COMPETITIVENESS AND CLIMATE CHANGE MITIGATION

Empirical Evidence on the Effects of Material Use and Material Productivity on Competitiveness and Greenhouse Gas Emissions in Europe

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A thesis submitted for the degree of

Doctor of Philosophy in Sustainable Resources and Economics

December 2017

Declaration

I, Florian Flachenecker, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis. Please refer to the List of Publications for details on work done in collaboration.

This thesis is 86,050 words in length (excluding bibliography and the Annex) and thus in line with the University College London Guidelines and Academic Regulations for PhD examinations.

[redacted]

Florian Flachenecker

13 December 2017

Date

Abstract

Aligning competitiveness with climate change mitigation objectives lies at the heart of contemporary discourses on sustainable development, resource efficiency, green growth, and the circular economy. While numerous scholars and policymakers, particularly in Europe, follow the notion that decreasing material use and increasing material productivity can boost competitiveness and help to mitigate climate change, the empirical evidence underlying this assertion has put little emphasis on two important issues. First, many studies predominantly rely on case studies, often not considering dynamic effects and heterogeneity across firms, sectors, countries, material subgroups, and material indicators. Second, the majority of investigations do not address the potential problem of endogeneity in empirical models. This dissertation attempts to shift the focus on these and other issues having received relatively little scrutiny in the existing literature by four interrelated analyses on European economies and firms. First, the effect of material use on greenhouse gas (GHG) emissions is empirically assessed, finding a robust and positive link mostly driven by fossil fuel use. Second, it is investigated whether economic growth is a driver of material use, suggesting that economic growth causes an increase in material use for Western European countries. Third, the effects of material productivity on indicators of macroeconomic competitiveness and GHG emissions are investigated, finding little evidence for any statically significant link, except of increased average wages and improvements in the current account. Fourth, the effects of eco-innovation induced material productivity increases on microeconomic competitiveness and firm level GHG emissions are studied, providing evidence that material productivity increases microeconomic competitiveness and reduces GHG emissions. However, these effects are heterogeneously distributed across sectors and countries. Overall, this dissertation draws a nuanced picture by providing new evidence that material use and material productivity can support competitiveness and climate change mitigation objectives, but such benefits are likely to be unequally distributed across firms, sectors, and countries. To this end, the results provide important policy insights, including that weight-based material indicators are linked to GHG emissions, internalising externalities is essential, and eco-innovations can enable certain firms, sectors, and countries to grasp the benefits of material productivity improvements. Moreover, it is important to further investigate the implications of moving towards more material productive economies based on greater emphasis on heterogeneity, endogeneity, and improved data.

Acknowledgments

First of all, I am extremely grateful to my primary supervisor, Raimund Bleischwitz, for all his advice and guidance throughout this dissertation project which would not have been possible without his support and encouragement.

Moreover, I would like to thank my secondary supervisor, Paolo Agnolucci, for his substantial comments, numerous discussions, and the motivation he spurred in me during crucial times. I also benefited greatly from the inspiration and knowledge of Paul Ekins (University College London).

Furthermore, I would like to thank Magnus Söderberg (University of Gothenburg) very much for his enthusiasm and advice which significantly improved the quality of this dissertation. Additionally, I would like to express my deepest gratitude to Jun Rentschler (University College London, World Bank) for the very many helpful discussions, detailed comments on an earlier draft of this dissertation, and the outstanding collaboration across several projects and articles.

Francesca Medda (UCL) and Julia Steinberger (University of Leeds) kindly agreed to examine this dissertation. Their very useful comments and the thought-provoking discussions during the Viva are gratefully acknowledged.

This dissertation additionally benefited from the discussions with Sandy Skelton (University of Cambridge), Frank Pothen (University of Hannover), Simone Cooper (University of Cambridge), Nigel Jollands (European Bank for Reconstruction and Development), Martin Kornejew (University of Kiel), Carel Cronenberg (European Bank for Reconstruction and Development), Stijn van Ewijk (University College London), Manfred Rosenstock (European Commission), Magnus Gislev (European Commission), Christoph Ernst (International Labour Organisation), Teresa Domenech (University College London), Michal Miedzinski (University College London), Stefan Moser (European Commission), Martin Hirschnitz-Garbers (Ecologic Institute), Birgit Schwenk (German Federal Ministry of the Environment), Irina Oswald (Apple), Erja Fagerlund (Finish Ministry of the Economy), Keith James (WRAP UK), Mohamed Sameh (European Investment Bank), Werner Bosmans (European Commission), Seyed Mehdi Mohaghegh (University College London), Victor Nechifor (University College London), and Michael von Hauff (University of Kaiserslautern).

The comments provided by the participants of the annual conference of the European Association of Environmental and Resource Economists in June 2017 in Athens, Greece, the Use Less Seminar of the University of Cambridge in January 2017 in Cambridge, United Kingdom, the European Bank for Reconstruction and Development Workshop on Investments in Resource Efficiency in December 2014 in London, United Kingdom, the Sino-European Circular Economy and Resource Efficiency (SINCERE) project seminars in October 2015 in Shanghai, China, and September 2016 in Paris, France, the Sustainable Use of Material Resources conference in March 2014 in Oskemen, Kazakhstan, the Minerals in the Circular Economy conference in November 2014 in Espoo, Finland, and the Aachen International Mining Symposium in Mai 2015 in Aachen, Germany, are all gratefully acknowledged.

I am thankful to the European Commission's Directorate-General Eurostat for providing the data of the Community Innovation Survey (research project proposal number 259/2014-CIS). Also, the European Central Bank kindly provided a rich data set featuring the Institutional Competitiveness Index. The results and conclusions are those of the authors and do not necessarily represent the official position of Eurostat, the European Commission, any of the national statistical authorities whose data have been used, or the European Central Bank.

I am also grateful to University College London Institute for Sustainable Resources for providing and organising a generous doctoral scholarship and research budget which enabled me to carry out this research. Additionally, I thank University College London Open Access for sponsoring open access fees for the publication of two research articles, thus making them available to a broader audience.

The views expressed in this dissertation are entirely my own and should not be attributed to any institution with which I am associated.

Last but certainly not least, the support, encouragement, and incredible patience of Lisa and my entire family throughout the years paved the way for successfully concluding this project.

List of publications

Journal publications

Flachenecker, Florian (2018). The causal impact of material productivity on macroeconomic competitiveness in the European Union. *Environmental Economics and Policy Studies* 20:1. 17-46.

Flachenecker, Florian*;* Bleischwitz, Raimund and Rentschler, Jun Erik (2017). Investments in Material Efficiency: The Introduction and Application of a Comprehensive Cost-Benefit Framework. *Journal of Environmental Economics and Policy* 6:2. 107-120.

Agnolucci, Paolo; ***Flachenecker, Florian*** and Söderberg, Magnus (2017). The causal impact of economic growth on material use in Europe. *Journal of Environmental Economics and Policy* 6:4. 415-432.

Rentschler, Jun Erik; Bleischwitz, Raimund and ***Flachenecker, Florian*** (2016). On Imperfect Competition and Market Distortions: The Causes of Corporate Under-Investment in Energy and Resource Efficiency. *International Economics and Economic Policy* [in print].

Submitted manuscripts

Flachenecker, Florian and Kornejew, Martin (under review). The causal impact of material productivity on competitiveness and environmental performance in the European Union – firm level evidence.

Rentschler, Jun Erik; ***Flachenecker, Florian*** and Kornejew, Martin (under review). Assessing carbon emission savings from corporate resource efficiency investments: theory and practice.

Book publications

Flachenecker, Florian and Rentschler, Jun Erik (contributing editors) (forthcoming). Investing in Resource Efficiency: The Economics and Politics of Financing the Resource Transition. *Featuring a preface by Ángel Gurría, Sectretary General OECD, and contributions by University College London, European Commission, European Investment Bank, and European Bank for Reconstruction and Development*. Springer International Publishing. Cham, Switzerland.

Bleischwitz, Raimund and ***Flachenecker, Florian*** (2017). Sustainable Resources: Managing Markets, Increasing Efficiency and Establishing Partnerships; in: von Hauff, Michael and Kuhnke, Claudia (eds). Sustainable Development Policy: A European Perspective. Routledge. Oxford, United Kingdom.

Report publications

Flachenecker, Florian and Rentschler, Jun Erik (2015). Investments in Resource Efficiency – Costs and Benefits, Investment Barriers and Intervention Measures. A Report prepared for the European Bank for Reconstruction and Development (EBRD). London: University College London, UK. [policy briefing]

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Conference proceedings

Flachenecker, Florian and Kornejew, Martin (2017). The causal impact of material productivity on competitiveness and environmental performance in the European Union – firm level evidence. 23rd Annual Conference of the European Association of Environmental and Resource Economists. 28 June – 01 July 2017, Athens, Greece.

Flachenecker, Florian and Rentschler, Jun Erik (2015). Investments in Resource Efficiency – An Analytical Assessment Framework and Review of Evidence, in *Aachen International Mining Symposia*. RWTH Aachen University. 27-28 May 2015, Aachen, Germany.

Rentschler, Jun Erik and ***Flachenecker, Florian*** (2014). Investments in Resource Efficiency – An Analytical Assessment Framework and Review of Evidence, in *Minerals in Circular Economy – Book of Abstracts*. VTT Technical Research Centre of Finland. First International Conference on Minerals in the Circular Economy, 26–27 November 2014, Espoo, Finland.

Media appearances

Flachenecker, Florian (2016). Crossing the divide – long held up leader in resource efficiency, the European Union is a work in progress. Commentary in *Corporate Waste Solutions*, Issue 2. Melbourne, Australia.

