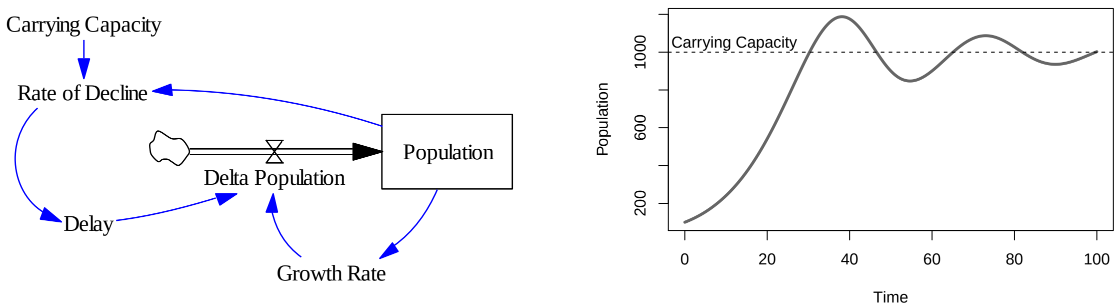
(a) Positive feedback: exponential growth

(b) Negative feedback: goal seeking

(c) Negative feedback with delay: oscillation

Figure A.2: Fundamental types of dynamic behavior, own illustration based on Sterman (2000, pp.108)

Other types of (more complex) dynamics can arise in systems in which combinations of positive and negative feedback loops and time delays are present. For instance, growth processes do not have to be exponential, but can also follow other trajectories, e.g. s-shapes, or reach a tipping point after which they turn into decline ("overshoot and collapse"). The emergence of complex dynamics out of multiple feedback loops can be illustrated with the help of another example. Figure A.3a shows a simple population model. In it, the population growth rate is assumed to positively depend on the size of the population, since the chances of reproduction rise with the size of the population. However, at the same time, the population growth rate also negatively depends on the population size because the environment in which it lives possesses only a certain carrying capacity. This effect, however, only occurs with a time delay. The interaction of positive population growth and delayed population decay then leads to oscillatory behavior, which eventually contracts around the long run equilibrium at the carrying capacity (Figure A.3b). In this sense, the interaction of positive and negative feedback loops can also be conceived of as a fight for control over a system's behavior (Radzicki, 2011).



(a) Simple population model with delayed adaptation mechanism, implemented in the simulation software Vensim®

(b) Growth trajectory turning into oscillation around carrying capacity with declining amplitude

Figure A.3: Illustration of simple population model

Systems of interdependent stocks and flows can be expressed through a set of first-order ordinary differential equations, since the flows are the rates of change of the stocks, i.e. their first derivatives. The rate of change of the stock S can thus be calculated in the following way:

$$\frac{dS}{dt} = I_t - O_t \tag{A.1}$$

where I_t and O_t are the inflows and outflows, respectively, at time t. The absolute value of the stock S_t at the current time t can then be calculated by adding the cumulative change of the stock in the time period between time t and initial time t_0 to the initial stock S_{t_0}:

$$S_t = S_{t_0} + \int_{t_0}^{t} [I_s - O_s]\, ds \tag{A.2}$$

where I_s and O_s represent the inflows and outflows at any time s between the initial and the current time.

With increasing complexity, especially in the presence of time delays, systems of differential equations become difficult or impossible to solve analytically. Therefore, System Dynamics modeling tools use numerical solution procedures, in which the continuous differential equations are transformed into discrete difference equations. One of the simplest and most commonly used numerical integration procedures is the explicit Euler method. The Euler method, which is also referred to as the Euler approximation, uses lower sums for each discrete time step to calculate stock changes and thereby approximates continuous integrals. The stock at the current time is thus the sum of the stock in the last period and the difference between inflow and outflow rates of the last period multiplied by the time interval between the periods dt:

$$S_t = S_{t-dt} + (I_{t-dt} - O_{t-dt})dt \tag{A.3}$$

The above equation only holds if the rates are assumed to remain constant in the given time interval, which is a reasonable assumption “if the dynamics of the system are slow enough and dt is small enough” (Sterman, 2000, p.904). From Equation A.3 it can be seen that with a decreasing time step size, the Euler approximation of the rate of change of the stock reduces to the differential equation A.1:

$$\lim_{dt \to 0} = \frac{S_t - S_{t-dt}}{dt} = \frac{dS}{dt} = I_t - O_t \tag{A.4}$$

While Sterman (2000) states that the Euler approximation is an adequate choice for most systems of differential equations that describe social and human systems, which may already be characterized by large errors in model parameters, initial conditions, historical data and even the model structure, other types of numerical integration procedures have been developed. The simulation software Vensim®, for instance, also offers different versions of the Runge-Kutta procedure, which is based on a division of the integration interval into smaller time steps. The size of the time steps can either be predetermined and kept constant, or set by an algorithm within the integration procedure that continuously reduces the step size and checks for improvements of the results. Once the results of the integration over a smaller time step do not diverge more than a predefined tolerance level from the previous results over a larger time step, the algorithm settles on the last step size.[1]

[1] See the the Vensim software documentation: https://www.vensim.com/documentation/index.html.

A.2 Additional information on the copper flow model

This section provides some additional information about the copper flow model. A more detailed overview of the model is given by Figure A.4, which is an enhanced version of Figure 4.1 in the main text, including the different semi-finished and end-use product categories, which are also summarized in Table A.1.

A key aspect of the copper flow model is the portrayal of different lifetimes for different end-use product categories. These lifetimes are modeled through lifetime distributions of the following form (Glöser et al., 2013):

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2}$$

where μ represents the average lifetime of the respective product, σ the standard deviation of the lifetime distribution and t the time step. The likelihood of failure $F(t)$, and in turn the likelihood of survival $R(t)$ can then be calculated from the density function:

$$F(t) = \int_0^t f(t)\,\mathrm{d}t; \quad R(t) = 1 - F(t)$$

From these, the failure rate $h(t)$ and the survival rate $s(t)$ can be calculated:

$$h(t) = \frac{f(t)}{R(t)}; \quad s(t) = 1 - h(t)$$

The failure rate is used to calculate the fraction of products in each vintage which reach the end of their lifetimes and do not move on to the next vintage. These variables are used to construct the aging chains depicted in Figure 4.2 in the main text.

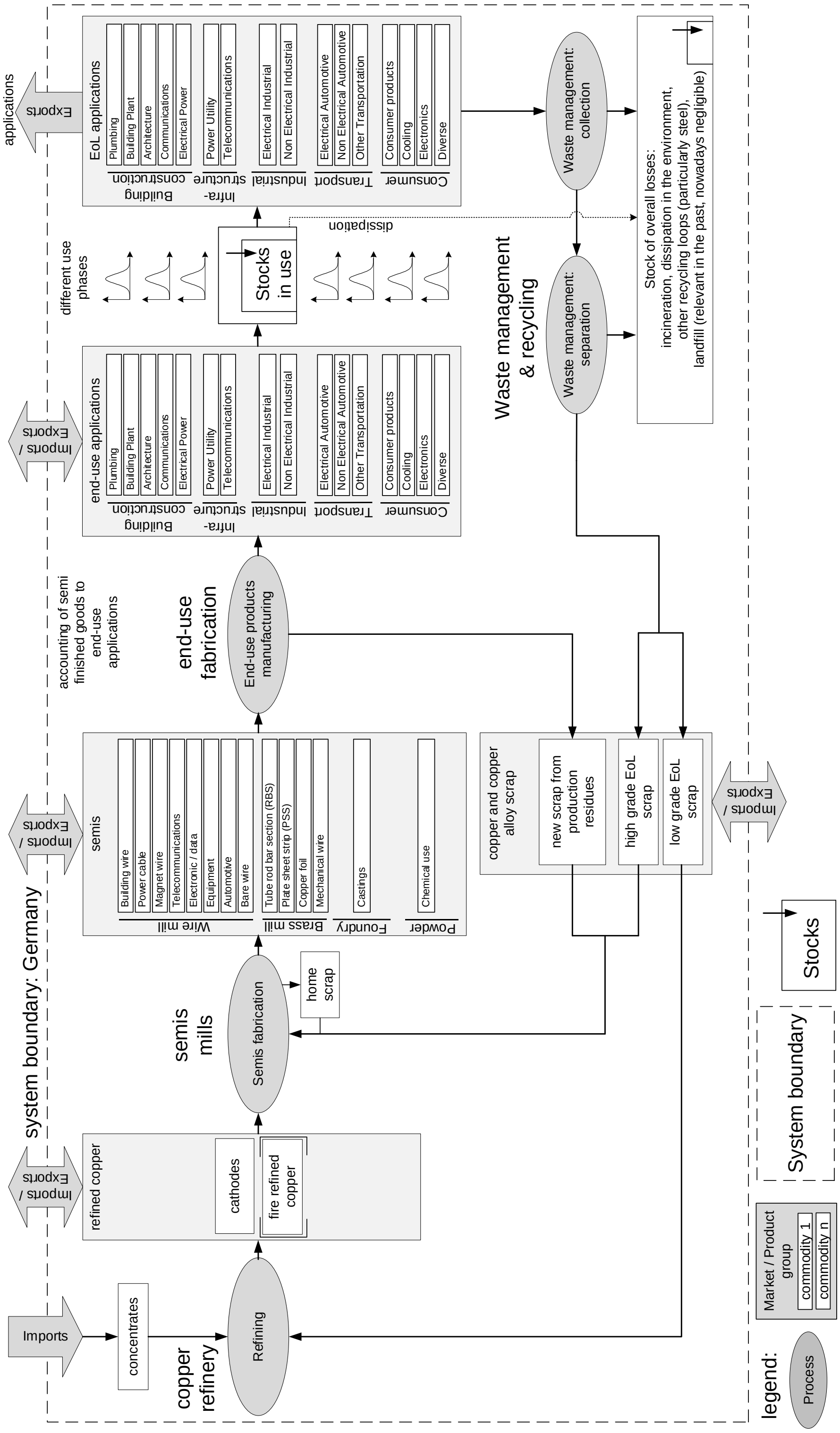


Figure A.4: Structure of the copper substance flow model for Germany

Table A.1: Assumptions regarding lifetime distributions and technical recovery efficiencies during recycling (see for example Spatari et al., 2005; Ruhrberg, 2006; Maung et al., 2017). As the effect of distribution shape on overall results is negligible (cf. Glöser et al., 2013), Gaussian distributions for all applications were used in the model. Fabrication efficiency refers to the occurrence of new scrap during end use fabrication, the separation rate describes the technical efficiency of copper scrap recovery from EoL applications.

Field of use	End-use sector	Average lifetime in years μ	Standard deviation σ	Fabrication efficiency	Separation efficiency
Building &Construction	Plumbing	40	8	0.95	0.9
	Building Plant	40	8	0.90	0.9
	Architecture	50	10	0.85	0.9
	Communications	30	6	0.90	0.9
	Electrical Power	40	8	0.90	0.9
Infrastructure	Telecommunications	30	6	0.90	0.8
	Power Utility	30	6	0.85	0.8
Industrial	Electrical Industrial	15	3	0.80	0.7
	Non Elec. Industrial	20	4	0.90	0.75
Transport	Electrical Automotive	12	2	0.75	0.6
	Non Elec. Automotive	15	3	0.90	0.6
	Other Transport	25	5	0.80	0.7
Consumer & Electronics	Consumer	8	1.5	0.75	0.6
	Cooling	10	2	0.80	0.6
	Electronic	8	1.5	0.75	0.6
	Diverse	15	3	0.75	0.6

A.3 Additional information on the model interface

As outlined in Section 4.3.2 in the main text, some manual adaptations were necessary for the matching of the product categories used in the copper flow model with the sector classification of the macroeconomic model (see Figure 4.11). Without these adaptations, the distribution of copper semis, end-use production and final goods would like like in Figure A.5.

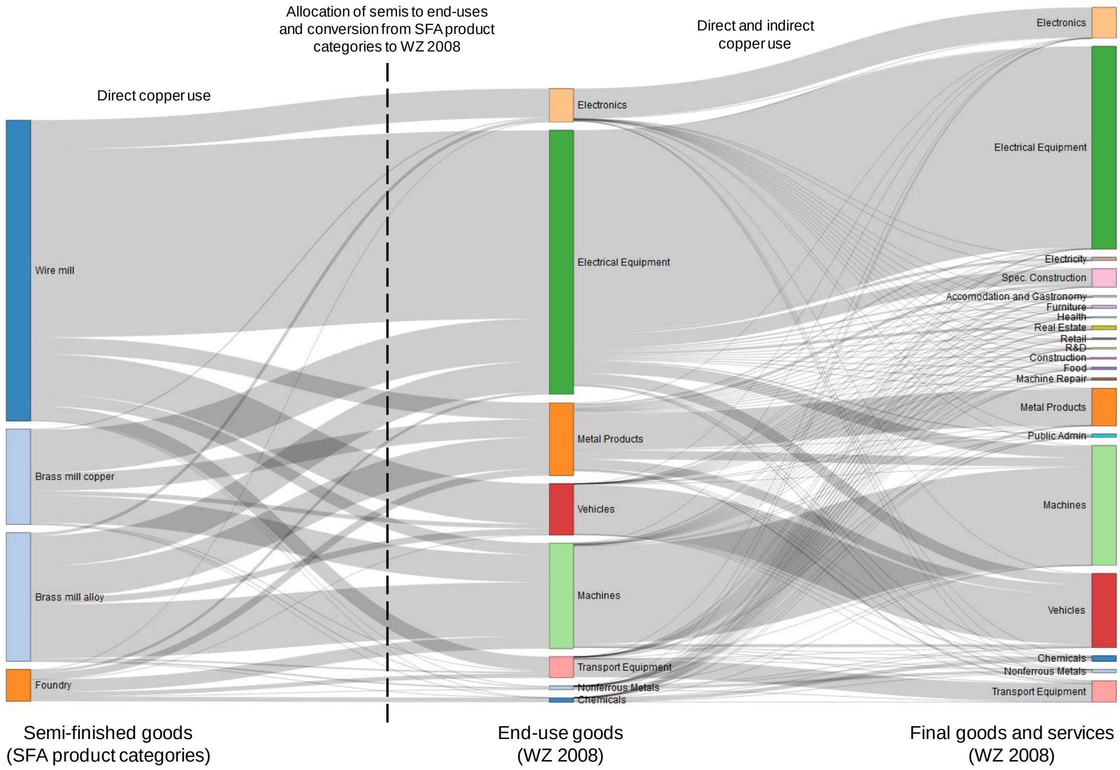


Figure A.5: Alternative distribution of copper in semis, end-use production and provision of final goods and services in Germany in 2012; sectors with either total in- our outflows below 2 kt are excluded for better visibility

In order to illustrate the difference of direct copper use per the allocation described in Section 4.3.2 in the main text and total (including indirect through the supply chain) copper use resulting from an IO calculation, Figure A.6 plots both sectoral copper uses next to each other. It thus reproduces the middle and the right part of Figure 4.16 in the main text in a more concise form and includes indirect copper use of all sectors (including the ones with copper use below 2 kt).