__**Work done in collaboration**__

Chapter	*Include work in collaboration from*	*Own contributions*
2.4	Rosenstock, Manfred and ***Flachenecker, Florian*** (forthcoming). Enabling Resource Efficiency Investments – A Review and Outlook of the Resource Efficiency Agenda of the European Union; in: ***Flachenecker, Florian*** and Rentschler, Jun Erik (contributing editors). Investing in Resource Efficiency: The Economics and Politics of Financing the Resource Transition. *Featuring a preface by Ángel Gurría, Secretary General OECD, and contributions by University College London, European Commission, European Investment Bank, and European Bank for Reconstruction and Development*. Springer International Publishing. Cham, Switzerland.	– Initiative for the chapter – Structuring the chapter – Drafting the chapter – Collecting evidence and reviewing the literature
4	***Flachenecker, Florian***; Bleischwitz, Raimund and Rentschler, Jun Erik (2017). Investments in Material Efficiency: The Introduction and Application of a Comprehensive Cost-Benefit Framework. *Journal of Environmental Economics and Policy* 6:2. 107-120.	– Fully independent research
6	Agnolucci, Paolo; ***Flachenecker, Florian*** and Söderberg, Magnus (2017). The causal impact of economic growth on material use in Europe. *Journal of Environmental Economics and Policy* 6:4. 415-432.	– Initiative for the paper – Data collection – Co-drafting of paper – Empirical analyses done in collaboration – Additional analyses on heterogeneity across countries, material subgroups, and material indicators
8	***Flachenecker, Florian*** and Kornejew, Martin (under review and presented at the EAERE annual conference 2017). The causal impact of material productivity on competitiveness and environmental performance in the European Union – firm level evidence.	– Writing proposal to Eurostat for accessing the survey data – Empirical analyses – Drafting the paper – Coming up with the conceptual idea behind the paper – Presenting the paper at the University of Cambridge and EAERE annual conference

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Chapter 1

Introduction

1 Introduction

"But our industrial system, at the end of its cycle of production and consumption, has not developed the capacity to absorb and reuse waste and by-products. We have not yet managed to adopt a circular model of production capable of preserving resources for present and future generations, while limiting as much as possible the use of non-renewable resources, moderating their consumption, maximizing their efficient use, reusing and recycling them. A serious consideration of this issue would be one way of counteracting the throwaway culture which affects the entire planet, but it must be said that only limited progress has been made in this regard." (Pope Francis 2015)

1.1 Background

Competitiveness and climate change mitigation – two crucial challenges of our time embedded within the broader context of sustainable development. A frequently debated question is whether competitiveness and climate change mitigation are mutually exclusive or in fact achievable simultaneously, thus enabling welfare creation while staying within the planetary boundaries of our ecosystems. By considering material use and material productivity, this dissertation attempts to empirically investigate the potential role of material resources in aligning competitiveness and climate change mitigation objectives, thereby complementing existing research by academics and international organisations (Bleischwitz and Steger 2009; Allwood et al. 2011; Steinberger and Krausmann 2011; Steger and Bleischwitz 2011; Barrett and Scott 2012; OECD 2016; UNEP IRP 2017).

Materials resources are usable and traded substances obtained or derived from natural resources and typically comprise biomass, minerals, metals, and fossil fuels (OECD 2007). As such, they are vital inputs to the economic system and welfare creation (O'Mahony and Timmer 2009), including for numerous low-carbon technologies (Allwood et al. 2011), and they are associated with environmental pressures across their life cycles, including greenhouse gas (GHG) emissions (UNEP IRP 2010a). Materials have both an economic as well as an environmental dimension which is reflected in this dissertation by focusing on the link between materials and competitiveness as well as GHG emissions.

Against this backdrop, the use and productivity of materials are factors determining competitiveness and the success of climate change mitigation efforts. The link between materials and competitiveness is often discussed in the context of developed and resource rich countries. This debate is particularly pronounced in Europe. The European Union (EU) considers materials not only as an environmental issue but also as an economic and strategic concern with regards to its competitiveness (EC 2008). By arguing that increased material productivity results in higher competitiveness, the EU motivates its resource efficiency and circular economy agenda, including the allocation of substantial investment capital to these policy areas (EC 2011a; EC 2011b; EBRD 2015a; EIB 2015). The combination between the relatively high availability of data and having made the use and productivity of materials an explicit policy and research domain, makes Europe an appropriate case to study.

Moreover, this thesis follows more recent discussions on the 'productivity puzzle', i.e. the fact that productivity growth across the developed world has essentially been stagnant since the Great Recession (Blundell et al. 2014; Patterson et al. 2016; Harris and Moffat 2017), by essentially studying the potential contribution of material productivity in compensating for the low levels of labour productivity growth, thereby fostering competitiveness.

The link between materials and climate change mitigation is reflected in discussions on resource efficiency and the circular economy (UNEP IRP 2011; EC 2011b; EC 2015a; OECD 2016). It is found that GHG emissions are directly or indirectly the result of material use across its life cycle (UNEP IRP 2010a). Accordingly, reducing the use of materials or increasing material productivity can reduce GHG emissions, thus contributing to mitigating climate change (Barrett and Scott 2012). Moreover, materials are explicitly or implicitly mentioned both as a cause and as part of a response to climate change in the Paris Agreement, the 17 Sustainable Development Goals (SGDs), and the Addis Ababa Action Agenda (UN 2015a; UN 2015b; UN 2015c).

Turning to the academic debate, some scholars argue that material use must decrease in absolute terms to mitigate climate change and achieve sustainability objectives (Allwood et al. 2010; Dahmus 2014; Akenji et al. 2016). These authors recognise the limitations of technological advancements to counterbalance an ever-increasing demand for materials, however, it remains unclear how the fundamental change to reduce material demand can be achieved in practice. Other scholars suggest to increase the productivity with which materials are converted into economic goods and services to generate welfare and improve competitiveness while mitigating climate change (Bleischwitz et al. 2010; Barrett and Scott 2012).

This dissertation predominantly attempts to contribute to the latter strand of the literature by focusing on two issues that have received relatively little attention but are argued to be relevant. First, the existing literature often relies on case studies, thus not taking dynamic effects and heterogeneity across firms, sectors, countries, material subgroups, and material indicators into account. Second, the vast majority of empirical studies do not adequately address the potential problem of endogeneity which could lead to biased and inconsistent estimates (Angrist and Pischke 2009).

To this end, this dissertation newly applies established empirical methods, thereby addressing the two (as well as other) limitations of the existing literature mentioned above. Hence, the aim of this dissertation is to shift the attention of the academic and policy debate on the importance of such limitations and inform about the newly gained insights from the empirical investigations. As such, the results of this dissertation can contribute to the discussions surrounding resource efficiency, circular economy, and – more broadly – sustainable development.

In short, the main aim of this thesis is to empirically investigate whether material use and material productivity can reconcile competitiveness and climate change mitigation objectives in Europe. Against this backdrop, combining the dissertation's individual parts allows making an overall assessment on the potential role of material use and material productivity in bringing together these two important topics. While this describes the overarching goal, thereby linking all chapters, numerous additional issues are being raised, discussed, and analysed throughout this thesis, the most important ones are summarised in the subsequent section.

1.2 Content summary

This dissertation attempts to contribute to the academic literature and policy debates on the effects of material use and material productivity on competitiveness and GHG emissions by addressing the following questions:

- What are the costs and benefits of reducing material use by investing in material productivity from an economic and environmental perspective taking externalities, secondary effects, and the cost of inaction into account?
- Is there a robust and statistically significant effect of material use (and its material subgroups) on GHG emissions in the EU, both in the short and long term?
- Is economic growth a driver of material use in Europe or has the link between economic growth and material use been broken?

- What are the effects of material productivity on macroeconomic competitiveness and GHG emissions on the country level in the EU?
- How does material productivity affect microeconomic competitiveness and GHG emissions on the firm level in the EU?

Accordingly, this dissertation investigates these questions by starting with an overview of materials (Chapter 2), how they are measured, their relationship to the environment, to the economy, and policymaking, with a particular focus on the EU. This overview is intended to clarify definitions, justify the scope of the subsequent analyses, and outline the reasons for choosing certain material indicators over others.

This overview is followed by an in-depth literature review of those bodies of the literature that are most related to the subsequent empirical analyses (Chapter 3), namely, the drivers of material use and productivity, material productivity and decoupling, and material productivity and competitiveness. The literature review intends to show the current knowledge, identify gaps and shortcomings in existing evidence base, and explain how this thesis attempts to address some of them.

To systematically discuss and analyse the existing literature that concludes that reducing material use or increasing material productivity can reconcile economic with environmental objectives, Chapter 4 analyses the costs and benefits of material productivity investments by introducing a comprehensive cost-benefit framework. This framework comprises several components by (i) comparing a business-as-usual scenario with a scenario of scaling up investments in material productivity, (ii) covering economic and environmental dimensions, and (iii) considering primary and secondary effects. To illustrate the framework's applicability in practice, it is matched to existing evidence from the literature, followed by an application of the framework to a firm level investment project financed by a multilateral development bank. The results suggest that the benefits of material productivity investments typically increase when externalities are internalised, the cost of inaction is considered, and non-monetary dimensions are additionally taken into account.

The empirical parts of the dissertation can be found in Chapters 5-8 and comprise the following four interrelated investigations, structured within two domains. Chapters 5 and 6 investigate the use of materials; Chapters 7 and 8 the productivity of materials and their role in reconciling competitiveness and climate change mitigation objectives in Europe. As mentioned previously, additional topics are being raised throughout the various chapters.

The use of materials

1) Interdisciplinary scholars have investigated the link between material use and GHG emissions. A connection between the use of materials comprising biomass, minerals, metals, and fossil fuels and GHG emissions appears evident at first sight. However, reductions in common material use indicators may not necessarily result in GHG emission reductions since changes in the composition of material use need to be accounted for as well. Parts of the existing literature try to mitigate this problem by complementing material with environmental data, expanding the scope of material use across its life cycle, or focusing on individual materials.

   However, two shortcomings remain present in the existing literature. First, it often does not distinguish between short and long term effects. Second, no empirical investigation exists on the macroeconomic level that takes the heterogeneity of countries, material subgroups, or material indicators into account. Chapter 5 addresses both limitations by considering the short and long term effects of domestic material consumption (DMC) on GHG emissions for 15 economies in the EU between 1995 and 2010.

   After applying a Koyck transformation, the dynamic model is estimated using a generalised methods of moments (GMM) approach, providing evidence for a positive effect of increases in DMC on GHG emissions in the short and long term. Disaggregating materials reveals that the results are mainly driven by the use of fossil fuels. Moreover, this chapter shows that country heterogeneity is important to consider in empirical investigations on the topic. Furthermore, heterogeneity across the DMC and raw material consumption (RMC) indicator is relevant as well, given that the effects are significantly different from each other.

2) Chapter 6 investigates whether economic growth drives material use in Europe. The existing literature and policymakers follow the notion that Europe, particularly Western Europe, has broken the link between economic growth and material use. To this end, this chapter identifies and addresses two major limitations in the existing literature. First, most studies do not address the heterogeneity across countries, material subgroups, and material indicators. Second, most studies do not take the endogeneity of economic growth into account.

Based on a panel data set of 32 European countries from 2000 to 2014, the causal impact of gross domestic product (GDP) on DMC is estimated applying an instrumental variable approach. It is argued that using the number of storm occurrences is a relevant and valid instrumentation strategy for GDP. The results provide new evidence that increasing the GDP growth rate causes the DMC growth rate to increase for Western Europe, whereas the effect is insignificant for the Eastern European economies and Europe as a whole. The results suggest large heterogeneity across countries, material subgroups, and material indicators. As such results partly question the current understanding of decoupling achievements, two explanations are offered that are consistent with these results.

The productivity of materials

1) Chapter 7 investigates whether increasing material productivity can improve the competitiveness of economies and support their climate change mitigation efforts; something that the majority of the existing literature suggests. However, the following three limitations in the literature are attempted to be addressed. First, most studies do not clarify the concept and measurement of macroeconomic competitiveness. Second, most investigations do not take the endogeneity of material productivity into account. Third, heterogeneity across countries or material indicators is mostly not considered. Addressing all three shortcomings, this chapter identifies six conventional macroeconomic indicators to approximate macroeconomic competitiveness. Moreover, using panel data of the EU's 28 member states between 2000-2014, the causal impact of material productivity on the six indicators is estimated, instrumenting material productivity with the number of deaths from disasters.

   The results provide evidence for a positive and causal impact of the material productivity growth rate on the wage growth rate and, with lower confidence, on the current account growth rate, while the remaining macroeconomic indicators are not significantly affected. Furthermore, there is no evidence that material productivity significantly affects GHG emissions. Additionally, heterogeneity across countries and material indicators is considered to be relevant.

   Overall, these results cannot support the notion that increasing material productivity improves macroeconomic competitiveness and reduces GHG emissions in the EU. Particularly the positive effect on the wage growth rate calls for considering possibilities to channel gains from increasing material productivity into alternatives to wage raises, for instance eco-innovations, to reduce the magnitude of potential rebound effects which could lead to an increase in GHG emissions.

2) While there appears to be limited evidence for a link between material productivity and competitiveness as well as GHG emissions on the macroeconomic level (Chapter 7), there might be heterogeneity across firms and sectors. Interdisciplinary scholars and policymakers in the EU have worked with the assumption that material productivity improves the competitiveness of firms while reducing GHG emissions.

   However, the current evidence base has two main shortcomings. First, most studies fail to provide evidence beyond case studies, thus not considering dynamic effects and heterogeneity across firms, sectors, and countries. Second, it does not take the endogeneity of material productivity into account. In Chapter 8, channels linking material productivity and microeconomic competitiveness are identified. Moreover, data from Eurostat's Community Innovation Survey is investigated comprising over 52,000 firms across 13 sectors and 12 EU member states using an instrumental variable approach. The availability of public financial support is used to instrument for material productivity.

   Interpreting the results in the spirit of the Local Average Treatment Effect (LATE), the findings provide evidence for a positive and causal impact of material productivity on microeconomic competitiveness for those firms that received targeted public financial support and realised an eco-innovation. These results are particularly strong in Eastern European countries and material-intensive sectors. Furthermore, it is shown that such material productivity improvements also reduce the firms' carbon dioxide footprint, thus achieving both competitiveness and climate change mitigation objectives. Therefore, the findings call on policymakers to provide and tailor public finance to eco-innovations that increase material productivity.

   These results appear to be contrary to the findings on the macroeconomic level (Chapter 7). However, the conclusions from Chapter 8 are only valid for a specific subgroup of firms, i.e. those having had an eco-innovation motivated by the availability of public financial support. Additionally, the sample is dominated by firms from material-intensive sectors, hinting to the possibility that the gains for one sector might be compensated by the loss of another sector, thus possibly explaining the insignificant effect on the macroeconomic level.

1.3 Contributions

This dissertation provides contributions to the academic literature, policymakers and international organisations working on material productivity (and related topics), and firms considering investing in material productivity improvements. Following the reviews and analyses in this dissertation, the main academic contributions of this dissertation can be summarised as follows.

1) ***Methodological advancements:*** This dissertation newly introduces established econometric techniques (i.e. instrumental variable and dynamic panel estimations) into the strands of the literature on drivers of material use, the impact of materials use on GHG emissions, and the effects of material productivity on competitiveness and GHG emissions. As such, the empirical analyses of this thesis complement the methods currently applied in the existing literature by more sophisticated quantitative methods in order to address the issue of heterogeneity and endogeneity. Thus, it aims to further link applied econometrics with environmental and resource economics.
2) ***Discovery of new knowledge:*** This dissertation provides new empirical evidence on the effects of material use and productivity on competitiveness and climate change mitigation efforts, including an in-depth review of the concept of macroeconomic and microeconomic competitiveness. By addressing several limitations, that are shown to be relevant, this work of research extents the existing knowledge base on these topics.
3) ***Revision of older views:*** While some of the findings are in line with the majority of previous investigations, results of two chapter do not support current views in the field. First, Chapter 6 suggests that Western European countries might not have decoupled material use from economic growth. Second, Chapter 7 finds that increasing material productivity might not necessarily lead to an increase in macroeconomic competitiveness and decrease of GHG emissions in Europe. While both chapters have their own limitations, such results could spur a new debate on the existing evidence base, thus potentially initiating revisions of existing views.
4) ***Application advancements:*** This dissertation explicitly considers the heterogeneity across firms, sectors, countries, material subgroups, and material indicators in the empirical investigations. Applying such investigations wherever possible throughout Chapters 5-8, this thesis advances the application of empirical methods towards taking various forms of heterogeneity into account. Crucially, it is shown that heterogeneity is important to consider in future analyses.

1.4 Lessons learned

The discussions and findings in this dissertation allows to draw several conclusions, relevant to academia, policymakers, international organisations, and firms. In particular, the following key insights are consistent with the results of this dissertation:

1) ***(Unequal) distribution of material productivity improvements:*** As summarised previously, increases in material productivity can boost competitiveness and reduce GHG emissions of firms in Europe. However, such benefits are likely to be unequally distributed across firms, sectors, and countries. For instance, the positive effects on competitiveness and GHG emissions apply in particular to material-intensive sectors such as manufacturing, construction, retail trade, food production, and transport. Additionally, Eastern European economies seem to benefit most from material productivity improvements. Lastly, these results are only valid for those firms having had an eco-innovation that improved their material productivity motivated by the availability of public financial support. Therefore, the results of this dissertation are coherent with the notion that not all firms, sectors, or countries are likely to benefit (equally) from increases in material productivity.
2) ***Importance of eco-innovations:*** The dissertation's results indicate those eco-innovations that increase material productivity are likely to increase a firm's competitiveness and reduce its GHG emissions, in particular in material-intensive sectors in Europe. This is an enormously important result in support of enabling and financing eco-innovations. Moreover, wage gains from material productivity improvements on the country-level might lead to rebound effects. Channelling wage increases into eco-innovations are found to decrease the magnitude of such effects. Thus, eco-innovations that increase material productivity could serve as an important strategy for policymakers and firms to achieve competitiveness and climate change mitigation objectives.
3) ***Focus on endogeneity:*** The academic literature has put relatively little attention to address the potential problem of endogeneity, caused by omitted factors, measurement errors, or simultaneity, all could make the results biased and inconsistent. This dissertation demonstrates that the effects of material productivity on competitiveness on the country and firm level are significantly different when endogeneity is taken into account. It is thus important to consider endogeneity in future empirical research.

4) ***Focus on heterogeneity:*** The empirical analyses show that the average effects between two variables often underlie heterogeneity across countries, sectors, firms, material subgroups, or material indicators. For instance, while material use as a whole increases GHG emissions in the EU, the effect is predominantly driven by fossil fuel use. Additionally, an increase in income positively affects material use in Western Europe. However, not all material groups are affected homogenously since biomass and particularly mineral use are increased. Moreover, there are large differences between using DMC or RMC as a material indicator in the investigations on the effect of material use on GHG emissions, the impact of economic growth on material use as well as how material productivity affects competitiveness on the country level. Thus, general recommendations across all material groups and indicators might lead to misguided strategies.

5) ***Increase data availability and quality:*** Better data availability and quality is essential in further researching the implications of moving towards more material productive economies. To this end, this dissertation indicates that developing adequate indicators and systematically monitoring developments across countries and time is crucial for empirical research on the issues. Currently, coherent data across time and space are sparse. International cooperation in advancing databases could support empirical research by providing methodologically robust, relevant, and practical indicators.

Overall, this dissertation draws a nuanced picture of how material use and material productivity can affect competitiveness and climate change mitigation objectives in Europe, as only specific firms, sectors, or countries are likely to increase their competitiveness and reduce their GHG emissions by improving material productivity. As such, this dissertation attempts to focus attention to neglected issues in the literature and provide new empirical results and insights of the role of materials in addressing two important challenges of our time – competitiveness and climate change mitigation.

Chapter 2

Materials – An Overview

An abridged version of Chapter 2.4 will be published as

Rosenstock, Manfred and ***Flachenecker, Florian*** (forthcoming). Enabling Resource Efficiency Investments – A Review and Outlook of the Resource Efficiency Agenda of the European Union; in: ***Flachenecker, Florian*** and Rentschler, Jun Erik (contributing editors). Investing in Resource Efficiency: The Economics and Politics of Financing the Resource Transition. Springer International Publishing. Cham, Switzerland.