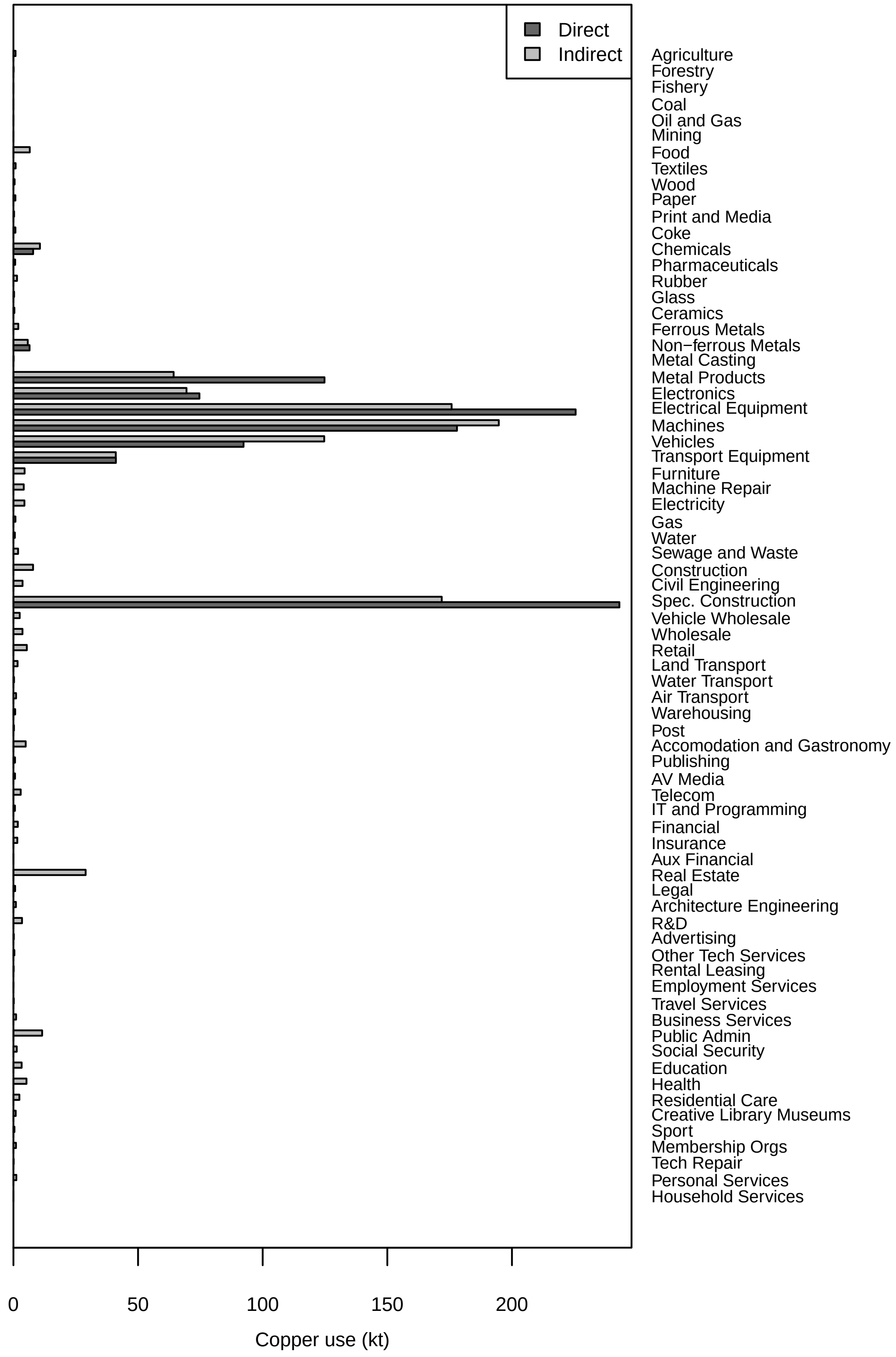


Figure A.6: Direct and indirect total domestic copper use per sector in 2012

A.4 Copper flow tables

Table A.2: Total copper flows from semi-finished product sectors to finished product sectors for the years 2006 to 2014, in kt

Sector	20	24.4	25	26	27	28	29	30	43	Total
2006										
24.4	0	7.52	125.65	25.57	241.29	208.86	99.29	7.42	296.84	**1012.43**
25	0	1.02	24.42	1.99	5.97	8.75	0	20.34	0	**62.50**
27	0	0.14	6.22	46.31	45.74	7.29	2.31	3.93	4.12	**116.07**
Total	**0**	**8.68**	**156.28**	**73.87**	**293.00**	**224.90**	**101.60**	**31.70**	**300.96**	**1191.00**
2007										
24.4	6.96	5.01	109.56	26.35	214.52	201.84	109.21	23.13	302.17	**998.75**
25	0	0.61	15.35	1.07	3.10	24.74	0	7.95	3.16	**55.99**
27	0	0.30	10.17	41.20	44.24	7.32	0	4.14	5.90	**113.27**
Total	**6.96**	**5.92**	**135.08**	**68.62**	**261.85**	**233.90**	**109.21**	**35.22**	**311.23**	**1168.00**
2008										
24.4	6.54	4.37	96.17	23.44	211.67	182.57	99.00	30.15	250.47	**904.38**
25	0	0.58	14.01	0.84	0.80	18.86	0	8.34	8.44	**51.87**
27	0	0.27	9.27	36.66	41.82	7.46	0	4.78	4.49	**104.75**
Total	**6.54**	**5.22**	**119.46**	**60.93**	**254.29**	**208.89**	**99.00**	**43.27**	**263.39**	**1061.00**
2009										
24.4	5.54	3.91	81.67	14.67	147.44	117.96	64.79	17.77	197.58	**651.32**
25	0	0.53	13.19	0.91	2.84	16.76	0	8.12	2.10	**44.45**
27	0	0.27	8.39	30.37	34.30	6.56	0	4.64	3.70	**88.23**
Total	**5.54**	**4.71**	**103.24**	**45.95**	**184.58**	**141.28**	**64.79**	**30.53**	**203.38**	**784.00**
2010										
24.4	6.95	5.45	92.18	18.29	177.99	154.65	84.57	21.19	216.77	**778.03**
25	0	0.70	13.54	0.67	2.51	18.50	0	7.15	2.08	**45.15**
27	0	0.44	11.27	36.12	44.67	8.12	0	6.44	4.77	**111.81**
Total	**6.95**	**6.59**	**116.99**	**55.08**	**225.17**	**181.27**	**84.57**	**34.77**	**223.62**	**935.00**
2011										
24.4	7.33	4.73	104.55	18.55	173.15	159.56	89.46	21.61	220.87	**799.82**
25	0	0.59	14.60	0.95	2.49	20.05	0	6.84	1.91	**47.43**
27	0	0.35	12.48	38.03	47.11	9.43	0	6.40	4.96	**118.76**
Total	**7.33**	**5.67**	**131.63**	**57.52**	**222.74**	**189.04**	**89.46**	**34.86**	**227.74**	**966.00**
2012										
24.4	7.59	5.08	94.10	16.62	169.26	147.54	85.32	21.16	213.98	**760.65**
25	0	0.71	14.99	0.74	2.43	20.81	0	7.30	1.98	**48.96**
27	0	0.41	12.47	38.83	48.19	7.92	0	6.58	4.99	**119.39**
Total	**7.59**	**6.21**	**121.56**	**56.19**	**219.87**	**176.27**	**85.32**	**35.03**	**220.95**	**929.00**
2013										
24.4	7.38	5.65	91.49	16.54	163.03	142.20	84.38	21.13	208.88	**740.69**
25	0	0.78	14.46	0.64	2.34	20.25	0	7.19	1.92	**47.58**
27	0	0.46	11.88	37.78	47.99	8.11	0	6.58	4.92	**117.73**
Total	**7.38**	**6.89**	**117.84**	**54.96**	**213.36**	**170.56**	**84.38**	**34.90**	**215.73**	**906.00**
2014										
24.4	7.28	5.10	91.03	16.40	164.10	141.57	84.56	20.93	209.90	**740.87**
25	0	0.69	14.42	0.77	2.23	20.08	0	6.94	1.90	**47.02**
27	0	0.41	11.87	38.03	47.98	8.41	0	6.46	4.94	**118.10**
Total	**7.28**	**6.21**	**117.32**	**55.20**	**214.30**	**170.06**	**84.56**	**34.33**	**216.74**	**906.00**

A.5 List of copper containing products

Table A.3: Copper containing products identified by Fraunhofer Institute for Systems and Innovation Research (ISI) based on an analysis by Wittmer (2006), and corresponding HS- and CPA-codes and estimated copper contents

HS92	CPA08	Short description	Est. Cu content
260300	072911	Copper ores and concentrates	30.0%
262030	381158	Ash or residues containing mainly copper	100.0%
282550	201212	Copper oxides and hydroxides	69.0%
282741	201331	Chloride oxides and chloride hydroxides of copper	60.0%
283325	201341	Copper sulphates	25.0%
310310	201541	Superphosphates, in packs >10 kg	0.0035%
310320	201549	Basic slag, in packs >10 kg	0.0035%
310390	201549	Phosphatic fertilizers, mixes, nes, pack >10kg	0.0035%
310410	201559	Carnallite, sylvite, crude potassium salts nes, >10kg	0.0004%
310420	201551	Potassium chloride, in packs >10 kg	0.0004%
310430	201552	Potassium sulphate, in packs >10 kg	0.0004%
310490	201559	Potassic fertilizers, mixes, nes, pack >10 kg	0.0004%
310510	201579	Fertilizer mixes in tablets etc or in packs <10 kg	0.0011%
310520	201571	Nitrogen-phosphorus-potassium fertilizers, pack >10kg	0.0011%
310530	201572	Diammonium phosphate, in packs >10 kg	0.0011%
310540	201573	Monoammonium phosphate & mix with diammonium, ≤10 kg	0.0011%
310551	201574	Fertilizers with nitrates and phosphates, nes, ≤10kg	0.0011%
310559	201574	Fertilizers with nitrogen and phosphorus nes, ≤10kg	0.0011%
310560	201575	Fertilizers containing phosphorus & potassium, ≤10kg	0.0011%
380810	202019	Insecticides, packaged for retail sale	1.0%
380820	202019	Fungicides, packaged for retail sale	1.0%
380830	202019	Herbicides, sprouting and growth regulators	1.0%
740110	244411	Copper mattes	60.0%
740120	244411	Cement copper (precipitated copper)	75.0%
740200	244412	Unrefined copper, copper anodes, electrolytic refining	95.0%
740311	244413	Copper cathodes and sections of cathodes unwrought	100.0%
740312	244413	Wire bars, copper, unwrought	100.0%
740313	244413	Billets, copper, unwrought	100.0%
740319	244413	Refined copper products, unwrought, nes	100.0%
740321	244413	Copper-zinc base alloys, unwrought	58.0%
740322	244413	Copper-tin base alloys, unwrought	85.0%
740323	244413	Copper-nickel, copper-nickel-zinc base alloy,unwrought	66.0%
740329	244413	Copper alloys, unwrought (other than master alloys)	75.0%
740400	381158	Copper/copper alloy waste or scrap	64% (Im) 82% (Ex)
740500	244413	Master alloys of copper	60.0%
740610	244421	Powders, copper, of non-lamellar structure	100.0%
740620	244421	Powders, copper, of lamellar structure and flakes	100.0%
740710	244422	Bars, rods & profiles of refined copper	100.0%
740721	244422	Bars, rods & profiles of copper-zinc base alloys	58.0%
740722	244422	Bar, rod, profiles, copper-nickel, copper-nickel-zinc	66.0%

Table A.3: Copper containing products identified by Fraunhofer ISI based on an analysis by Wittmer (2006), and corresponding HS- and CPA-codes and estimated copper contents