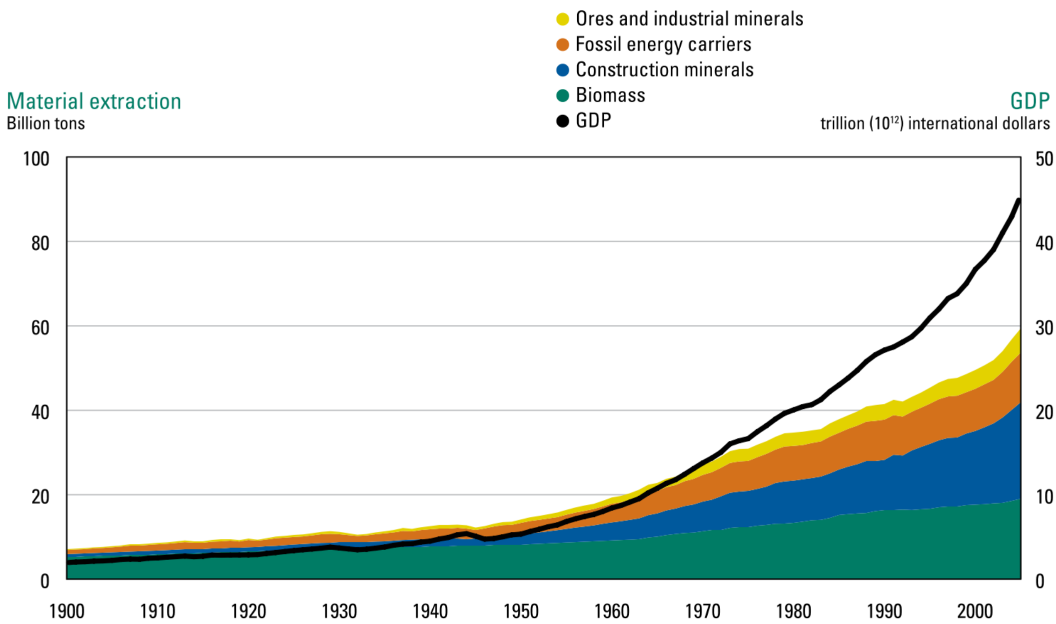
2 Materials – an overview

This chapter provides an overview of how materials are defined in this dissertation, how they are measured (Chapter 2.1), and how they relate to the environment (Chapter 2.2), to the economy (Chapter 2.3), and to policy (Chapter 2.4). As such, this chapter clearly defines the underlying concepts that will later be used during the empirical analyses, it justifies the scope of the investigations, and motivates the reason for choosing certain material indicators over others.

The word material originates from the Latin word *materialis*, i.e. made from matter, and describes "the matter from which a thing is or can be made" (Oxford Dictionary 2017). Materials are thus ubiquitous physical substances which facilitate our everyday lives in essentially everything we do from satisfying vital needs such as nutrition and shelter to the use of electronics and cars. In fact, materials take directly or indirectly part in essentially every product or service that is consumed or produced in modern economies – our current way of life appears to be inconceivable without them (Allwood et al. 2011). Materials are considered "the backbone of the economic production and consumption systems" (Bahn-Walkowiak and Steger 2015). Their importance can best be understood when imagining a world without them: there would be no buildings, no transportation infrastructure, no modern energy generation, no agriculture, no technology, no medical equipment, etc. In short, materials are the foundation of our modern lives.

Their extraction has been growing almost exponentially over time as Figure 1 depicts. What is more, material use is expected to increase by a factor of 2-3 between 2000 and 2050 (Allwood et al. 2011; UNEP IRP 2017), which will have major repercussions for (i) the environment due to higher environmental pressures associated with material extraction, (ii) the economy, in particular when certain materials become scarce or their prices become volatile, and (iii) policymaking to address such challenges as well as their geopolitical implications (Andrews-Speed et al. 2014).

Figure 1: Global material extraction 1900-2005 in billion tonnes.



Notes: Source UNEP IRP 2011, based on Krausmann et al. 2009

According to the consensual definition among academia, international organisations, and public institutions, materials are usable and desired substances (i.e. the existence of a market is assumed) obtained or derived from natural resources (OECD 2007; OECD 2015a). As summarised in Table 1, natural resources can be grouped into renewable and non-renewable resources.

The former comprises resources that regenerate within a *reasonable* timeframe, for instance wood, fish, and freshwater. The latter lacks the ability for timely renewal such as metals, minerals, and fossil fuels. Hence, materials are a subset of both renewable and non-renewable natural resources, excluding water, air, land, and biodiversity. Materials typically comprise biomass, construction and industrial minerals, metals, and fossil fuels (OECD 2008a; EC 2013a).

For the purposes of this dissertation, this definition of materials is taken. However, it should be acknowledged that sometimes energy carriers are excluded or soil is additionally considered part of materials (OECD 2014; OECD 2015a). Moreover, materials cover raw materials, intermediate products made out of materials as well as final products from materials.

Table 1: Natural resources and materials.

Natural resource category	Subcategory	Covered in this dissertation
Renewable resources	Biomass (wood, fish)	Yes
	Water	No
	Air	No
	Biodiversity	No
Non-renewable resources	Minerals	Yes
	Metals	Yes
	Fossil fuels	Yes
	Land	No

Materials are not only an integral part of the environment, from which they are extracted, but are also used throughout the entire economic system. Therefore, it is not surprising that the use of materials has wide-ranging implications. This dissertation focuses predominantly on the effects on competitiveness and climate change mitigation, while acknowledging that material use additionally comprises a social or socio-economic dimension, often focusing on the distributional aspects of material use (Steinberger et al. 2010; UNIDO and AFD 2013; von Hauff et al. 2015; Teixidó-Figueras et al. 2016). Analysing this dimension of materials lies outside the scope of this dissertation.

To set the basis for the empirical analyses on the implications of materials for competitiveness and climate change mitigation objectives, it is crucial to discuss the definition of materials, how they are measured as well as their relationship to the environment, economy, and policymaking.

2.1 Measuring materials

As briefly outlined above, materials comprise biomass, minerals, metals, and fossil fuels. In order to measure material use, there are several methodologies available (OECD 2008a); economy-wide material flow accounting (EW-MFA) is among the most commonly used methodology (Lutter et al. 2016). It is an established methodology to quantify and monitor human use of natural resources, and systematically assesses material throughput and stock additions within and throughout systems such as countries and sectors. Since most of the analyses in this dissertation focus on the country level, EW-MFA is predominantly used.

Alternative methods to measure materials are substance flow analyses, material system analyses, life cycle assessments, business level MFAs, and input-output analyses (Femia and Moll 2005; OECD 2008a).

- ***Substance flow analyses*** are mainly used to measure chemical elements and substances (CO_2, nitrogen etc.).
- ***Material system analyses*** are frequently applied to measure individual subgroups of raw and semi-finished materials.
- ***Life cycle assessments*** typically measure material requirements or environmental pressures of specific materials across their entire life cycle. Information resulting from life cycle assessments are sometimes used to calculate raw material equivalents which are used to derive consumption-based material indicators.
- ***Business level MFAs*** focus on material flows of specific firms.
- ***Input-output analyses*** are closely related to EW-MFA, as it also allows to calculate and aggregate various materials across systems and time, often in monetary terms. In fact, the material indicators used in this dissertation are calculated using both EW-MFA and input-output analysis.

EW-MFA originated from the biological concept of *metabolism* and can be traced back to as early as the 1860s, but mostly developed in the 1960s when environmental concerns rose (Ayres and Kneese 1969; Fischer-Kowalski 1998). The fundamental principle underlying the EW-MFA is the connection between society, the economy, and the environment within a closed system. For instance, materials are extracted from nature to become an input into the economy and then return to nature as residuals or waste, based on the first law of thermodynamics (Talmon-Gros 2013). This closed system can be described and measured using EW-MFA and applied to the material flows of countries and industries as well as products, services, and individual material flows (OECD 2008a). It is thus a flexible methodology to measure material flows across time and space, making it a suitable method for the purposes of this dissertation.

EW-MFA can also be used to quantify material stocks. Anthropogenic material stocks are an approximation for the future potential of reuse, recycling, and remanufacturing activities, which is particularly high in developed countries (Müller et al. 2011). Material stocks are generated when material inflows differ from material outflows in a given spatial boundary and time (UNEP IRP 2010b). While facing several challenges such as data restrictions, material stocks can be approximated (Gerst and Graedel 2008). Generally, only a limited amount of studies have attempted to estimate material stocks in society (Worrell et al. 2016). An investigation on the stocks of the residential buildings and transportation networks in the EU finds that most material flows are used to maintain existing material stocks rather than generating new stock additions (Wiedenhofer et al. 2015), while another analysis finds that socio-economic material stocks are still rising, including in the EU (Haas et al. 2015). In short, while EW-MFA can also be applied to measure flows stocks, the main focus of this dissertation will be on material flows.

The fact that EW-MFA can measure material flows and approximate stocks makes it also increasingly used in the context of a circular economy to account or estimate the 'circularity' of materials re-entering the economic system, in particular recycling rates (Haas et al. 2015). However, material indicators derived from EW-MFA might not be optimal for assessing the circular economy, because they do not capture all 'hidden', i.e. *indirect* and *unused*, flows and characteristics of the circular economy (Geng et al. 2013). For instance, excreta or bio-waste used as fertilizer are accounted for as outputs rather than recycled materials in the EW-MFA (Haas et al. 2015). Additionally, existing recycling indicators based on EW-MFA often apply heterogeneous definitions on boundaries, thus restricting their comparability (Moriguchi 2007). Therefore, developing indicators that specifically address the needs of measuring the circular economy are being developed and are expected to be published by the end of 2017 (EC 2015a).

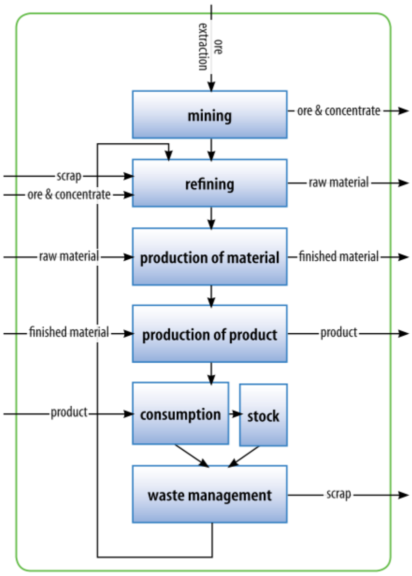
The following subsections will outline and discuss which material indicators are derived from EW-MFA, how they can be matched to the System of National Accounts, and their limitations.

2.1.1 Material indicators derived from material flow accounts

Numerous material (flow) indicators can be derived applying the EW-MFA methodology. Such indicators are mostly input and consumption indicators, but the methodology also allows calculating output indicators (Moll et al. 2005). Material input and consumption indicators can further be distinguished between measuring *used* and *unused* materials. While *used* materials enter the economic system in production, consumption, and trade, *unused* materials are extracted from the environment but instead of entering the economic system, they are returned to the environment as residuals or waste. For instance, overburden from mining or rock excavated during construction are taken from the environment but are not used any further and discarded (OECD 2015a).

Additionally, *direct* and *indirect* material flows can be differentiated; *direct* flows account for the actual mass of a material and *indirect* flows additionally account for the mass along the value-chain which was necessary to produce the material, i.e. 'embodied' materials (Fischer-Kowalski et al. 2011). For illustrative purposes, Figure 2 shows that throughout all stages in a material life cycle material inputs enter a stage and are converted into material outputs or waste, thus covering *direct* and *indirect* as well as *used* and *unused* materials.

Figure 2: Life cycle of materials (source: UNEP IRP 2010).



Material input indicators comprise of materials extracted within a territory and adds imported materials. The difference between material input and consumption indicators is that consumption indicators additionally subtract the exports of materials. Four frequently used material consumption indicators are explained hereafter (based on Moll et al. 2005 and EC 2001):

1) ***Domestic material consumption (DMC)*** comprises domestically extracted *used* materials, adds all imported materials (resulting in domestic material input (DMI)) and subtracts all exported materials. Since material imports and exports account for *direct* flows, excluding *indirect* materials, and domestic extraction considers *used* materials, DMC measures the consumption of *direct used* material flows.
2) ***Raw material consumption (RMC)*** measures domestically extracted *used* materials, adds all imported materials including their *direct* and *indirect* flows (resulting in raw material input (RMI)) and subtracts all exported materials including their *direct* and *indirect* flows. Since material imports and exports account for their *direct* and *indirect* flows and domestic extraction considers *used* materials, RMC measures the consumption of *direct* and *indirect used* material flows. This type of material indicators has also been referred to as the ***material footprint (MF)*** (Wiedmann et al. 2013a).
3) ***Total material consumption (TMC)*** comprises domestically extracted *used* and *unused*

materials, adds all imported materials including their *direct* and *indirect* flows (resulting in TMR) and subtracts all exported materials including their *direct* and *indirect* flows. Since material imports and exports account for their *direct* and *indirect* flows and domestic extraction considers *used* and *unused* materials, TMC measures the consumption of *direct* and *indirect used* and *unused* material flows.

These indicators can be summarised in Table 2, representing material input and consumption indicators for the various defining classifications: *used* and *unused* materials, and *direct* and *indirect* flows.

Table 2: Material flow indicators derived from EW-MFA.

	Used materials	*Used and unused materials*
	Input indicators	
Direct flows	DMI	-
Direct and indirect flows	RMI	TMR
	Consumption indicators	
Direct flows	DMC	-
Direct and indirect flows	RMC/MF	TMC

The material indicators TMR/TMC are not subject of this dissertation mainly due to the lack of data availability across countries and time which is necessary for applying empirical methods. Accordingly, those indicators are not treated further herein. However, DMC data will be considered for later empirical analyses, as standardised methods are used to calculate the data across countries and time, in particular in Europe. RMC/MF data are increasingly accessible, but as Eisenmenger et al. (2016) show, different methods exist and results in heterogeneous indicators.

Nevertheless, RMC/MF data are approximated for the empirical analyses. Compared to DMC, RMC/MF better account for the environmental pressures associated with material use, reducing the risk of 'material leakage'. Thus, the RMC/MF is approximation using a simple method to draw comparisons between DMC and RMC/MF. Unfortunately, no coherent and robust data on RMC/MF is publically available for a sufficient period of time and across countries to use them in empirical analyses which would have avoided the approximation used in this dissertation.

The following descriptive analysis considers the DMC as well as the RMC indicator for the EU-

28 aggregate. Table 3 provides an overview of the individual materials forming the two consumption-based material indicators and their magnitude in terms of weight relative to the EU-28 aggregate in 2013. Negative shares indicate that more materials were exported than domestically extracted and imported. This goes back to the discussion about stocks and flows above: If in a given year more materials are exported than domestically extracted and imported, the material stock of a country diminishes.

Table 3: Subgroups of DMC and RMC for the EU-28 aggregate in 2013.

Material group	Material subgroup	% share of DMC	% share of RMC
Biomass	**Total biomass**	**25.82**	**23.30**
	Crops (excluding fodder crops)	10.00	9.38
	Crop residues (used), fodder crops and grazed biomass	11.33	9.81
	Wood	4.39	4.00
	Wild fish catch, aquatic plants/animals, hunting and gathering	0.13	0.10
	Live animals other than in 1.4, and animal products	-0.09	-
	Products mainly from biomass	0.06	-
Metals	**Total metals**	**3.98**	**9.91**
	Iron	-	-
	Non-ferrous metal	-	-
	Products mainly from metals	-0.33	-
Minerals	**Total minerals**	**46.49**	**42.65**
	Marble, granite, sandstone, porphyry, basalt, other ornamental or building stone	4.98	4.69
	Chalk and dolomite	-	-
	Slate	0.03	0.04
	Chemical and fertiliser minerals	-	-
	Salt	-	0.75
	Limestone and gypsum	6.89	-
	Clays and kaolin	0.98	1.13
	Sand and gravel	30.72	27.70
	Other non-metallic minerals	-	-
	Products mainly from non-metallic minerals	-0.36	-
Fossil Fuels	**Total fossil fuels**	**23.69**	**24.14**
	Coal and other solid energy materials/carriers	10.86	10.64
	Liquid and gaseous energy materials/carriers	12.83	13.51
	Products mainly from fossil energy products	-0.01	-
	Other products	0.02	-

The table serves as an illustration to clarify the definition, subgroups, and relative importance of certain materials forming aggregated material indicators. For instance, it becomes apparent that minerals, and in particular sand and gravel, dominate both the DMC and RMC indicators.

However, the DMC indicator's share of biomass and minerals is larger compared to RMC which puts more emphasis on metals (by a factor of 2.5) and fossil fuels. Thus, the *indirect* materials used by metals are estimated to be the largest for the EU-28 aggregate in 2013.

Table 4 shows the different components of the DMC and RMC indicators. As mentioned previously, material consumption indicators are calculated by adding imports and subtracting exports to domestic extraction. The table reveals four insights. First, domestically extracted materials dominate the DMC and RMC indicators especially those of the minerals subgroup. Second, the EU imports more materials than it exports on aggregate but not for all subgroups. Third, calculating the material indicators according to the figures in the table below would indicate that some materials are being stored (i.e. stock additions) or not included within these four material subgroups (i.e. other products or waste). Fourth, the RMC indicator puts significantly more emphasis on metals compared to the DMC indicator.

Table 4: Domestic extraction, exports, and imports for the EU-28 in 2013.

Component	**Material subgroup**	**% share of DMC**	**% share of RMC**
		100	*100*
Domestic extraction	***Total***	***85.95***	***82.10***
	Biomass	20.30	24.08
	Metals	2.94	3.07
	Minerals	46.24	44.03
	Fossil fuels	11.46	10.91
Exports	***Total***	***34.79***	***34.56***
	Biomass	9.86	4.23
	Metals	6.12	11.58
	Minerals	4.96	7.52
	Fossil fuels	11.48	11.23
Imports	***Total***	***50.39***	***52.46***
	Biomass	9.87	3.44
	Metals	7.71	18.42
	Minerals	4.63	6.13
	Fossil fuels	25.53	24.46

There is yet another way to statistically analyse material indicators. Table 5 illustrates the various manufacturing stages of materials measured in DMC terms, as no equivalent data for RMC exists. Two aspects are visible. First, the EU imports mainly raw products, i.e. raw materials. Second, the EU exports materials mainly in finished products, e.g. cars and machines.

Table 5: Manufacturing stages of material trade for the EU-28 in 2013.

Component	Manufacturing stages	% share of DMC
Exports	***Total***	***100***
	Raw products	25.68
	Semi-finished products	35.61
	Finished products	38.71
Imports	***Total***	***100***
	Raw products	50.64
	Semi-finished products	24.51
	Finished products	24.85

Combining the information from the various tables presented so far indicates that the EU is a net material importer, mainly of raw materials, specifically of fossil fuels. Despite the different methods to calculate DMC and RMC, their aggregated figures are relatively similar. However, it has to be noted that all figures shown across these tables are weight-based figures. As such, heavy and frequently used materials dominate the DMC and RMC indicators.

2.1.2 Material productivity

Material indicators based on EW-MFA are established among academia, international organisations, national institutions, and policymakers (Christ and Burritt 2014; Huysman et al. 2015). The concepts and methods of EW-MFA have been increasingly standardised and taken up in a number of statistical offices in industrial countries, including those in all EU economies and Japan (Hinterberger et al. 2003). Similarly, several reports from international organisations directly refer to EW-MFA indicators (e.g. UNEP IRP 2011; OECD 2015).