HS92	CPA08	Short description	Est. Cu content
740729	244422	Bars, rods & profiles, copper alloy nes	75.0%
740811	244423	Wire of refined copper > 6mm wide	100.0%
740819	244423	Wire of refined copper < 6mm wide	100.0%
740821	244423	Wire, copper-zinc base alloy	58.0%
740822	244423	Wire, copper-nickel or copper-nickel-zinc base alloy	66.0%
740829	244423	Wire, copper alloy, except nickel/zinc alloys	75.0%
740911	244424	Plate, sheet, strip, refined copper, coil, t > 0.15mm	100.0%
740919	244424	Plate, sheet, strip, refined copper, flat, t > 0.15mm	100.0%
740921	244424	Plate/sheet/strip, copper-zinc alloy, coil,t > 0.15mm	58.0%
740929	244424	Plate/sheet/strip, copper-zinc alloy, flat, t > 0.15m	58.0%
740931	244424	Plate/sheet/strip, copper-tin alloy, coil, t > 0.15mm	85.0%
740939	244424	Plate/sheet/strip, copper-tin alloy, flat, > t >0.15m	85.0%
740940	244424	Plate, sheet, strip, Copper nickel alloys, t > 0.15mm	66.0%
740990	244424	Plate, sheet, strip, copper alloy nes, t > 0.15mm	75.0%
741011	244425	Foil of refined copper, not backed, t < 0.15mm	100.0%
741012	244425	Foil, copper alloy, not backed, t < 0.15mm	75.0%
741021	244425	Foil of refined copper, backed, t < 0.15mm	100.0%
741022	244425	Foil, copper alloy, backed, t < 0.15mm	75.0%
741110	244426	Pipes or tubes, refined copper	100.0%
741121	244426	Pipes or tubes, copper-zinc base alloy	58.0%
741122	244426	Pipes or tubes, copper-nickel alloys	66.0%
741129	244426	Pipes or tubes, copper alloy except nickel/zinc alloy	75.0%
741210	244426	Pipe & tube fittings, of refined copper	100.0%
741220	244426	Pipe & tube fittings, of copper alloys	75.0%
741300	259312	Stranded copper wire/cable/plaits/etc, uninsulated	90.0%
741410	259313	Endless bands of copper wire for machinery	75.0%
741490	259313	Copper wire cloth, grill, netting, expanded metal, ne	75.0%
741510	259314	Copper nails, tacks, drawing pins, staples etc	60.0%
741521	259413	Copper washers, including spring washers	60.0%
741529	259413	Copper cotters/cotter pins/unthreaded hardware nes	60.0%
741531	259413	Wood screws of copper and copper alloys	60.0%
741532	259413	Copper screws, bolts or nuts except wood screws	60.0%
741539	259413	Copper screw hooks and similar articles	60.0%
741600	259313	Copper springs	85.0%
741700	275211	Copper cooking, heating apparatus, non-electric, part	75.0%
741810	259912	Table/kitchen articles of copper, pot scourers	90.0%
741820	259911	Sanitary ware and parts thereof of copper	90.0%
741910	259317	Chain and parts thereof of copper	95.0%
741991	259929	Articles of copper, cast/moulded/stamped, nfw	95.0%
741999	259313	Articles of copper, nes	95.0%
830110	257211	Padlocks of base metal	45.0%
830120	257211	Locks of a kind used for motor vehicles of base metal	45.0%
830130	257211	Locks of a kind used for furniture of base metal	45.0%
830140	257212	Locks of base metal, nes	45.0%

Table A.3: Copper containing products identified by Fraunhofer ISI based on an analysis by Wittmer (2006), and corresponding HS- and CPA-codes and estimated copper contents

HS92	CPA08	Short description	Est. Cu content
830150	257213	Clasps etc incorporating locks, of base metal	45.0%
830160	257213	Lock parts, etc, of base metal,	45.0%
830170	257213	Keys, including blanks for keys, of base metal	45.0%
830210	257214	Hinges of base metal	10.0%
830220	257214	Castors of base metal	30.0%
830230	257214	Motor vehicle mountings, fittings, of base metal, nes	30.0%
830241	257214	Mountings, fittings, of base metal, for buildings, ne	10.0%
830242	257214	Mountings, fittings, of base metal, for furniture, ne	30.0%
830249	257214	Mountings, fittings, of base metal, nes	30.0%
830250	257214	Hat-racks/hat-pegs/brackets etc, of base metal, nes	30.0%
830260	257214	Door closures, automatic, of base metal	10.0%
830400	259922	Office equipment of base metal eg filing cabinet, tra	25.0%
830510	259923	Office binder/file fittings, of base metal	75.0%
830520	259923	Staples, office, upholstery, package etc of base meta	75.0%
830590	259923	Letter corners, paper clips, metal office articles ne	75.0%
830610	259929	Bells, gongs and the like, of base metal	80.0%
830810	259925	Hooks, eyes, eyelets, for clothing, footwear, bags et	80.0%
830820	259925	Rivets, for clothing, footwear, bags/etc	80.0%
830890	259925	Clasps/buckles, etc for clothing, footwear, bags etc	80.0%
831110	259315	Electrodes, coated, of base metal, for arc welding	10.0%
831120	259315	Wire, cored, of base metal, for electric arc welding	10.0%
831130	259315	Coated rods/cored wire for flame solder/braze/weld	10.0%
831190	259315	Electrodes etc of base metal or metal carbide, nes	10.0%
840310	252112	Central heating boilers nes	2.4%
841410	281321	Vacuum pumps	4.0%
841420	281322	Hand or foot-operated air pumps	4.0%
841430	281323	Compressors for refrigerating equipment	4.0%
841440	281324	Air compressors mounted on wheeled chassis for towing	4.0%
841451	275115	Table, window, ceiling fans, electric motor <125 watt	7.7%
841459	282520	Electric fans, motor > 125 watts	4.6%
841460	275115	Ventilating hoods having a maximum width < 120 cm	3.4%
841480	281325	Air or gas compressors, hoods	3.4%
841490	281332	Parts of vacuum pumps, compressors,fans,blowers,hoods	4.0%
841510	282512	Air conditioners window/wall types, self-contained	9.9%
841581	282512	Air conditioners nes with reverse cycle refrigeration	17.1%
841582	282512	Air conditioners nes, with refrigerating unit	9.9%
841583	282512	Air conditioners nes, without refrigerating unit	9.9%
841590	282530	Parts for air conditioners	8.0%
841810	275111	Combined refrigerator-freezers, two door	3.1%
841821	275111	Refrigerators, household compression type	4.7%
841822	275111	Refrigerators, household absorption type, electric	4.7%
841829	275111	Refrigerators, household type, including non-electric	4.7%
841830	275111	Freezers of the chest type, < 800 litre capacity	3.2%
841840	275111	Freezers of the upright type, < 900 litre capacity	3.5%

Table A.3: Copper containing products identified by Fraunhofer ISI based on an analysis by Wittmer (2006), and corresponding HS- and CPA-codes and estimated copper contents

HS92	CPA08	Short description	Est. Cu content
841850	282513	Refrigerator/freezer chests/cabinets/showcases	1.0%
841911	275214	Instantaneous gas water heaters	4.9%
841919	275214	Instantaneous/storage water heaters, not electric nes	4.9%
841950	282511	Heat exchange units, non-domestic, non-electric	4.0%
842112	289423	Clothes-dryers, centrifugal	1.0%
842211	275112	Dish washing machines (domestic)	2.6%
842219	282950	Dish washing machines commercial	2.0%
845011	275113	Automatic washing machines, of a dry capacity < 10 kg	1.9%
845012	275113	Washing machines nes, capacity <10 kg, built-in drier	2.0%
845019	275113	Household/laundry-type washing machines <10 kg, nes	1.9%
845020	289422	Household or laundry-type washing machines, cap >10kg	2.0%
845090	289452	Parts of household or laundry-type washing machines	2.0%
845110	289422	Dry-cleaning machines	2.0%
845121	275113	Drying machines, capacity <10 kg, except washer-drier	2.7%
845129	289422	Drying machines, nes	2.0%
845130	289421	Ironing machines and presses including fusing presses	2.0%
845140	289421	Washing, bleaching or dyeing machines (non-domestic)	2.0%
846910	262018	Automatic typewriters and word-processing machines	4.0%
846921	282311	Typewriters, electric, > 12 kg, non-automatic	4.0%
846929	282311	Typewriters, electric, < 12 kg, non-automatic	4.0%
847021	282312	Electronic calculators, printing, external power	4.0%
847029	282312	Electronic calculators, non-printing, external power	4.0%
847040	282313	Accounting machines	4.0%
847050	282313	Cash registers	4.0%
847110	262011	Analogue or hybrid computers	4.0%
847120	262011	Digital computers with cpu and input-output units	10.0%
847191	262011	Digital computer cpu with some of storage/input/output	4.0%
847192	262018	Computer input or output units	4.0%
847193	262011	Computer data storage units	4.0%
847199	282321	Automatic data processing machines and units, nes	4.0%
848110	281214	Valves, pressure reducing	30.0%
848120	281214	Valves for oleohydraulic or pneumatic transmissions	30.0%
848130	281411	Valves, check	30.0%
848140	281411	Valves, safety or relief	30.0%
848180	281412	Taps, cocks, valves and similar appliances, nes	30.0%
848190	281420	Parts of taps, cocks, valves or similar appliances	30.0%
848510	259926	Ships' or boats' propellers and blades thereof	80.0%
848590	281524	Machinery parts, non-electrical, nes	1.0%
850110	271110	Electric motors of an output < 37.5 watts	10.0%
850120	271121	Universal AC/DC motors of an output < 37.5 watts	10.0%
850131	271110	DC motors, DC generators, of an output < 750 watts	10.0%
850132	271110	DC motors, DC generators, of an output 0.75-75 kW	11.2%
850133	271110	DC motors, DC generators, of an output 75-375 kW	5.7%
850134	271110	DC motors, DC generators, of an output >375 kW	10.0%

Table A.3: Copper containing products identified by Fraunhofer ISI based on an analysis by Wittmer (2006), and corresponding HS- and CPA-codes and estimated copper contents

HS92	CPA08	Short description	Est. Cu content
850140	271122	AC motors, single-phase, nes	10.0%
850151	271123	AC motors, multi-phase, of an output < 750 Watts	10.0%
850152	271124	AC motors, multi-phase, of an output 0.75-75 kW	10.0%
850153	271125	AC motors, multi-phase, of an output > 75 kW	5.7%
850161	271126	AC generators, of an output < 75 kVA	10.0%
850162	271126	AC generators, of an output 75-375 kVA	10.0%
850163	271126	AC generators, of an output 375-750 kVA	10.0%
850164	271126	AC generators, of an output > 750 kVA	10.0%
850211	271131	Generating sets, diesel, output < 75 kVA	10.0%
850212	271131	Generating sets, diesel, output 75-375 kVA	10.0%
850213	271131	Generating sets, diesel, output > 375 kVA	10.0%
850220	271132	Generating sets, with spark ignition engines	10.0%
850230	281124	Electric generating sets, nes	10.0%
850240	271132	Electric rotary converters	10.0%
850300	271161	Parts for electric motors and generators	1.0%
850410	271150	Ballasts for discharge lamps or tubes	10.8%
850421	271141	Liquid dielectric transformers < 650 KVA	15.4%
850422	271141	Liquid dielectric transformers 650-10,000KVA	14.9%
850423	271141	Liquid dielectric transformers > 10,000 KVA	4.0%
850431	271142	Transformers electric, power capacity < 1 KVA, nes	4.0%
850432	271142	Transformers electric, power capacity 1-16 KVA, nes	4.0%
850433	271143	Transformers electric, power capacity 16-500 KVA	3.9%
850434	271143	Transformers electric, power capacity > 500 KVA, nes	4.0%
850440	271150	Static converters, nes	4.0%
850450	271150	Inductors, electric	4.0%
850490	271162	Parts of electrical transformers and inductors	4.0%
850530	279040	Electro-magnetic lifting heads	50.0%
850590	279040	Electro-magnets nes and parts of magnetic devices	50.0%
850810	282411	Drills, hand-held, with self-contained electric motor	4.0%
850820	282411	Saws, hand-held, with self-contained electric motor	4.0%
850880	281325	Tools, hand-held, with electric motor, not drills/saw	4.0%
850890	281332	Parts, hand tools with self-contained electric motor	4.0%
850910	275121	Domestic vacuum cleaners	4.0%
850920	275121	Domestic floor polishers	4.0%
850930	275121	Domestic kitchen waste disposers	4.0%
850940	275121	Domestic food grinders, mixers, juice extractors	4.0%
850980	275124	Domestic appliances, with electric motor, nes	4.0%
850990	275130	Parts of domestic appliances with electric motor	4.0%
851010	275122	Shavers, with self-contained electric motor	4.0%
851020	275122	Hair clippers, with self-contained electric motor	4.0%
851090	275130	Parts of shavers/hair clippers, electric	4.0%
851120	293121	Ignition magnetos, magneto-generators and flywheels	10.0%
851130	293121	Distributors and ignition coils	10.0%
851140	293122	Starter motors	10.0%

Table A.3: Copper containing products identified by Fraunhofer ISI based on an analysis by Wittmer (2006), and corresponding HS- and CPA-codes and estimated copper contents

HS92	CPA08	Short description	Est. Cu content
851150	293122	Generators and alternators	10.0%
851180	293122	Glow plugs & other ignition or starting equipment nes	10.0%
851190	293130	Parts of electrical ignition or starting equipment	10.0%
851310	274021	Portable battery and magneto-electric lamps	2.0%
851390	274042	Parts for portable battery & magneto electric lamps	2.0%
851511	279031	Electric soldering irons and guns	4.0%
851519	289939	Electric brazing, soldering machines and apparatus ne	4.0%
851521	289939	Electric resistance welding equipment, automatic	4.0%
851529	289939	Electric resistance welding equipment, non-automatic	4.0%
851531	279031	Automatic electric plasma, other arc welding equipmen	4.0%
851539	279031	Non-automatic electric plasma and other arc welders	4.0%
851580	284111	Electric, laser and ultrasonic welding equipment nes	4.0%
851590	284921	Parts of electric solder, weld or braze equipment	4.0%
851610	275125	Electric instant, storage and immersion water heaters	6.7%
851621	275126	Electric storage heating radiators	0.3%
851629	275126	Electric space heating nes and soil heating apparatus	6.9%
851631	275123	Electric hair dryers	8.0%
851632	275123	Electro-thermic hairdressing apparatus, nes	8.0%
851633	275123	Electro-thermic hand drying apparatus	8.0%
851640	275123	Electric smoothing irons	8.0%
851650	275127	Microwave ovens	8.0%
851660	275128	Electric cooking, grilling & roasting equipment nes	8.6%
851671	275124	Electric coffee or tea makers, domestic	8.0%
851672	275124	Electric toasters, domestic	8.0%
851679	275124	Electro-thermic appliances, domestic, nes	8.0%
851680	275129	Electric heating resistors	8.0%
851690	275130	Parts of electro-thermic apparatus, domestic, etc	8.0%
851710	263021	Telephone sets	4.0%
851720	262016	Teleprinters	4.0%
851730	263023	Telephonic or telegraphic switching apparatus	4.0%
851740	262018	Apparatus, for carrier-current line systems, nes	4.0%
851781	263023	Telephonic apparatus, nes	4.0%
851782	262018	Telegraphic apparatus, nes	4.0%
851790	282326	Parts of line telephone/telegraph equipment, nes	4.0%
851810	264041	Microphones and stands thereof	4.0%
851821	264042	Single loudspeakers, mounted in enclosure	4.0%
851822	264042	Multiple loudspeakers, mounted in single enclosure	4.0%
851829	264042	Loudspeakers, nes	4.0%
851830	264042	Headphones, earphones, combinations	4.0%
851840	264043	Audio-frequency electric amplifiers	4.0%
851850	264043	Electric sound amplifier sets	4.0%
851890	264051	Parts of non-recording electronic equipment	4.0%
851910	264031	Coin or disc-operated record-players	4.0%
851921	264031	Record-players without built-in loudspeaker, nes	4.0%

Table A.3: Copper containing products identified by Fraunhofer ISI based on an analysis by Wittmer (2006), and corresponding HS- and CPA-codes and estimated copper contents

HS92	CPA08	Short description	Est. Cu content
851929	264031	Record-players with loudspeakers, nes	4.0%
851931	264031	Turntables with automatic record changing mechanism	4.0%
851939	264031	Turntables, without record changers	4.0%
851940	264031	Transcribing machines	4.0%
851991	264031	Cassette players, non-recording	4.0%
851999	264031	Sound reproducing apparatus, non-recording, nes	4.0%
852010	264031	Dictating machine requiring external power source	4.0%
852020	263023	Telephone answering machines	4.0%
852031	264031	Cassette type audio tape recorders, sound reproducing	4.0%
852039	264031	Non-cassette audio tape recorders, sound reproducing	4.0%
852090	264031	Audio recording equipment without sound reproduction	4.0%
852110	264033	Video recording/reproducing apparatus, magnetic tape	1.0%
852190	264033	Video record/reproduction apparatus not magnetic tape	1.0%
852510	263023	Transmission apparatus for radio, telephone and TV	4.0%
852520	263022	Transmit-receive apparatus for radio, TV, etc.	4.0%
852530	263023	Television cameras	4.0%
852610	265120	Radar apparatus	4.0%
852691	265120	Radio navigational aid apparatus	4.0%
852692	265120	Radio remote control apparatus	4.0%
852711	264011	Radio receivers, portable, with sound reproduce/recor	4.0%
852719	264011	Radio receivers, portable, non-recording	4.0%
852721	264012	Radio receivers, external power,sound reproduce/recor	4.0%
852729	264012	Radio receivers, external power, not sound reproducer	4.0%
852731	264011	Radio-telephony receiver, with sound reproduce/record	4.0%
852732	264011	Radio-telephony etc receivers, nes	4.0%
852739	264011	Radio-broadcast receivers nes	4.0%
852790	263023	Radio reception apparatus nes	4.0%
852810	263023	Colour television receivers/monitors/projectors	4.0%
852820	263023	Monochrome television receivers/monitors/projectors	4.0%
853010	279070	Electric signal, safety & traffic controls, railway	7.5%
853080	279070	Electric signal, safety & traffic controls, nes	7.5%
853090	279033	Electric signal, safety & traffic controller parts	7.5%
853400	261210	Electronic printed circuits	10.0%
853910	274011	Sealed beam lamp units	7.5%
853921	274012	Filament lamps, tungsten halogen	7.5%
853922	274013	Filament lamps, of a power $\leq$ 200 Watt, $>$ 100 volts	7.5%
853929	274014	Filament lamps, except ultraviolet or infra-red, nes	7.5%
853931	274015	Fluorescent lamps, hot cathode	7.5%
853939	274015	Discharge lamps, other than ultra-violet lamps, nes	7.5%
853940	274015	Ultra-violet or infra-red lamps, arc lamps	7.5%
853990	274041	Parts of electric filament or discharge lamps	7.5%
854211	261230	Monolithic integrated circuits, digital	25.0%
854219	261230	Monolithic integrated circuits, except digital	25.0%
854220	261130	Hybrid integrated circuits	25.0%

Table A.3: Copper containing products identified by Fraunhofer ISI based on an analysis by Wittmer (2006), and corresponding HS- and CPA-codes and estimated copper contents

HS92	CPA08	Short description	Est. Cu content
854280	279033	Electronic integrated circuits/microassemblies, nes	25.0%
854290	261230	Parts of electronic integrated circuits etc	25.0%
854411	273211	Insulated winding wire of copper	65.0%
854420	273212	Co-axial cable and other co-axial electric conductors	65.0%
854430	293110	Ignition/other wiring sets for vehicles/aircraft/ship	65.0%
854441	273213	Electric conductors, nes < 80 volts, with connectors	38.0%
854449	273213	Electric conductors, nes < 80 volts, no connectors	38.0%
854451	273213	Electric conductors, 80-1,000 volts, with connectors	65.0%
854459	273213	Electric conductors, 80-1,000 volts, no connectors	65.0%
854460	273214	Electric conductors, for over 1,000 volts, nes	65.0%
854800	261130	Electrical parts of machinery and apparatus, nes	25.0%
860110	302011	Rail locomotives, externally electrically powered	8.0%
860120	302013	Rail locomotives powered by electric accumulators	8.0%
860210	302012	Rail locomotives, diesel-electric	40.0%
860310	302020	Self-propelled railway cars, external electric power	7.0%
860500	302032	Railway passenger and special purpose coaches	2.0%
870110	283010	Pedestrian controlled tractors	2.0%
870120	291043	Road tractors for semi-trailers (truck tractors)	2.0%
870130	289250	Track-laying tractors (crawlers)	2.0%
870190	283021	Wheeled tractors nes	2.0%
870210	291030	Diesel powered buses	0.7%
870290	291030	Buses except diesel powered	0.7%
870321	291021	Automobiles, spark ignition engine of <1000 cc	0.7%
870322	291021	Automobiles, spark ignition engine of 1000-1500 cc	0.7%
870323	291022	Automobiles, spark ignition engine of 1500-3000 cc	0.7%
870324	291022	Automobiles, spark ignition engine of >3000 cc	0.7%
870331	291023	Automobiles, diesel engine of <1500 cc	0.7%
870332	291023	Automobiles, diesel engine of 1500-2500 cc	0.7%
870333	291023	Automobiles, diesel engine of >2500 cc	0.7%
870390	291024	Automobiles nes including gas turbine powered	0.7%
870410	289229	Dump trucks designed for off-highway use	2.0%
870421	291041	Diesel powered trucks weighing < 5 tonnes	2.0%
870422	291041	Diesel powered trucks weighing 5-20 tonnes	2.0%
870423	291041	Diesel powered trucks weighing > 20 tonnes	2.0%
870431	291042	Spark ignition engine trucks weighing < 5 tonnes	2.0%
870432	291042	Spark ignition engine trucks weighing > 5 tonnes	2.0%
870490	291042	Trucks nes	2.0%
870831	293230	Mounted brake linings for motor vehicles	3.0%
870891	293230	Radiators for motor vehicles	3.0%
871110	309111	Motorcycles, spark ignition engine of < 50 cc	1.0%
871120	309112	Motorcycles, spark ignition engine of 50-250 cc	1.0%
871130	309112	Motorcycles, spark ignition engine of 250-500 cc	1.0%
871140	309112	Motorcycles, spark ignition engine of 500-800 cc	1.0%
871150	309112	Motorcycles, spark ignition engine of > 800 cc	1.0%

Table A.3: Copper containing products identified by Fraunhofer ISI based on an analysis by Wittmer (2006), and corresponding HS- and CPA-codes and estimated copper contents

HS92	CPA08	Short description	Est. Cu content
871190	309113	Motorcycles with other than a spark ignition engine	1.0%
871200	309210	Bicycles, other cycles, not motorized	1.0%
900810	267016	Slide projectors	4.0%
900911	262018	Electrostatic photo-copyers, direct process	4.0%
900912	262018	Electrostatic photo-copyers, indirect process	4.0%
900921	282321	Photo-copying equipment with an optical system, nes	4.0%
900922	282321	Contact type photo-copying apparatus,nes	4.0%
900930	282321	Thermo-copying apparatus	4.0%
901710	265132	Drafting tables and machines	4.0%
911120	265226	Watch cases of base metal including gold/silver-plate	58.0%
911190	265226	Parts of watch cases	58.0%
911210	265226	Clock, etc cases, of metal	58.0%
920510	322013	Brass-wind instruments	85.0%
930610	254013	Cartridges for rivet etc tools, humane killers, etc	95.0%
930621	254013	Cartridges, shotgun	95.0%
930690	254013	Munitions of war, ammunition/projectiles and parts	95.0%
950410	264060	Video games used with a television receiver	4.0%

A.6 List of economic sectors (WZ 2008)

Table A.4: Economic sectors according to the WZ 2008 classification

CPA	WZ 2008 - Description (n.e.c. = not elsewhere classified)
01	Crop and animal production, hunting and related service activities
02	Forestry and logging
03	Fishing and aquaculture
05	Mining of coal and lignite
06	Extraction of crude petroleum and natural gas
07-09	Mining and quarrying of metal ores and minerals, support activities
10-12	Manufacture of food, beverages and tobacco products
13-15	Manufacture of textiles, wearing apparel and leather products
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
17	Manufacture of paper and paper products
18	Printing and reproduction of recorded media
19	Manufacture of coke and refined petroleum products
20	Manufacture of chemicals and chemical products
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
22	Manufacture of rubber and plastic products
23.1	Manufacture of glass and glass products
23.2-23.9	Manufacture of ceramics, building materials and mineral products
24.1-24.3	Manufacture of basic iron, steel and of ferro-alloys, and products of first processing of steel
24.4	Manufacture of basic precious and other non-ferrous metals
24.5	Casting of metals
25	Manufacture of fabricated metal products, except machinery and equipment
26	Manufacture of computer, electronic and optical products
27	Manufacture of electrical equipment
28	Manufacture of machinery and equipment n.e.c.
29	Manufacture of motor vehicles, trailers and semi-trailers
30	Manufacture of other transport equipment
31-32	Manufacture of furniture, other manufacturing
33	Repair and installation of machinery and equipment
35.1, 35.3	Electric power generation, transmission and distribution; steam and air conditioning supply
35.2	Manufacture of gas; distribution of gaseous fuels through mains
36	Water collection, treatment and supply
37-39	Sewerage, waste collection, treatment and disposal activities; materials recovery
41	Construction of buildings
42	Civil engineering
43	Specialised construction activities
45	Wholesale and retail trade and repair of motor vehicles and motorcycles
46	Wholesale trade, except of motor vehicles and motorcycles
47	Retail trade, except of motor vehicles and motorcycles
49	Land transport and transport via pipelines
50	Water transport

Table A.4: Economic sectors according to the WZ 2008 classification

CPA	WZ 2008 - Description (n.e.c. = not elsewhere classified)
51	Air transport
52	Warehousing and support activities for transportation
53	Postal and courier activities
55-56	Accommodation, food and beverage service activities
58	Publishing activities
59-60	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
61	Telecommunications
62-63	Computer programming, consultancy and related activities; information service activities
64	Financial service activities, except insurance and pension funding
65	Insurance, reinsurance and pension funding, except compulsory social security
66	Activities auxiliary to financial services and insurance activities
68	Real estate activities
69-70	Legal and accounting activities; activities of head offices; management consultancy activities
71	Architectural and engineering activities; technical testing and analysis
72	Scientific research and development
73	Advertising and market research
74-75	Other professional, scientific and technical activities; veterinary activities
77	Rental and leasing activities
78	Employment activities
79	Travel agency, tour operator and other reservation service and related activities
80-82	Security and investigation activities; services to buildings and landscape activities; office administrative, office support and other business support activities
84.1-84.2	Administration of the State and the economic and social policy of the community, provision of services to the community as a whole
84.3	Compulsory social security activities
85	Education
86	Human health activities
87-88	Residential care activities, social work activities without accommodation
90-92	Creative, arts and entertainment activities, libraries, archives, museums and other cultural activities, gambling and betting activities
93	Sports activities and amusement and recreation activities
94	Activities of membership organisations
95	Repair of computers and personal and household goods
96	Other personal service activities
97-98	Activities of households as employers of domestic personnel; undifferentiated goods- and services-producing activities of private households for own use

A.7 Additional information on prospective simulations

A.7.1 Scenario definition

The technologies considered in the material efficiency scenario described in Section 6.1.2 are only known to the extent of their theoretical maximum potential within Germany but not how they will be scaled to that potential. It is therefore necessary to define plausible generic diffusion trajectories for the technologies. A number of models exist with which technology diffusion can be portrayed. The most common types are epidemic and discrete-choice models. The latter model the specific technology adoption behavior of utility maximizing agents, usually in the form of logit or probit models, and are therefore more concrete in the way they describe technology diffusion (Stengel, 2014; Train, 2009). The former are based on the idea that innovations spread in a similar fashion as contagious diseases and are in this way more abstract (Geroski, 2000; Meade and Islam, 2006). According to these models, the rate of the diffusion depends on the size of the "infected" population (in the present case the population which has adopted a specific technology). Because of their more abstract nature, epidemic models are more suitable in cases where little is known about the technologies and/or the actors involved in adopting it. The majority of epidemic models are applied to consumer goods, though for simplicity it can be assumed that industrial technologies diffuse in a similar fashion.