Numerous countries base (binding and non-binding) material targets on indicators derived from it (Bahn-Walkowiak and Steger 2015). The uptake of such targets was facilitated by research illustrating the possibilities and magnitudes of increasing material productivity (von Weizsäcker et al. 2009). For instance, Germany attempts to double its material productivity by 2020 compared to 1994 and uses the abiotic parts of DMI for monitoring progress towards this target (BMUB 2015). The EU has discussed adopting a material productivity target based on RMC (Council of the EU 2014; EP 2015; EREP 2014). Italy aims to reduce its material use based on TMR (EEA 2011a). The SDGs feature the indicator material productivity based on the EW-MFA method (UN 2015b).

One of the core advantages of EW-MFA indicators is that they are compatible with the System of National Accounts (UN 2009). Based on the guidelines stated in the System of Environmental-Economic Accounting (SEEA), this allows to make direct comparisons between material indicators and conventional economic statistics, in particular GDP (United Nations et al. 2014). Despite minor discrepancies with regards to the definition of boundaries (e.g. the inclusion of cross-border transport), the SEEA is a frequently used and continuously improved method to monitor developments concerning economic and environmental indicators. Therefore, EW-MFA indicators in combination with the SEEA are chosen for the purposes of this dissertation.

The SEEA has led to the construction of ratios, for instance, material productivity and its inverse material intensity. Productivity is typically measured as the ratio between the output of a production process and its inputs (OECD 2007). It measures the efficiency with which inputs are converted into outputs (Syverson 2011). Two types of productivity can be distinguished.

1) ***Total factor productivity***, which takes the ratio of all possible inputs such as labour, capital, materials, energy, services, and total output. It measures the output generated by the various inputs and represents the aggregated production function of an economy (Isaksson 2009).

2) ***Single factor productivity***, which measures total output generated by one unit of a particular input. Single-factor productivity allows to focus on an individual input, but it depends on the relationship between the particular input and the excluded inputs as well as their relationship to total output. There is a wide body of literature on the determinants and impacts of productivity ratios (e.g. Lee and Tang 2000; Alcala and Ciccone 2004; Syverson 2011; Costinot et al. 2012).

Material productivity is a single factor productivity measure. It can be computed similarly to more commonly used productivity indices such as labour and capital productivity, both in terms of gross-output and value-added. More precisely, material productivity measures the effectiveness by which added value or useful output has been created from each unit of material input (Dahlstrom and Ekins 2005). The inverse of material productivity is called material intensity and essentially measures how much input is required per unit of output. There are on-going discussions to include materials into conventional growth models, which would allow material productivity also to become an explicit part of total factor productivity (in contrast to being measured as a residual), in line with labour and capital productivity (O'Mahony and Timmer 2009).

There is often confusion with the related, yet different concept of material efficiency, which is more aligned with the engineering view of relating two variables in terms of their mass and not their value-added or gross-output (OECD 2007; Allwood et al. 2013; Baptist and Hepburn 2013; Worrell et al. 2016). Material efficiency is reached (i) when "a production process has achieved the maximum amount of output that is physically achievable with current technology given fixed amounts of inputs" (Lawrence and Diewert 1999, p.162) or (ii) by reducing material inputs to the maximum possible for a given material output measured in mass (Dahmus 2014). Material efficiency according to economic thinking, however, describes the point in which the marginal rate of substitution between inputs equals to the negative price ratio of these inputs (Varian 2010; Aidt et al. 2017). Thus, economists take the relative costs of inputs into consideration and not only the technological feasible.

Since the conventional economic model requires to estimate the marginal rate of substitution and the relative price ratio, in practice, the concept of material productivity comes into play. Material productivity considers an input-output relationship, regardless of how efficient the output could have theoretically been generated (OECD 2007). In mathematic terms, material productivity can be expressed as follows.

$$MP_{t,i} = \frac{Y_{t,i}}{M_{t,i}} \tag{1}$$

where *MP* is material productivity, *Y* represents output, M material input ($M_{t,i} > 0$), *t* time and *i* the level, i.e. country, sector, or firm.

2.1.3 The limitations of material indicators

The advantages of using EW-MFA indicators, in particular DMC, are clear: (i) These indicators follow an established, coherent, and robust methodology, (ii) they are publically available across time and space, especially for European countries, and (iii) they can easily be compared to standard economic indicators such as GDP. As such, EW-MFA indicators are suitable for the empirical analyses conducted in this dissertation. Alternative methods or indicators are either incoherent or not sufficiently available for empirical analyses (Flachenecker 2017).

However, material indicators derived from EW-MFA suffer from several inherent limitations (Lutter et al. 2016). Obviously, no *perfect* indicator exists and even GDP, arguably the most considered economic indicator, suffers from numerous flaws (Stiglitz et al. 2009; Reilly 2012). Nonetheless, the following represents a summary of the main shortcomings.

1) ***Weight-based aggregation***: Material flow indicators are weight-based indicators. Thus, individual materials are aggregated taking their individual weights into account. Table 2 shows that minerals represent almost half of the DMC indicator for the EU-28 in 2013 which is roughly twice as much as biomass or fossil fuels. Decomposing the different material groups even further shows that sand and gravel account for 31% of the DMC indicator. Hence, the indicators are skewed towards heavy and frequently used materials, especially construction minerals. This has implications for (i) the relationship to monetary indicators and (ii) the link to environmental pressures.

   i. Material productivity directly relates material use to economic performance. There is criticism towards simply linking weight-based material measures to value-added-based economic indicators since the relationship between the two indicators is unclear (Cleveland and Ruth 1998). For instance, nickel accounted for 0.17% of DMC for the EU-28 in 2013. Eliminating nickel use would not significantly change DMC, but is very likely to change GDP. On the other hand, changing the use of construction materials is likely to have significant implications on DMC and GDP. In short, the relationship depends on the specific changes in the use of materials. This is also related to the way material flows are calculated, often not revealing their specific use within an economy, i.e. their use is considered a 'black box' (Femia and Moll 2005).

      Additionally, there is a fundamental difference in the way trade is accounted for in DMC and GDP. DMC adds imports and subtracts exports; GDP adds exports and subtracts imports. Thus, trade is accounted for differently across both indicators. For instance, increasing exports will *ceteris paribus* always increase material productivity, while the opposite occurs with imports. However, it is not clear that increasing exports automatically triggers or is the result of increased material productivity since this depends on changes in technology or substitution effects. Thus, linked to the different way trade is accounted for, changes in material productivity might be misinterpreted.

   ii. There are discussions on whether material use is a proxy for environmental pressures (Bringezu et al. 2003). Some scholars argue that despite its limitations, material flow indicators "are useful measures of potential environmental impact"

(World Resource Institute 2000). However, changes in aggregated material use indicators may or may not trigger changes in environmental pressures (Steinberger and Krausmann 2011; Fischer-Kowalski et al. 2011).

For instance, assuming that a reduction in material use is caused by a reduction of sand use while gold use is increased by less than the sand use reduction. This would decrease overall material use, but is very likely to increase environmental pressures (UNEP IRP 2010a). Nevertheless, some scholars argue that material use represents generic (in contrast with substance-specific) environmental pressures (Bringezu et al. 2003, OECD 2008). Additionally, there are methodologies available to combine EW-MFA-based material indicators with environmental impacts more directly. Linking life cycle analyses with the EW-MFA methodology is one possibility (Voet et al. 2005a), calculating material footprints another (Wiedmann et al. 2006). A comprehensive summary of various environmental pressures associated with material use can be found in UNEP IRP (2010a). This will be discussed in greater detail in Chapter 5.

On a more fundamental level, Steinberger and Krausmann (2011) find that biomass is inelastic to changes in GDP, while fossil fuels, minerals, and metals are relatively more elastic to income. By construction, this means that the higher GDP is, the higher material productivity is likely to be, thus overestimating the level of 'sustainability' of highly-developed countries. Therefore, the authors argue that resource productivity, including material productivity, is an inadequate indicator for environmental pressures, as high-income countries are not *per se* more environmentally sustainable.

2) ***Data availability, quality, and comparability***: Since EW-MFA is still a relatively recent methodology, several methodologies for calculating material indicators exist using different assumptions and material groupings, in particular for RMC/MF and TMC indicators (Schoer et al. 2013; Hirschnitz-Garbers et al. 2014). Using indicators that use different methodologies either across time or across countries is highly problematic for empirical analyses. This is particularly relevant for approximating the *indirect* material use from traded materials, as reliable data is often lacking. International organisations have supported the standardisation of methodologies to calculate DMC (OECD 2008a; EC 2013a). This, however, is currently under discussion for other EW-MFA indicators such as RMC/MF or TMR (Eisenmenger et

al. 2016; Lutter et al. 2016). This is why RMC/MF data used in this dissertation is approximated, as no comparable and robust data on country level across the EU and time is publically available.

Table 6: Data sources for material flows.

Database	Indicators	Time	Countries	Scope and method	Sources
Eurostat [DMC]	DE, IMP, EXP, DMI, DMC	1990-2014 (mostly from 2000)	EU-28, Turkey, Serbia, Albania, Switzerland, Norway	– 50 material categories – Based on EU regulation	EU national statistical offices
Eurostat [RMC]	RMC	2000-2014	EU-28 as an aggregate	– 50 material categories – 182 product groups	EU national statistical offices
Eurostat FIGARO project	DE, IMP, EXP, DMI, DMC, RMC	2010 (under development)	EU-28 member states	– 64 sectors	EU national statistical offices
OECD	DE, IMP, EXP, DMI, DMC, RMC	1995-2011	63 countries	– Based on the OECD Inter-Country Input-Output database	Harmonised country supply and use as well as input-output tables
UN Environment Material Extraction Database *(formerly materialflows.net)*	DE, IMP, EXP, PTB, DMI, DMC	1980-2010	229 countries	– 331 materials – MFA based on EU and OECD standards – Estimates for missing data	IEA, UNSD, EIA, BGS, USGS, WMD, FAO
Material footprint, RMC *Wiedmann et al. 2013 (only 2008 publically available)*	DE, DMC, RMC	1980-2008	191 countries	– Global multi-region input–output	Eora, Global Material Flow Database by CSIRO
Environmentally weighted material flows *Voet et al. 2005*	Impacts per kilogramme	2000	Netherlands	– 100 materials – Combination of MFA and LCA	Eurostat DMC, various life cycle studies and databases (mainly ETH database)
TMC *Bringezu et al. 2001 (not publically available)*	TMC, TMR, DMI	1988-1997	EU-12, EU-15	– fossil fuels, minerals, metals, biomass, and erosion	Eurostat, authors' own estimates
Global input-output databases *(Eora, EXIOBASE, WIOD)*	DE, IMP, EXP, DMI, DMC, RMC	1990-2012, 2000-2014	Between 43 and 187 countries	– various material categories – various industry breakdowns	National input-output databases, numerous other sources

In line with the overview on databases available on material flows in Table 6, it becomes apparent that econometric analyses, which require continuous data across countries or time (or both), is only possible using DMC data from Eurostat. As mentioned previously, this DMC data then serves as a basis to approximate RMC data.