A variety of epidemic diffusion models have been presented since the 1960s. Most of them share the characteristic that the diffusion takes place at different speeds relative to a predefined saturation point (which usually represents the size of the 'market' for the innovation). Various diffusion trajectories up to this saturation point can be envisioned, the most common type resembling an s-shaped[2] curve with initial inertia, a phase of accelerated technology adoption and deceleration towards the end of the diffusion period (Mansfield, 1961; Rogers, 1962; Bass, 1969; see Modis, 2007 for a critical discussion of S-curves).

Two broad diffusion trajectories are illustrated in Figure A.7, where the "fast diffusion" trajectory reaches the maximum much earlier than the "slow diffusion" trajectory. In the context of material efficiency, this means that the effects of material savings accrue to the overall economy faster in the former than in the latter case. The range of possible diffusion trajectories can be represented by a logistic function of the following simplified form:[3]

$$y(t) = \frac{M}{1 + e^{-a(t-t_0)}} \tag{A.5}$$

[2]The specification of discrete-choice based diffusion models generally also leads to s-shaped diffusion trajectories.

[3]The seminal epidemic diffusion model by Bass (1969) differentiates between innovation and imitation as influencing factors of diffusion paths. However, for the purpose of defining a generic s-shaped diffusion trajectory, a simple logistic function with the stated parameters suffices.

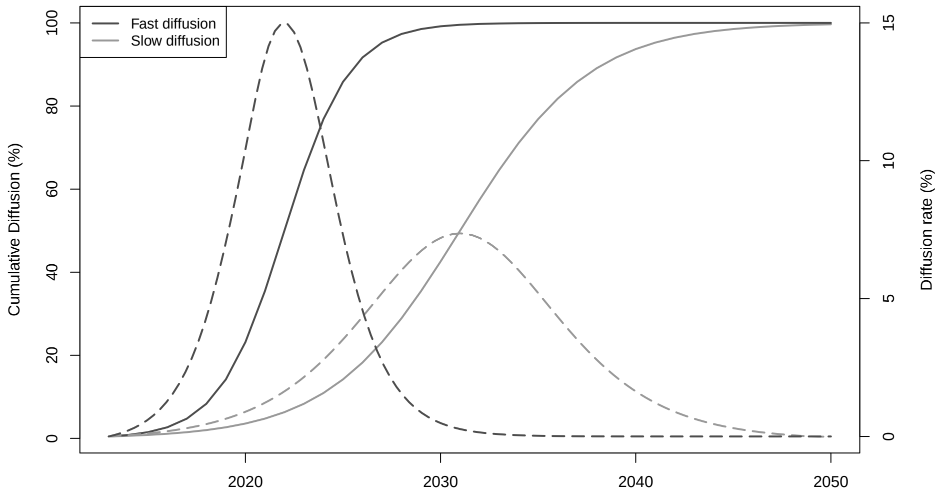


Figure A.7: Schematic representation of possible innovation diffusion paths: solid lines indicate cumulative diffusion and dashed lines indicate diffusion rate, own illustration

where $y(t)$ = cumulative diffusion, M = maximum diffusion, a = 'steepness' of the diffusion, t = time step and t_0 = the point in time, at which half of the maximum diffusion is reached. The set of parameters chosen for the two examples depicted in Figure A.7 are summarized in Table A.5. The maximum diffusion is in this case assumed to be the same at 100 % for both cases even though it is conceivable that this theoretical maximum will not be reached.

Table A.5: Parameters for diffusion trajectories

	M	a	t_0
Fast diffusion	100 %	0.6	10
Slow diffusion	100 %	0.3	19

Among the scenario inputs into the model, the technology investments constitute a special case as they are defined in such way that the total investment sum will be reached at the end of the simulation period. Thus, the the s-shape described above applies to cumulative investments and not to yearly values. This means that the yearly investments must equal the derivative of the s-shaped logistic function, which leads to a bell shape (see Equation A.6). The total yearly investment sum is thus initially low, steadily increases, reaches a maximum, and then decreases again towards the end of the simulation period, as depicted by the dashed lines in Figure A.7.

$$\frac{\mathrm{d}y}{\mathrm{d}t} = \frac{ae^{a(t+t_0)}}{(e^{at} + e^{at_0})^2} \tag{A.6}$$

Contrary to the autonomous investments in the model, which are based on historical investment behavior, the scenario investments do not per se include replacement investments. However, theoretically these are required when the implemented technologies wear down and finally get scrapped. Once a capital vintage has retired, a reinvestment of the same or a similar size has to be made in the following period. In the material efficiency scenario analyzed in Section 6.1 in the main text, investments only play a minor role and so replacement investments are left out for simplicity.

A.7.2 Manual adaptations to technical coefficients

In order to ensure that total supply equals total use in the IO table, the intermediate deliveries matrix $\boldsymbol{Z}$ must be re-balanced after manually changing individual inter-industry flows or technical coefficients manually. Various matrix balancing techniques exist, of which a widely used method in an IO context is the biproportional iterative "RAS" procedure (Bacharach, 1965; Stone and Brown, 1962). While this procedure utilizes an original Z- or A-matrix and additional information on total inter-industry in- and outputs as well as gross output, as a purely mathematical balancing technique it is critically viewed from an economic perspective (Miller and Blair, 2009). Its main application is the inter- or extrapolation of existing IO tables with limited information, but not necessarily manual adaptations to technical coefficients in existing tables. Such iterative approaches are in addition difficult to implement in a dynamic modeling environment with discrete time steps.

Therefore, a different, ad hoc approach has been chosen to ensure the equality of total supply and total use. In this approach, all changes to individual intermediate deliveries Δz_{ij} are first added to the original intermediate deliveries matrix $\boldsymbol{Z}$ to get a new hypothetical intermediate deliveries matrix $\boldsymbol{Z}^*$:

$$\boldsymbol{Z}^* = \boldsymbol{Z} + \Delta z_{ij} \tag{A.7}$$

The changes to individual intermediate deliveries are then summed across columns to project a total demand change for intermediate inputs akin to a final demand change:

$$\Delta \boldsymbol{z} = \sum_{j=1}^{n} \Delta z_{ij} \tag{A.8}$$

This change is then used to calculate a hypothetical new gross output vector $\boldsymbol{x}^*$ in the same way a gross output delta is calculated from a change in final demand:

$$\boldsymbol{x}^* = \boldsymbol{L}\Delta\boldsymbol{z} \tag{A.9}$$

The new gross output vector is then multiplied with the original technical coefficient matrix $\boldsymbol{A}$ in order to get the induced deltas in intermediate deliveries Δz^*_{ij}:

$$\Delta z^*_{ij} = \boldsymbol{A}\hat{\boldsymbol{x}}^* \tag{A.10}$$

The induced deltas in intermediate deliveries are finally added to the hypothetical intermediate deliveries matrix in order to balance it:

$$\boldsymbol{Z}^\dagger = \boldsymbol{Z}^* + \Delta z^*_{ij} \tag{A.11}$$

This balanced version of the changed intermediate deliveries matrix is then used to calculate the new A-matrix as in Equation 4.19 in the main text. This method assumes that the change in intermediate deliveries Δz_{ij} only affects the input structures of the sectors j that change one or several of their intermediate inputs, shifting the relative weights of intermediate (a_{ij}) and primary inputs (v_{ij}). The induced effect leads to an instantaneous adaptation of the absolute intermediate deliveries and of the corresponding primary inputs of all sectors, including the ones not directly affected by Δz_{ij} (based on the previous overall production structure and not the hypothetical new one). However, it does not change the relative production structures of the sectors not directly affected by Δz_{ij}. The forwarding of gains or losses from changed intermediate inputs between sectors, which would result in changed input structures for all sectors, is thus implicitly excluded. Due to the construction of the input-output module in the model (see Section 4.2.2), the overall level of primary inputs remains constant, but its distribution changes in accordance with the changes in intermediate deliveries.

A.8 Additional information on EXIOBASE

A.8.1 Double counting in MRIO analysis

As described in Section 5.1.2 in the main text, double counting in MRIO analysis can cause results to deviate from results of other types of analyses. The issue of double counting will be illustrated in more detail below.

A country's gross exports to the world can be defined in the following way (Koopman et al., 2014, p.481):

$$\boldsymbol{v}_{s^*} = \sum_{r \neq s}^{N} (\boldsymbol{A}_{s,r}\boldsymbol{x}_r + \boldsymbol{y}_{s,r}) \tag{A.12}$$

Gross exports of materials from Germany to the rest of the world, which are the sum of materials contained in final product and intermediate delivery exports, can be expressed in the following way (Koopman et al., 2014, p.481):

$$\begin{aligned}\boldsymbol{m}_{s^*} = &\ \boldsymbol{e}_s \sum_{r\neq s}^{N} \boldsymbol{L}_{s,s}\boldsymbol{y}_{s,r} + \boldsymbol{e}_s \sum_{r\neq s}^{N} \boldsymbol{L}_{s,r}\boldsymbol{y}_{r,r} + \boldsymbol{e}_s \sum_{r\neq s}^{N}\sum_{t\neq s,r}^{N} \boldsymbol{L}_{s,r}\boldsymbol{y}_{r,t} \\ &+ \boldsymbol{e}_s \sum_{r\neq s}^{N} \boldsymbol{L}_{s,r}\boldsymbol{y}_{r,s} + \boldsymbol{e}_s \sum_{r\neq s}^{N} \boldsymbol{L}_{s,r}\boldsymbol{A}_{r,s}(\boldsymbol{I}-\boldsymbol{A}_{s,s})^{-1}\boldsymbol{y}_{s,s} \\ &+ \boldsymbol{e}_s \sum_{r\neq s}^{N} \boldsymbol{L}_{s,r}\boldsymbol{A}_{r,s}(\boldsymbol{I}-\boldsymbol{A}_{s,s})^{-1}\boldsymbol{v}_{s^*} \\ &+ \sum_{t\neq s}^{N}\sum_{r\neq s}^{N} \boldsymbol{e}_t\boldsymbol{L}_{t,s}\boldsymbol{y}_{s,r} + \sum_{t\neq s}^{N}\sum_{r\neq s}^{N} \boldsymbol{e}_t\boldsymbol{L}_{t,s}\boldsymbol{A}_{s,r}(\boldsymbol{I}-\boldsymbol{A}_{r,r})^{-1}\boldsymbol{y}_{r,r} \\ &+ \sum_{t\neq s}^{N} \boldsymbol{e}_t\boldsymbol{L}_{t,s}\boldsymbol{A}_{s,r}\sum_{r\neq s}^{N}(\boldsymbol{I}-\boldsymbol{A}_{r,r})^{-1}\boldsymbol{v}_{r^*}\end{aligned} \tag{A.13}$$

The individual components of Equation A.13 are reflected in the nine summands with the following meaning:

1. Domestic material embodied in final product exports finally consumed abroad
2. Domestic material embodied in intermediate delivery exports finally consumed abroad
3. Domestic material embodied in intermediate delivery exports to one foreign country and re-exported as final goods to another country
4. Domestic material initially embodied in intermediate exports but returned as part of Germany's imports of final products
5. Domestic material initially exported by Germany as intermediate products to the rest of the world, but then returned via intermediate imports from the rest of the world to produce final products that are consumed in Germany
6. Domestic material initially exported by Germany as intermediate products to the rest of the world, but then returned via intermediate imports from the rest of the world to produce exports of final and intermediate goods from Germany to the rest of the world
7. Foreign material embodied in intermediate imports that are used for Germany's gross exports of final products
8. Foreign material embodied in Germany's gross exports of intermediate products that are used to produce final products in the rest of the world which remain there

9. Foreign material initially imported from the rest of the world as intermediate products, but then exported again as intermediate products to the rest of the world where they are used to produce exports of final and intermediate products (including but not exclusively to Germany)

Both 4. and 5. represent domestic material embodied in Germany's production, which is exported to the rest of the world, but then returned to Germany where it remains. Therefore these two terms are counted at least twice and possibly several times as long as the origin and the final destination is Germany. This also does not qualify them as exports in the strictest sense, since the final destination is Germany. 9. represents foreign material that enters Germany contained in intermediate goods but leaves Germany again in the form of intermediate goods to be partially re-imported as either intermediate or final goods (the rest is imported in other countries). This term is also counted at least twice. In fact, it can be seen from the above list that apart from 1. and 2. all terms are double counted components of the bilateral[4] trade between Germany and the rest of the world. When assessing the material content of trade flows, one therefore has to be aware of this double counting issue (see also Arto et al., 2015, for an illustration of this issue).

[4]The term "bilateral" refers here to the simplified two region case. In fact, actual trade flows are multilateral, i.e. trade between Germany and the rest of the world happens in the form of multiple trade flows between Germany and all other countries. In addition, there may be multiple internal trade flows within the rest of the world before or after bilateral trade between Germany and another country.