Additionally, there is still a lack of comprehensive and comparable data on industry and firm level. Besides data from some individual countries, there is only one EU-wide survey that specifically considers the material use for firms – the Community Innovation Survey of the European Commission. Otherwise, there is no comprehensive way to research material use on the firm-level. Lots of research efforts are hence undermined by the lack of comprehensive and high-quality data, despite the urge for a harmonised i0nternational database (Bleischwitz 2010). The lack of comparable data on materials across time and space remains one of the most important bottlenecks to empirically research on the issue.

2.2 Materials and the environment

Materials affect the environment, both locally and globally. The United Nations Environmental Programme's International Resource Panel (UNEP IRP) concludes that materials are responsible for environmental pressures along their life cycles which arise during their extraction, production, consumption, and disposal stages (UNEP IRP 2013). This can comprise various forms of pressures, including GHG emissions, noise, dust, and erosion. A stylised life cycle of materials has been illustrated previously (see Figure 2). Each stage is associated with different environmental pressures.

Environmental pressures associated with the use of materials can take various forms and occur at different stages. For instance, materials can harm the environment through particulates (e.g. dust, swarf), erosions from mining, leakages of chemicals used in the separation process of ores into the environment, indirectly through 'embodied' energy use, and mining accidents (Azam and Li 2010; UNEP IRP 2010a). Such effects are mainly local or regional and can be directly associated with the relevant materials.

Besides local effects, materials can have effects on a global scale as well. Material production is estimated to account for 25% of global carbon dioxide (CO_2) emissions (Worrell et al. 2016).

According to the International Energy Agency (IEA), 77% of the total direct CO_2 emissions by the industrial sector are due to the production of just four material groups, namely iron and steel, cement, pulp and paper, and aluminium (IEA 2010). In the EU, the manufacturing industry accounts for 27% of all direct GHG emissions, 27% of all direct emissions of ground-level ozone precursor gases, and 15% of direct emissions of acidifying gases (EEA 2013). Additionally, the GHG methane, for instance, is emitted from agricultural production (i.e. biomass) and material landfills, thus not only negatively impacting the environment locally, but also globally by contributing to climate change (IPCC 2007). Additionally, such global effects often also account for the indirect effects from materials through energy use for production and transportation which results in environmental pressures.

The UNEP IRP differentiates between ecological and human health impacts arising from environmental pressures (UNEP IRP 2010a). According to its evaluation, ecologic impacts from materials arise due to habitat change, nitrogen and phosphorus pollution, and overexploitation of biotic renewables resources such as fish and forests. Human health is affected by polluted drinking water and urban air, lead exposure, and household combustion of solid fuel. Both groups additionally feature climate change. Such environmental pressures are often associated with being negative environmental externalities, lacking to be internalised in the decision-making by economic agents. In the absence of binding price mechanisms to internalise the arising costs on third parties, these impacts and pressures are inefficiently high causing excessive environmental damages and repercussions on human health and labour productivity (Chang and Neidell 2012; OECD 2015b).

Considering each material subgroup individually illustrates how material use and the environmental are linked, focusing on GHG emissions:

- ***Biomass***: Agriculture, forestry, and fishery account for around one-fourth of global GHG emissions (IPCC 2014). Additionally, agricultural activity often negatively affects land quality by overusing fertilizers and pesticides. However, some biomass materials can also be beneficial to the environment. For example, forests – if managed sustainably – store CO_2 emissions and transform them into oxygen. Nevertheless, the majority of impact studies of biomass materials conclude that in particular the indirect resources required for agricultural production have severe negative implications on the environment (UNEP IRP 2010a).
- ***Minerals***: Minerals are mainly indirectly associated with environmental pressures through their use in infrastructure construction. However, the extraction of minerals

can adversely affect land use, land quality, water use, and biodiversity directly as well as indirectly through 'embodied' energy use for extraction, transportation, production, usage, and disposal (UNEP IRP 2013). Even though they are dominant in weight-based indicators such as DMC or RMC, their environmental impacts per kg are relatively low compared to biomass and fossil fuel materials (UNEP IRP 2010a).

- ***Metals***: Metals are similarly linked to the environment like minerals, in particular through their high energy use during the extraction phase. Mining, processing, and refining metals are estimated to account for 7-8% of global energy use (UNEP IRP 2013). However, metals play a crucial role in low-carbon technologies and – at least theoretically – can be recycled infinitively, thus potentially contributing to climate change mitigation efforts (Graedel et al. 2011; Allwood et al. 2011).
- ***Fossil fuels***: The combustion of fossil fuels is responsible for over two-thirds of global GHG emissions (IPCC 2014). As such, there is a direct link between the use of fossil fuels and environmental pressures, in particular GHG emission. However, the extraction of fossil fuels, similarly to minerals and metals, is also indirectly linked to additional energy use and directly affects land use, quality, water use, and biodiversity. Therefore, it is often argued that fossil fuels are the most important source when it comes to material related GHG emissions (UNEP IRP 2010a).

Chapter 5 will analyse the short and long term effects of material use on GHG emissions. This investigation will not only reveal that material use today immediately triggers GHG emissions, but also for years to come. Moreover, the results of this study show that most of the link between material use and GHG emissions in Europe arise from fossil fuels, thus confirming the considerations made by the IPCC (2014) and the UNEP IRP (2010a). Overall, these are important insights suggesting that materials play a crucial role in the climate change debate since their continuously increasing use seems to perpetuate unsustainable levels of GHG emissions.

There have been many other attempts to estimate the environmental pressures associated with direct and indirect material use. For instance, the report by the UNEP IRP (2010a) summarises the existing literature on three perspectives between materials and environmental pressures, comprising a production perspective, a consumption perspective, and a material use perspective. By focusing on the latter, there are three methodologies available that allow to measure certain environmental pressures associated with material use.

1) ***Life cycle analyses*** measure environmental pressures of material use along the supply chain, including 'embodied' resources, e.g. energy and water that are required during the life cycle of materials (Gilbert et al. 2016). This method is thought to be the most accurate way of accounting for environmental pressures, but suffers from its specificity, data requirements, and assumptions on boundaries. The European Commission has developed and collected a comprehensive database to make the very many different methodologies comparable (EC 2012a). The availability of life cycle analyses for a wide range of products or materials is often the bottleneck for more broader analyses on firms, sectors, or countries (Femia and Moll 2005). However, the great advantage of life cycle analyses is their methodological depths in accounting for specific pressures and materials.

2) ***Input-output data*** can be used or extended to measure pressures by extending conventional input-output data with environmental satellite accounts, i.e. environmentally extended input-output analysis (Haan and Keuning 2001; United Nations et al. 2014). This is particular relevant to identify environmental pressures across sectors and countries. However, given the structure of input-output data, theoretically only sectoral, national, or international pressures can be measured, lacking to consider firm-specific or local pressures. In practice, the level of disaggregation is limited by the availability of disaggregated environmental data, as these are often only available for air emissions and energy use (Femia and Moll 2005). Additionally, input-output calculations assume that each sector produces a homogenous product or service (i.e. equal value-to-mass ratio across material uses), thus distorting the results in particular in those sectors which produce different products with heterogeneous material inputs (Lutter et al. 2016).

3) ***Material flow accounts*** are not suitable to adequately measure material-specific environmental pressures but rather provide a general sense of direction. However, EW-MFA can be complimented with additional data sources, for instance, data from life cycle analyses to measure environmentally weighted material consumption, RMC/MF, or TMC (Voet et al. 2003; Giljum et al. 2013). As shown in Table 3 and Table 4, the RMC/MF indicator somewhat corrects for the bias towards heavy construction minerals and puts a higher emphasis on metals. The data has become increasingly available but still lacks broad time horizons across countries and consistent methods to be useable for econometric research (Eisenmenger et al. 2016).

The challenge of comprehensively measuring all environmental pressures associated with materials is to account for all stages of the material life cycle, especially those that are *ex ante* not clearly defined. This is particular relevant for the use and disposal stages since materials can be used in many different products and applications (together with other materials), and might be landfilled, recycled, or incinerated. But even the production stage bears several uncertainties since environmental pressures often do not arise from materials themselves, but are a rather a combination of technology, production processes, and the nexus with other resources (e.g. energy, water, air). All such complexities make it challenging to disentangle the environmental pressures arising from individual materials. Averages and aggregation are thus typically used to approximate the associated environmental pressures from material use.

While local environmental pressures can be observed, they are mostly not systematically recorded. The environmental pressure for which most data is available and thus suited for empirical research are GHG emissions. To this end, the bulk of GHG emissions of aluminium, for example, are linked to the energy-intensive stages of the aluminium production, namely primary refining and smelting, which account for 99% of all GHG emissions of aluminium production (Ciacci et al. 2014). This is one reason why secondary aluminium production reduces the GHG emissions by approximately 85% compared to primary production (Hammond and Jones 2008). Hence, the GHG emissions from aluminium predominantly depend on the average energy-mix underlying the production and not necessarily the material itself. This is similar for a wide range of metals. To put this into perspective, roughly 7% of global energy use stems from the metal sector (UNEP IRP 2010a).