A.8.2 Background tables

Table A.6: List of countries in EXIOBASE v3.4

No.	Code	Country	No.	Code	Country
1	AT	Austria	26	SI	Slovenia
2	BE	Belgium	27	SK	Slovak Republic
3	BG	Bulgaria	28	GB	United Kingdom
4	CY	Cyprus	29	US	United States
5	CZ	Czech Republic	30	JP	Japan
6	DE	Germany	31	CN	China
7	DK	Denmark	32	CA	Canada
8	EE	Estonia	33	KR	South Korea
9	ES	Spain	34	BR	Brazil
10	FI	Finland	35	IN	India
11	FR	France	36	MX	Mexico
12	GR	Greece	37	RU	Russian Federation
13	HR	Croatia	38	AU	Australia
14	HU	Hungary	39	CH	Switzerland
15	IE	Ireland	40	TR	Turkey
16	IT	Italy	41	TW	Taiwan
17	LT	Lithuania	42	NO	Norway
18	LU	Luxembourg	43	ID	India
19	LV	Latvia	44	ZA	South Africa
20	MT	Malta	45	WA	RoW Asia and Pacific
21	NL	Netherlands	46	WL	RoW America
22	PL	Poland	47	WE	RoW Europe
23	PT	Portugal	48	WF	RoW Africa
24	RO	Romania	49	WM	RoW Middle East
25	SE	Sweden			

Table A.7: List of used material categories in EXIOBASE v3.4; unused material categories are almost identical but exclude honey and beeswax in the agricultural category, but differentiate between different types of coal, oil and gas in the fossil fuel category (see footnote 16 in the main text)

No.	Group	Material category
1	Primary Crops	Rice
2	Primary Crops	Wheat
3	Primary Crops	Barley
4	Primary Crops	Buckwheat
5	Primary Crops	Canary Seed
6	Primary Crops	Maize
7	Primary Crops	Millet
8	Primary Crops	Mixed Grain

Table A.7: List of used material categories in EXIOBASE v3.4

No.	Group	Material category
9	Primary Crops	Oats
10	Primary Crops	Rye
11	Primary Crops	Sorghum
12	Primary Crops	Triticale
13	Primary Crops	Cereals nec
14	Primary Crops	Fonio
15	Primary Crops	Quinoa
16	Primary Crops	Potatoes
17	Primary Crops	Sweet Potatoes
18	Primary Crops	Yams
19	Primary Crops	Lentils
20	Primary Crops	Lupins
21	Primary Crops	Vetches
22	Primary Crops	Pulses nec
23	Primary Crops	Olives
24	Primary Crops	Artichokes
25	Primary Crops	Asparagus
26	Primary Crops	Cabbages
27	Primary Crops	Carrots
28	Primary Crops	Cauliflower
29	Primary Crops	Chillies and peppers, green
30	Primary Crops	Cucumbers and Gherkins
31	Primary Crops	Eggplants
32	Primary Crops	Garlic
33	Primary Crops	Leeks and other Alliac. Veg.
34	Primary Crops	Lettuce
35	Primary Crops	Mushrooms
36	Primary Crops	Peas, Green
37	Primary Crops	Pumpkins, Squash, Gourds
38	Primary Crops	Spinach
39	Primary Crops	Tomatoes
40	Primary Crops	Vegetables Fresh nec
41	Primary Crops	Apples
42	Primary Crops	Apricots
43	Primary Crops	Avocados
44	Primary Crops	Blueberries
45	Primary Crops	Carobs
46	Primary Crops	Cherries
47	Primary Crops	Currants
48	Primary Crops	Dates
49	Primary Crops	Figs
50	Primary Crops	Gooseberries
51	Primary Crops	Grapefruit and Pomelos
52	Primary Crops	Grapes
53	Primary Crops	Kiwi Fruit
54	Primary Crops	Lemons and Limes
55	Primary Crops	Oranges

Table A.7: List of used material categories in EXIOBASE v3.4

No.	Group	Material category
56	Primary Crops	Peaches and Nectarines
57	Primary Crops	Pears
58	Primary Crops	Persimmons
59	Primary Crops	Pineapples
60	Primary Crops	Plums
61	Primary Crops	Quinces
62	Primary Crops	Raspberries
63	Primary Crops	Sour Cherries
64	Primary Crops	Strawberries
65	Primary Crops	Tang. Mand Clement. Satsma
66	Primary Crops	Berries nec
67	Primary Crops	Citrus Fruit nec
68	Primary Crops	Stone Fruit nec,
69	Primary Crops	Almonds
70	Primary Crops	Chestnuts
71	Primary Crops	Hazelnuts
72	Primary Crops	Pistachios
73	Primary Crops	Walnuts
74	Primary Crops	Cassava
75	Primary Crops	Roots and Tubers, nes
76	Primary Crops	Taro
77	Primary Crops	Yautia
78	Primary Crops	Bambara beans
79	Primary Crops	Beans, dry
80	Primary Crops	Beans, green
81	Primary Crops	Broad beans, horse beans, dry
82	Primary Crops	Chick peas
83	Primary Crops	Cow peas, dry
84	Primary Crops	Peas, dry
85	Primary Crops	Pigeon peas
86	Primary Crops	String beans
87	Primary Crops	Coconuts
88	Primary Crops	Okra
89	Primary Crops	Onions
90	Primary Crops	Onions, dry
91	Primary Crops	Other melons
92	Primary Crops	Watermelons
93	Primary Crops	Bananas
94	Primary Crops	Cashewapple
95	Primary Crops	Cranberries
96	Primary Crops	Fruit Fresh Nes
97	Primary Crops	Fruit, tropical fresh nes
98	Primary Crops	Mangoes, mangosteens, guavas
99	Primary Crops	Papayas
100	Primary Crops	Plantains
101	Primary Crops	Arecanuts
102	Primary Crops	Brazil nuts, with shell

Table A.7: List of used material categories in EXIOBASE v3.4

No.	Group	Material category
103	Primary Crops	Cashew nuts, with shell
104	Primary Crops	Kolanuts
105	Primary Crops	Nuts, nes
106	Primary Crops	Leguminous vegetables, nes
107	Primary Crops	Maize, green
108	Primary Crops	Pome fruit, nes
109	Primary Crops	Cassava leaves
110	Primary Crops	Groundnuts in Shell
111	Primary Crops	Hempseed
112	Primary Crops	Linseed
113	Primary Crops	Melonseed
114	Primary Crops	Mustard Seed
115	Primary Crops	Poppy Seed
116	Primary Crops	Rapeseed
117	Primary Crops	Safflower Seed
118	Primary Crops	Sesame Seed
119	Primary Crops	Soybeans
120	Primary Crops	Sunflower Seed
121	Primary Crops	Oilseeds nec
122	Primary Crops	Oil Palm Fruit
123	Primary Crops	Castor oil seed
124	Primary Crops	Karite Nuts
125	Primary Crops	Tung Nuts
126	Primary Crops	Jojoba Seeds
127	Primary Crops	Tallowtree Seeds
128	Primary Crops	Cottonseed
129	Primary Crops	Sugar Beets
130	Primary Crops	Sugar Cane
131	Primary Crops	Sugar Crops nes
132	Primary Crops	Cotton Lint
133	Primary Crops	Flax Fibre and Tow
134	Primary Crops	Hemp Fibre and Tow
135	Primary Crops	Abaca
136	Primary Crops	Agave Fibres nes
137	Primary Crops	Coir
138	Primary Crops	Fibre Crops nes
139	Primary Crops	Ramie
140	Primary Crops	Sisal
141	Primary Crops	Kapok Fibre
142	Primary Crops	Jute and Jute-like Fibres
143	Primary Crops	Other Bastfibres
144	Primary Crops	Anise, Badian, Fennel
145	Primary Crops	Chicory Roots
146	Primary Crops	Coffee, Green
147	Primary Crops	Hops
148	Primary Crops	Peppermint
149	Primary Crops	Pyrethrum, Dried Flowers

Table A.7: List of used material categories in EXIOBASE v3.4

No.	Group	Material category
150	Primary Crops	Tea
151	Primary Crops	Spices nec
152	Primary Crops	Cocoa Beans
153	Primary Crops	Mate
154	Primary Crops	Tobacco Leaves
155	Primary Crops	Natural Rubber
156	Primary Crops	Cinnamon
157	Primary Crops	Cloves
158	Primary Crops	Ginger
159	Primary Crops	Nutmeg, mace and cardamoms
160	Primary Crops	Vanilla
161	Primary Crops	Pepper
162	Primary Crops	Chillies and peppers, dry
163	Primary Crops	Tea nes
164	Primary Crops	Honey
165	Primary Crops	Beeswax
166	Primary Crops	Kapokseed in Shell
167	Crop residues	Straw
168	Crop residues	Feed
169	Fodder crops	Alfalfa for Forage and Silage
170	Fodder crops	Beets for Fodder
171	Fodder crops	Cabbage for Fodder
172	Fodder crops	Carrots for Fodder
173	Fodder crops	Clover for Forage and Silage
174	Fodder crops	Maize for Forage and Silage
175	Fodder crops	Other grasses
176	Fodder crops	Rye Grass, Forage and Silage
177	Fodder crops	Sorghum for Forage and Silage
178	Fodder crops	Swedes for Fodder
179	Fodder crops	Turnips for Fodder
180	Fodder crops	Vegetables and Roots, Fodder
181	Fodder crops	Forage Products nec
182	Fodder crops	Grasses nec for Forage and Silage
183	Fodder crops	Leguminous nec for forage and Silage
184	Fodder crops	Green Oilseeds for Fodder
185	Fodder crops	Grazing
186	Forestry	Coniferous wood - Industrial roundwood
187	Forestry	Coniferous wood - Wood fuel
188	Forestry	Non-coniferous wood - Industrial roundwood
189	Forestry	Non-coniferous wood - Wood fuel
190	Forestry	Raw materials other than wood
191	Forestry	Kapok Fruit
192	Forestry	Natural Gums
193	Fishery	Aquatic plants
194	Fishery	Marine fish catch
195	Fishery	Inland waters fish catch
196	Fishery	Other (e.g. Aquatic mammals)

Table A.7: List of used material categories in EXIOBASE v3.4

No.	Group	Material category
197	Metal Ores	Uranium and thorium ores
198	Metal Ores	Iron ores
199	Metal Ores	Copper ores
200	Metal Ores	Nickel ores
201	Metal Ores	Bauxite and aluminium ores
202	Metal Ores	Gold ores
203	Metal Ores	PGM ores
204	Metal Ores	Silver ores
205	Metal Ores	Lead ores
206	Metal Ores	Tin ores
207	Metal Ores	Zinc ores
208	Metal Ores	Other non-ferrous metal ores
209	Non-Metallic Minerals	Other minerals
210	Non-Metallic Minerals	Limestone, gypsum, chalk, dolomite
211	Non-Metallic Minerals	Slate
212	Non-Metallic Minerals	Building stones
213	Non-Metallic Minerals	Clays and kaolin
214	Non-Metallic Minerals	Gravel and sand
215	Non-Metallic Minerals	Salt
216	Non-Metallic Minerals	Chemical and fertilizer minerals
217	Fossil Fuels	Total

Table A.8: List of product categories in EXIOBASE v3.4

No.	Product category
p01.a	Paddy rice
p01.b	Wheat
p01.c	Cereal grains nec
p01.d	Vegetables, fruit, nuts
p01.e	Oil seeds
p01.f	Sugar cane, sugar beet
p01.g	Plant-based fibers
p01.h	Crops nec
p01.i	Cattle
p01.j	Pigs
p01.k	Poultry
p01.l	Meat animals nec
p01.m	Animal products nec
p01.n	Raw milk
p01.o	Wool, silk-worm cocoons
p01.w.1	Manure (conventional treatment)
p01.w.2	Manure (biogas treatment)
p02	Products of forestry, logging and related services
p05	Fish and other fishing products; services incidental of fishing

Table A.8: List of product categories in EXIOBASE v3.4

No.	Product category
p10.a	Anthracite
p10.b	Coking Coal
p10.c	Other Bituminous Coal
p10.d	Sub-Bituminous Coal
p10.e	Patent Fuel
p10.f	Lignite/Brown Coal
p10.g	BKB/Peat Briquettes
p10.h	Peat
p11.a	Crude petroleum and services related to crude oil extraction, excluding surveying
p11.b	Natural gas and services related to natural gas extraction, excluding surveying
p11.b.1	Natural Gas Liquids
p11.c	Other Hydrocarbons
p12	Uranium and thorium ores
p13.1	Iron ores
p13.20.11	Copper ores and concentrates
p13.20.12	Nickel ores and concentrates
p13.20.13	Aluminium ores and concentrates
p13.20.14	Precious metal ores and concentrates
p13.20.15	Lead, zinc and tin ores and concentrates
p13.20.16	Other non-ferrous metal ores and concentrates
p14.1	Stone
p14.2	Sand and clay
p14.3	Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.
p15.a	Products of meat cattle
p15.b	Products of meat pigs
p15.c	Products of meat poultry
p15.d	Meat products nec
p15.e	products of Vegetable oils and fats
p15.f	Dairy products
p15.g	Processed rice
p15.h	Sugar
p15.i	Food products nec
p15.j	Beverages
p15.k	Fish products
p16	Tobacco products
p17	Textiles
p18	Wearing apparel; furs
p19	Leather and leather products
p20	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials
p20.w	Wood material for treatment, Re-processing of secondary wood material into new wood material
p21.1	Pulp
p21.w.1	Secondary paper for treatment, Re-processing of secondary paper into new pulp
p21.2	Paper and paper products
p22	Printed matter and recorded media
p23.1.a	Coke Oven Coke

Table A.8: List of product categories in EXIOBASE v3.4

No.	Product category
p23.1.b	Gas Coke
p23.1.c	Coal Tar
p23.20.a	Motor Gasoline
p23.20.b	Aviation Gasoline
p23.20.c	Gasoline Type Jet Fuel
p23.20.d	Kerosene Type Jet Fuel
p23.20.e	Kerosene
p23.20.f	Gas/Diesel Oil
p23.20.g	Heavy Fuel Oil
p23.20.h	Refinery Gas
p23.20.i	Liquefied Petroleum Gases (LPG)
p23.20.j	Refinery Feedstocks
p23.20.k	Ethane
p23.20.l	Naphtha
p23.20.m	White Spirit & SBP
p23.20.n	Lubricants
p23.20.o	Bitumen
p23.20.p	Paraffin Waxes
p23.20.q	Petroleum Coke
p23.20.r	Non-specified Petroleum Products
p23.3	Nuclear fuel
p24.a	Plastics, basic
p24.a.w	Secondary plastic for treatment, Re-processing of secondary plastic into new plastic
p24.b	N-fertiliser
p24.c	P- and other fertiliser
p24.d	Chemicals nec
p24.e	Charcoal
p24.f	Additives/Blending Components
p24.g	Biogasoline
p24.h	Biodiesels
p24.i	Other Liquid Biofuels
p25	Rubber and plastic products
p26.a	Glass and glass products
p26.w.1	Secondary glass for treatment, Re-processing of secondary glass into new glass
p26.b	Ceramic goods
p26.c	Bricks, tiles and construction products, in baked clay
p26.d	Cement, lime and plaster
p26.d.w	Ash for treatment, Re-processing of ash into clinker
p26.e	Other non-metallic mineral products
p27.a	Basic iron and steel and of ferro-alloys and first products thereof
p27.a.w	Secondary steel for treatment, Re-processing of secondary steel into new steel
p27.41	Precious metals
p27.41.w	Secondary preciuos metals for treatment, Re-processing of secondary preciuos metals into new preciuos metals
p27.42	Aluminium and aluminium products
p27.42.w	Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium

Table A.8: List of product categories in EXIOBASE v3.4

No.	Product category
p27.43	Lead, zinc and tin and products thereof
p27.43.w	Secondary lead for treatment, Re-processing of secondary lead into new lead
p27.44	Copper products
p27.44.w	Secondary copper for treatment, Re-processing of secondary copper into new copper
p27.45	Other non-ferrous metal products
p27.45.w	Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
p27.5	Foundry work services
p28	Fabricated metal products, except machinery and equipment
p29	Machinery and equipment n.e.c.
p30	Office machinery and computers
p31	Electrical machinery and apparatus n.e.c.
p32	Radio, television and communication equipment and apparatus
p33	Medical, precision and optical instruments, watches and clocks
p34	Motor vehicles, trailers and semi-trailers
p35	Other transport equipment
p36	Furniture; other manufactured goods n.e.c.
p37	Secondary raw materials
p37.w.1	Bottles for treatment, Recycling of bottles by direct reuse
p40.11.a	Electricity by coal
p40.11.b	Electricity by gas
p40.11.c	Electricity by nuclear
p40.11.d	Electricity by hydro
p40.11.e	Electricity by wind
p40.11.f	Electricity by petroleum and other oil derivatives
p40.11.g	Electricity by biomass and waste
p40.11.h	Electricity by solar photovoltaic
p40.11.i	Electricity by solar thermal
p40.11.j	Electricity by tide, wave, ocean
p40.11.k	Electricity by Geothermal
p40.11.l	Electricity nec
p40.12	Transmission services of electricity
p40.13	Distribution and trade services of electricity
p40.2.a	Coke oven gas
p40.2.b	Blast Furnace Gas
p40.2.c	Oxygen Steel Furnace Gas
p40.2.d	Gas Works Gas
p40.2.e	Biogas
p40.2.1	Distribution services of gaseous fuels through mains
p40.3	Steam and hot water supply services
p41	Collected and purified water, distribution services of water
p45	Construction work
p45.w	Secondary construction material for treatment, Re-processing of secondary construction material into aggregates
p50.a	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries
p50.b	Retail trade services of motor fuel

Table A.8: List of product categories in EXIOBASE v3.4

No.	Product category
p51	Wholesale trade and commission trade services, except of motor vehicles and motorcycles
p52	Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods
p55	Hotel and restaurant services
p60.1	Railway transportation services
p60.2	Other land transportation services
p60.3	Transportation services via pipelines
p61.1	Sea and coastal water transportation services
p61.2	Inland water transportation services
p62	Air transport services
p63	Supporting and auxiliary transport services; travel agency services
p64	Post and telecommunication services
p65	Financial intermediation services, except insurance and pension funding services
p66	Insurance and pension funding services, except compulsory social security services
p67	Services auxiliary to financial intermediation
p70	Real estate services
p71	Renting services of machinery and equipment without operator and of personal and household goods
p72	Computer and related services
p73	Research and development services
p74	Other business services
p75	Public administration and defence services; compulsory social security services
p80	Education services
p85	Health and social work services
p90.1.a	Food waste for treatment: incineration
p90.1.b	Paper waste for treatment: incineration
p90.1.c	Plastic waste for treatment: incineration
p90.1.d	Intert/metal waste for treatment: incineration
p90.1.e	Textiles waste for treatment: incineration
p90.1.f	Wood waste for treatment: incineration
p90.1.g	Oil/hazardous waste for treatment: incineration
p90.2.a	Food waste for treatment: biogasification and land application
p90.2.b	Paper waste for treatment: biogasification and land application
p90.2.c	Sewage sludge for treatment: biogasification and land application
p90.3.a	Food waste for treatment: composting and land application
p90.3.b	Paper and wood waste for treatment: composting and land application
p90.4.a	Food waste for treatment: waste water treatment
p90.4.b	Other waste for treatment: waste water treatment
p90.5.a	Food waste for treatment: landfill
p90.5.b	Paper for treatment: landfill
p90.5.c	Plastic waste for treatment: landfill
p90.5.d	Inert/metal/hazardous waste for treatment: landfill
p90.5.e	Textiles waste for treatment: landfill
p90.5.f	Wood waste for treatment: landfill
p91	Membership organisation services n.e.c.
p92	Recreational, cultural and sporting services

Table A.8: List of product categories in EXIOBASE v3.4

No.	Product category
p93	Other services
p95	Private households with employed persons
p99	Extra-territorial organizations and bodies

A.9 Conversion tables

Table A.9: Conversion from WZ 2008/CPA sector classification to generic end-use categories of SFA model

	20	**24.4**	**25**	**26**	**27**	**28**	**29**	**30**	**43**
Plumbing	0	0	0.09	0	0.15	0.33	0	0	0
Building plant	0	0	0	0	0	0.01	0	0	0
Architecture	0	0	0	0	0	0	0	0	0.08
Communications	0	0	0	0	0.05	0	0	0	0
Electrical power	0	0	0	0	0	0	0	0	0.92
Power utility	0	0	0	0	0.28	0	0	0	0
Telecommunications use	0	0	0	0.55	0	0	0	0	0
Electrical industrial	0	0	0	0	0.22	0.06	0	0	0
Non electrical industrial	0	0	0	0	0	0.43	0	0	0
Electrical automotive	0	0	0	0	0	0.02	0.97	0.02	0
Non Electrical Automotive	0	0	0.03	0	0	0	0.03	0	0
Other Transport	0	0	0.01	0.07	0	0	0	0.98	0
Consumer products	0	0	0.09	0.13	0.20	0.05	0	0	0
Cooling	0	0	0	0	0.08	0.10	0	0	0
Electronic use	0	0	0	0.26	0.01	0.00	0	0	0
Diverse	1	1	0.78	0	0.01	0	0	0	0

Table A.10: Sector conversion from WZ 2003 to WZ 2008 – Part 1

	1	2	3	5	6	7-9	10-12	13-15	16	17	18	19	20	21	22	23.1	23.2-23.9	24.1-24.3	24.4	24.5	25	26	27	28	29	30	31-32	33	35.1, 35.3	35.2	36	37-39	41	42	43	45
01	0.78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0.99	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0.48	0.52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15.1-15.8	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15.9	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0.96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0	0	0	0	0	0	0	0
21.1	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21.2	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.2-22.3	0	0	0	0	0	0	0	0	0	0	0.61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0
25.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26.2-26.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27.1-27.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.91	0	0	0	0.09	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.60	0	0	0	0	0.40	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.99	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
40.1, 40.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0
40.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
45.1-45.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.49	0.27	0.24	0
45.3-45.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.91
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60.2-60.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08	0	0	0
71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
73	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75.1-75.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.87	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.11: Sector conversion from WZ 2003 to WZ 2008 – Part 2

	46	47	49	50	51	52	53	55-56	58	59-60	61	62-63	64	65	66	68	69-70	71	72	73	74-75	77	78	79	80-82	84.1-84.2	84.3	85	86	87-88	90-92	93	94	95	96	97-98
01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.22	0	0	0	0	0	0	0	0	0	0	0
02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15.1-15.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.1	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.2-22.3	0	0	0	0	0	0	0	0	0.39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26.2-26.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27.1-27.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40.1, 40.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.1-45.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.3-45.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0.02	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60.1	0	0	0.95	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60.2-60.3	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0.91	0	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0.78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.09	0	0	0.08	0	0	0	0.05	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0.68	0	0	0	0.32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.70	0	0	0	0	0	0	0	0	0.22	0	0	0	0	0	0	0	0	0	0	0
71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	0	0	0	0	0	0	0	0	0.16	0	0	0.84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
73	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0.30	0.18	0	0.08	0.04	0	0.05	0	0.32	0	0	0	0	0	0	0	0	0	0	0
75.1-75.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0
75.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0.90	0.09	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0
92	0	0	0	0	0	0	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0.10	0	0	0	0	0	0	0.54	0.31	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0
95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00

Table A.12: Sector conversion from EXIOBASE v3.4 (based on NACE Rev. 1.1) to WZ 2008 (based on NACE Rev. 2) – Part 1, entries not portrayed in parts 1-4 have the value 0

No.	Sector	1	2	3	5	6	7-9	10-12	13-15	16	17	18	19	20	21	22	23.1	23.2-23.9	...	33	...	58
1	Paddy rice	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Wheat	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Cereal grains nec	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Vegetables, fruit, nuts	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Oil seeds	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Sugar cane, sugar beet	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Plant-based fibers	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Crops nec	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Cattle	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Pigs	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Poultry	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Meat animals nec	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Animal products nec	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Raw milk	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Wool, silk-worm cocoons	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Manure (conventional treatment)	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
1	Manure (biogas treatment)	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
2	Products of forestry, logging and related services	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
3	Fish and other fishing products; services incidental of fishing	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
5	Anthracite	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
5	Coking Coal	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
5	Other Bituminous Coal	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
5	Sub-Bituminous Coal	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
5	Patent Fuel	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
5	Lignite/Brown Coal	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
5	BKB/Peat Briquettes	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
5	Peat	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
6	Crude petroleum and services related to crude oil extraction	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
6	Natural gas and services related to natural gas extraction	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
6	Natural Gas Liquids	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
6	Other Hydrocarbons	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
7	Uranium and thorium ores	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
7	Iron ores	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
7	Copper ores and concentrates	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
7	Nickel ores and concentrates	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
7	Aluminium ores and concentrates	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
7	Precious metal ores and concentrates	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
7	Lead, zinc and tin ores and concentrates	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
7	Other non-ferrous metal ores and concentrates	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
8	Stone	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
8	Sand and clay	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
8	Chemical and fertilizer minerals, salt and other mining and quarrying products	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Products of meat cattle	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Products of meat pigs	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Products of meat poultry	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Meat products nec	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	products of Vegetable oils and fats	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Dairy products	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Processed rice	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Sugar	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Food products nec	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Beverages	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
10	Fish products	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
12	Tobacco products	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	...	0	...	0
13	Textiles	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	...	0	...	0
14	Wearing apparel; furs	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	...	0	...	0
15	Leather and leather products	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	...	0	...	0
16	Wood and products of wood and cork (except furniture); articles of straw	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	...	0	...	0
16	Wood material for treatment, Re-processing	0	0	0	0	0	0	0	0	0.96	0	0	0	0	0	0	0	0	...	0.04	...	0
17	Pulp	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	...	0	...	0
17	Secondary paper for treatment, Re-processing of secondary paper into new pulp	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	...	0	...	0
17	Paper and paper products	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	...	0	...	0
18/58	Printed matter and recorded media	0	0	0	0	0	0	0	0	0	0	0.61	0	0	0	0	0	0	...	0	...	0.39
19	Coke Oven Coke	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Gas Coke	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Coal Tar	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Motor Gasoline	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Aviation Gasoline	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Gasoline Type Jet Fuel	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Kerosene Type Jet Fuel	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Kerosene	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Gas/Diesel Oil	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Heavy Fuel Oil	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Refinery Gas	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Liquefied Petroleum Gases (LPG)	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Refinery Feedstocks	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Ethane	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Naphtha	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	White Spirit & SBP	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Lubricants	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Bitumen	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Paraffin Waxes	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Petroleum Coke	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Non-specified Petroleum Products	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
19	Nuclear fuel	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	...	0	...	0
20	Plastics, basic	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	...	0	...	0
20	Secondary plastic for treatment, Re-processing of secondary plastic into new plastic	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	...	0	...	0
20	N-fertiliser	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	...	0	...	0
20	P- and other fertiliser	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	...	0	...	0
21	Chemicals nec	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	...	0	...	0
20	Charcoal	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	...	0	...	0
20	Additives/Blending Components	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	...	0	...	0
20	Biogasoline	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	...	0	...	0
20	Biodiesels	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	...	0	...	0
20	Other Liquid Biofuels	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	...	0	...	0
22	Rubber and plastic products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	...	0	...	0
23.1	Glass and glass products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	...	0	...	0
23.1	Secondary glass for treatment, Re-processing of secondary glass into new glass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	...	0	...	0
23.2	Ceramic goods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	...	0	...	0
23.2	Bricks, tiles and construction products, in baked clay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	...	0	...	0

Table A.13: Sector conversion from EXIOBASE v3.4 (based on NACE Rev. 1.1) to WZ 2008 (based on NACE Rev. 2) – Part 2

No.	Sector	...	23.2-23.9	24.1-24.3	24.4	24.5	25	26	27	28	29	30	31-32	33	35.1, 35.3	35.2	36	37-39	41	42
23.2	Cement, lime and plaster	...	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23.2	Ash for treatment, Re-processing of ash into clinker	...	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23.2	Other non-metallic mineral products	...	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Basic iron and steel and of ferro-alloys and first products thereof	...	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Secondary steel for treatment, Re-processing of secondary steel into new steel	...	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Precious metals	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary preciuos metals for treatment, Re-processing	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Aluminium and aluminium products	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary aluminium for treatment, Re-processing	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Lead, zinc and tin and products thereof	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary lead for treatment, Re-processing of secondary lead into new lead	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Copper products	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary copper for treatment, Re-processing of secondary copper into new copper	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Other non-ferrous metal products	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary other non-ferrous metals for treatment, Re-processing	...	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.5	Foundry work services	...	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Fabricated metal products, except machinery and equipment	...	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0
28	Machinery and equipment n.e.c.	...	0	0	0	0	0	0	0	0.91	0	0	0	0.09	0	0	0	0	0	0
26	Office machinery and computers	...	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0
27	Electrical machinery and apparatus n.e.c.	...	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0
26/95	Radio, television and communication equipment and apparatus	...	0	0	0	0	0	0.95	0	0	0	0	0	0	0	0	0	0	0	0
26/31-33	Medical, precision and optical instruments, watches and clocks	...	0	0	0	0	0	0.60	0	0	0	0	0.40	0	0	0	0	0	0	0
29/95	Motor vehicles, trailers and semi-trailers	...	0	0	0	0	0	0	0	0	0.99	0	0	0	0	0	0	0	0	0
30	Other transport equipment	...	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0
31-32	Furniture; other manufactured goods n.e.c.	...	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0
38	Secondary raw materials	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
38	Bottles for treatment, Recycling of bottles by direct reuse	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
35.1	Electricity by coal	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by gas	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by nuclear	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by hydro	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by wind	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by petroleum and other oil derivatives	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by biomass and waste	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by solar photovoltaic	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by solar thermal	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by tide, wave, ocean	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity by Geothermal	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Electricity nec	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Transmission services of electricity	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.1	Distribution and trade services of electricity	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
35.2	Coke oven gas	...	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
35.2	Blast Furnace Gas	...	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
35.2	Oxygen Steel Furnace Gas	...	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
35.2	Gas Works Gas	...	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
35.2	Biogas	...	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
35.2	Distribution services of gaseous fuels through mains	...	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
35.3	Steam and hot water supply services	...	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
36	Collected and purified water, distribution services of water	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0
43	Construction work	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.20	0.11
43	Secondary construction material for treatment, Re-processing	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.20	0.11
45	Sale, maintenance, repair of motor vehicles and parts etc.	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	Retail trade services of motor fuel	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	Wholesale trade and commission trade services, except of motor vehicles	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	Retail trade services, except of motor vehicles and parts etc.	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	Hotel and restaurant services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	Railway transportation services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	Other land transportation services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	Transportation services via pipelines	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	Sea and coastal water transportation services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	Inland water transportation services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	Air transport services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	Supporting and auxiliary transport services; travel agency services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	Post and telecommunication services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
64	Financial intermediation services, except insurance and pension funding services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	Insurance and pension funding services, except compulsory social security services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	Services auxiliary to financial intermediation	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	Real estate services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08	0
77	Renting services of machinery and equipment without operator	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	Computer and related services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	Research and development services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	Other business services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	Public administration and defence services; compulsory social security services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	Education services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	Health and social work services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: incineration	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Paper waste for treatment: incineration	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Plastic waste for treatment: incineration	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Intert/metal waste for treatment: incineration	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Textiles waste for treatment: incineration	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Wood waste for treatment: incineration	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Oil/hazardous waste for treatment: incineration	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Food waste for treatment: biogasification and land application	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Paper waste for treatment: biogasification and land application	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Sewage sludge for treatment: biogasification and land application	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Food waste for treatment: composting and land application	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Paper and wood waste for treatment: composting and land application	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Food waste for treatment: waste water treatment	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Other waste for treatment: waste water treatment	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Food waste for treatment: landfill	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Paper for treatment: landfill	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Plastic waste for treatment: landfill	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Inert/metal/hazardous waste for treatment: landfill	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Textiles waste for treatment: landfill	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
37	Wood waste for treatment: landfill	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
94	Membership organisation services n.e.c.	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	Recreational, cultural and sporting services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	Other services	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	Private households with employed persons	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
99	Extra-territorial organizations and bodies	...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.14: Sector conversion from EXIOBASE v3.4 (based on NACE Rev. 1.1) to WZ 2008 (based on NACE Rev. 2) – Part 3

No.	Sector	43	45	46	47	49	50	51	52	53	55-56	58	59-60	61	62-63	64	65	66	68	69-70
23.2	Cement, lime and plaster	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23.2	Ash for treatment, Re-processing of ash into clinker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23.2	Other non-metallic mineral products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Basic iron and steel and of ferro-alloys and first products thereof	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Secondary steel for treatment, Re-processing of secondary steel into new steel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Precious metals	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary preciuos metals for treatment, Re-processing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Aluminium and aluminium products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary aluminium for treatment, Re-processing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Lead, zinc and tin and products thereof	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary lead for treatment, Re-processing of secondary lead into new lead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Copper products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary copper for treatment, Re-processing of secondary copper into new copper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Other non-ferrous metal products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary other non-ferrous metals for treatment, Re-processing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.5	Foundry work services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Fabricated metal products, except machinery and equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	Machinery and equipment n.e.c.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Office machinery and computers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Electrical machinery and apparatus n.e.c.	0	0	0	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26/95	Radio, television and communication equipment and apparatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26/31-33	Medical, precision and optical instruments, watches and clocks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29/95	Motor vehicles, trailers and semi-trailers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	Other transport equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31-32	Furniture; other manufactured goods n.e.c.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	Secondary raw materials	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	Bottles for treatment, Recycling of bottles by direct reuse	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by coal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by nuclear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by hydro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by petroleum and other oil derivatives	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by biomass and waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by solar photovoltaic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by solar thermal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by tide, wave, ocean	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by Geothermal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity nec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Transmission services of electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Distribution and trade services of electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Coke oven gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Blast Furnace Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Oxygen Steel Furnace Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Gas Works Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Biogas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Distribution services of gaseous fuels through mains	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.3	Steam and hot water supply services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	Collected and purified water, distribution services of water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	Construction work	0.69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	Secondary construction material for treatment, Re-processing	0.69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	Sale, maintenance, repair of motor vehicles and parts etc.	0	0.91	0	0.02	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0
45	Retail trade services of motor fuel	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	Wholesale trade and commission trade services, except of motor vehicles	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	Retail trade services, except of motor vehicles and parts etc.	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	Hotel and restaurant services	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0
49	Railway transportation services	0	0	0	0	0.95	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0
49	Other land transportation services	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	Transportation services via pipelines	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	Sea and coastal water transportation services	0	0	0	0	0	0.91	0	0.09	0	0	0	0	0	0	0	0	0	0	0
50	Inland water transportation services	0	0	0	0	0	0.91	0	0.09	0	0	0	0	0	0	0	0	0	0	0
51	Air transport services	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0
52	Supporting and auxiliary transport services; travel agency services	0	0	0	0	0	0	0	0.78	0	0	0	0	0	0	0	0	0	0	0
53	Post and telecommunication services	0	0	0	0	0	0	0	0	0.68	0	0	0	0.32	0	0	0	0	0	0
64	Financial intermediation services, except insurance and pension funding services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
65	Insurance and pension funding services, except compulsory social security services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0
66	Services auxiliary to financial intermediation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
68	Real estate services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.70	0
77	Renting services of machinery and equipment without operator	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	Computer and related services	0	0	0	0	0	0	0	0	0	0	0.16	0	0	0.84	0	0	0	0	0
72	Research and development services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	Other business services	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0.30
84	Public administration and defence services; compulsory social security services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	Education services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	Health and social work services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Paper waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Plastic waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Intert/metal waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Textiles waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Wood waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Oil/hazardous waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: biogasification and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Paper waste for treatment: biogasification and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Sewage sludge for treatment: biogasification and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: composting and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Paper and wood waste for treatment: composting and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: waste water treatment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Other waste for treatment: waste water treatment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Paper for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Plastic waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Inert/metal/hazardous waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Textiles waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Wood waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	Membership organisation services n.e.c.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	Recreational, cultural and sporting services	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0	0	0	0	0	0
96	Other services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	Private households with employed persons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
99	Extra-territorial organizations and bodies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.15: Sector conversion from EXIOBASE v3.4 (based on NACE Rev. 1.1) to WZ 2008 (based on NACE Rev. 2) – Part 4

No.	Sector	71	72	73	74-75	77	78	79	80-82	84.1-84.2	84.3	85	86	87-88	90-92	93	94	95	96	97-98
23.2	Cement, lime and plaster	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23.2	Ash for treatment, Re-processing of ash into clinker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23.2	Other non-metallic mineral products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Basic iron and steel and of ferro-alloys and first products thereof	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Secondary steel for treatment, Re-processing of secondary steel into new steel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Precious metals	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary preciuos metals for treatment, Re-processing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Aluminium and aluminium products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary aluminium for treatment, Re-processing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Lead, zinc and tin and products thereof	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary lead for treatment, Re-processing of secondary lead into new lead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Copper products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary copper for treatment, Re-processing of secondary copper into new copper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Other non-ferrous metal products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.4	Secondary other non-ferrous metals for treatment, Re-processing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.5	Foundry work services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Fabricated metal products, except machinery and equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	Machinery and equipment n.e.c.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Office machinery and computers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Electrical machinery and apparatus n.e.c.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26/95	Radio, television and communication equipment and apparatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0
26/31-33	Medical, precision and optical instruments, watches and clocks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29/95	Motor vehicles, trailers and semi-trailers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0
30	Other transport equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31-32	Furniture; other manufactured goods n.e.c.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	Secondary raw materials	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	Bottles for treatment, Recycling of bottles by direct reuse	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by coal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by nuclear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by hydro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by petroleum and other oil derivatives	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by biomass and waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by solar photovoltaic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by solar thermal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by tide, wave, ocean	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity by Geothermal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Electricity nec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Transmission services of electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.1	Distribution and trade services of electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Coke oven gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Blast Furnace Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Oxygen Steel Furnace Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Gas Works Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Biogas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.2	Distribution services of gaseous fuels through mains	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35.3	Steam and hot water supply services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	Collected and purified water, distribution services of water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	Construction work	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	Secondary construction material for treatment, Re-processing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	Sale, maintenance, repair of motor vehicles and parts etc.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	Retail trade services of motor fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	Wholesale trade and commission trade services, except of motor vehicles	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	Retail trade services, except of motor vehicles and parts etc.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	Hotel and restaurant services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	Railway transportation services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	Other land transportation services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	Transportation services via pipelines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	Sea and coastal water transportation services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	Inland water transportation services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	Air transport services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	Supporting and auxiliary transport services; travel agency services	0	0	0	0.09	0	0	0.08	0	0	0	0.05	0	0	0	0	0	0	0	0
53	Post and telecommunication services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
64	Financial intermediation services, except insurance and pension funding services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	Insurance and pension funding services, except compulsory social security services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	Services auxiliary to financial intermediation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	Real estate services	0	0	0	0	0	0	0	0.22	0	0	0	0	0	0	0	0	0	0	0
77	Renting services of machinery and equipment without operator	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	Computer and related services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	Research and development services	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	Other business services	0.18	0	0.08	0.04	0	0.05	0	0.32	0	0	0	0	0	0	0	0	0	0	0
84	Public administration and defence services; compulsory social security services	0	0	0	0	0	0	0	0	0.86	0.14	0	0	0	0	0	0	0	0	0
85	Education services	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0
86	Health and social work services	0	0	0	0.01	0	0	0	0	0	0	0	0.90	0.09	0	0	0	0	0	0
37	Food waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Paper waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Plastic waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Intert/metal waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Textiles waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Wood waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Oil/hazardous waste for treatment: incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: biogasification and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Paper waste for treatment: biogasification and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Sewage sludge for treatment: biogasification and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: composting and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Paper and wood waste for treatment: composting and land application	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: waste water treatment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Other waste for treatment: waste water treatment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Food waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Paper for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Plastic waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Inert/metal/hazardous waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Textiles waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Wood waste for treatment: landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	Membership organisation services n.e.c.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0
93	Recreational, cultural and sporting services	0	0	0	0	0	0	0.10	0	0	0	0	0	0	0.54	0.31	0	0	0	0
96	Other services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0
97	Private households with employed persons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00
99	Extra-territorial organizations and bodies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Over the past century, global material use has increased by a factor of eight and is now mainly fueled by non-renewable sources. This is accompanied by many environmental and social issues, including the declining availability of raw materials for future generations. In order to address these issues, it is necessary to know which activities in society are the main drivers of material use and what steps could be taken towards a dematerialization of the economy without hampering its performance. In this thesis, model-based analyses are conducted for the case of Germany to determine its overall material demand in the recent past and the underlying drivers of this demand. Subsequently, prospective simulations are run in order to assess the potential impacts of hypothetical material efficiency measures on Germany's material demand and its economy, as well as on the development of material fixated in anthropogenic stocks. The analyses show that while trade-offs within and between individual efficiency measures have to be taken into account, they can be a major contributor to making Germany's and other economies more sustainable.

ISBN 978-3-8396-1588-1