This goes back to fact that resources are interconnected, thus a change in the use of one resource has repercussions on the use of another, i.e. the resource nexus (Andrews-Speed et al. 2012) or systems challenge (Graedel and Voet 2010). In recent years, databases based on life cycle analyses have emerged to systematically measure impacts for a broad range of products (Frischknecht et al. 2005; Mongelli et al. 2005) and individual materials (Wuppertal Institute 2014).

For example, Hammond and Jones (2008) compiled a publically available database of around 200 materials. It estimates the embodied tonnes GHG emissions for a tonne of material applying the energy-mix and recycling rate of the United Kingdom. Despite limitations, such as data availability to account for the entire life cycles (i.e. cradle-to-gate instead of cradle-to-grave) and a strong focus on construction materials, it is a good example of how environmental pressures of individual materials could be approximated. The Wuppertal Institute (2014) calculates cradle-to-gate material intensity factors which essentially consider all indirect resources (materials, water, air, and land use) used to produce one kilogramme of a specific material. European recycling and efficiency levels are typically taken as thresholds. Besides its limited scope, this database provides a valuable insight for the magnitude of the 'embodied' resource use for certain materials and thus for the resource nexus. However, there are materials other than fossil fuels, which even considered in isolation from other resources, directly trigger environmental pressures. Biomass waste emits methane and burning wood directly releases stored CO_2, which in its extreme cases can cause haze (Aiken 2004).

In summary, despite all such challenges to adequately measure the environmental pressures associated with material use, the discussions above indicate a clear positive relationship between increases in material use and environmental pressures (UNEP IRP 2010a). Nevertheless, there are possible exceptions to this rule, in particular when the composition of material use changes. Thus, it is not *always* clear that more (or less) material use necessarily results in higher (or lower) environmental pressures, especially when measured in weight-based indicators. This is one motivation to empirically investigate the relationship between material use and GHG emissions, an environmental pressure for which most data exist.

2.3 Materials and the economy

Materials are used across the economy system. Materials take part in essentially every transaction of goods or services, and they are traded directly as commodities, and indirectly in intermediate or final products. They are exchanged both locally and globally. Materials comprise durable and non-durable properties. This brief overview demonstrates how complex and multifaceted the interrelation between materials and the economy is likely to be.

Materials play an important role in the value creation of economies since they are an input in the production function of economies (O'Mahony and Timmer 2009). Accordingly, materials, which have no intrinsic value, are converted into economic goods and services by adding labour, capital, and energy during the extraction, processing, and using phase of a material life cycle. This interplay between materials and other inputs can generate enormous value to the economic system (McKinsey Global Institute 2011).

However, material use does not *per se* generate value. Material-rich countries, for example, could benefit greatly in economic terms from extracting and trading materials, but paradoxically, this is often not the case, i.e. they experience the 'resource curse' (Mehlum et al. 2006; Bleischwitz and Corey 2012; Crivelli and Gupta 2014). Such complexities stress the importance of discussing the interactions between materials and the economic system.

Accordingly, it would go beyond the scope of this dissertation to cover all possible links between materials and the economy. To set the scope for the further analyses, connections between materials and the economy are exemplified by discussing material price volatility (Chapter 2.3.1), the criticality of materials (Chapter 2.3.2), and eco-innovations (Chapter 2.3.3).

2.3.1 Material price volatility

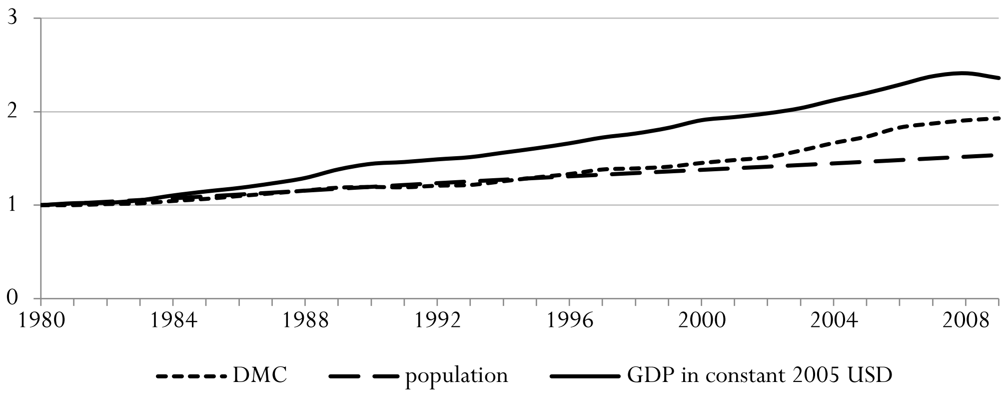
In accordance to the very definition of materials, they are desired and traded on markets (OECD 2007). Thus, materials have prices and are therefore directly connected to the economic system. This subsection focuses on the volatility of material prices since they have become increasingly relevant to research and policymakers in recent years (EC 2008; Valiante and Egenhofer 2013).

In order to evaluate the effects of material price volatility, it is important to first understand the determinants behind changes in material prices, such as changes in supply and demand. A global perspective is necessary in discussing material price changes since some materials are traded globally, especially metals and fossil fuels. Material use has increased in absolute terms over time alongside population and income growth (UNEP IRP 2014), in particular since the post-war era (Krausmann et al. 2009). The increase in absolute terms has occurred despite substantial productivity improvements in material use which historically has only led to a temporary absolute decrease of material use in times of effective policy measures, pressures from high material prices, and 'successful' innovations (Dahmus 2014).

More recent trends paint a similar picture. Global material use has almost doubled in absolute terms between 1980 and 2009 (most recent data; retrieved from the Global Material Flows database (SERI 2013)). Figure 3 displays data on GDP from the World Bank showing a higher increase compared to DMC, whereas data on population from the UN grew at a lowest rate (UN 2017; World Bank 2017). The figure shows that material use per capita and material productivity have increased between 1980 and 2009.

Figure 3 shows the global average of material use, thus hiding the substantial heterogeneity across countries. Most notably, China has increased its DMC between 1980 and 2009 by 639% and was thus the strongest driver for the increase in global DMC, as it accounts for almost one-third of global consumption in 2009. China's increasing trend is particularly strong since the early 2000s when its industrialisation and exports grew substantially (Economy and Levi 2014). But there are also several other examples of rising material use: Vietnam increased its material use by 727%, Singapore by 481%, Iran by 329%, Malaysia by 328%, Chile by 290%, and India by 208%. Nevertheless, there are also examples of countries that have decreased their absolute material consumption. For instance, Germany decreased its DMC between 1980 and 2009 by 26%, Japan by 21%, the United Kingdom by 18%, France by 9%, and Canada by 6%.

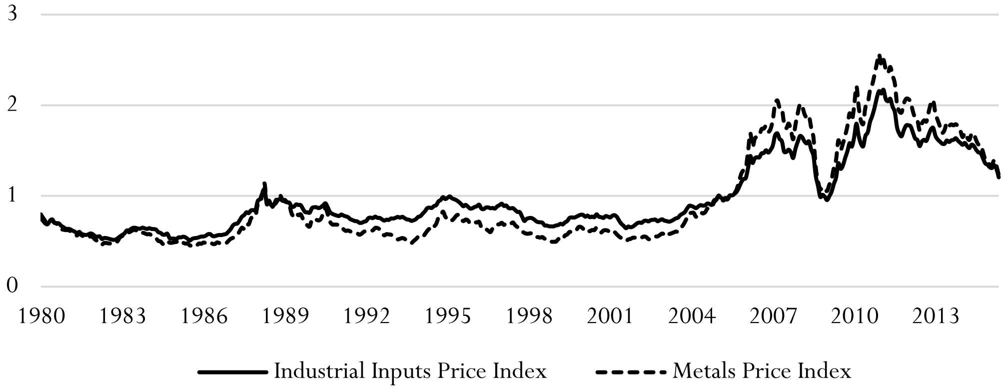
Figure 3: Trends in DMC, GDP, and population from 1980-2009 (1980=1).



This may lead to the impression that the industrialised world – on average – experiences a lower (or even negative) growth in material use compared to emerging economies, i.e. emerging economies might be catching-up. However, one has to keep in mind that the *per capita* consumption in the industrialised world is still higher compared to that of emerging economies. In 2009, the United States of America consumed 21 tonnes of materials per person compared to 4 tonnes in India, almost 16 tonnes in China, and 12 tonnes in Russia (Lutter et al. 2014). The majority of EU countries consumed more than 16 tonnes per capita (EC 2017a). Resource-rich economies such as Chile with 43 tonnes per capita can be considered outliers.

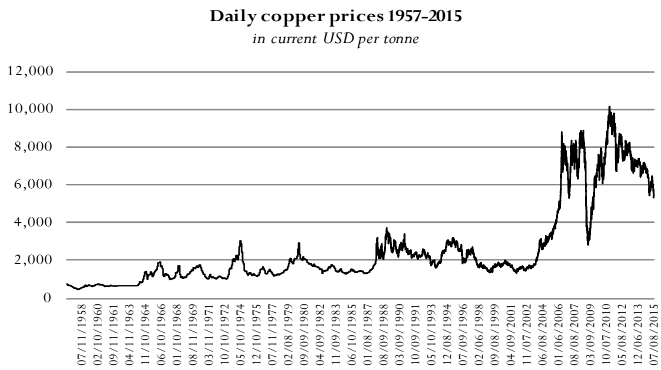
This increase in material use is one factor why material prices have increased, both in levels and volatility. However, it cannot fully explain material price volatility and only partly the recent low levels of material prices. Nevertheless, changes in the fundamentals, i.e. supply and demand, are often argued to be one determinant of material price volatility (Valiante and Egenhofer 2013). Before turning to other drivers of material prices volatility, it is worth appreciating the extent to which volatility has increased. As Figure 4, Figure 5, and Figure 6 show, material prices have become highly volatile. Such changes, in particular the intra-day volatility, cannot only be explained by more rigid changes in supply and demand.

Figure 4: Material prices from 1980-2015 (2005=1).



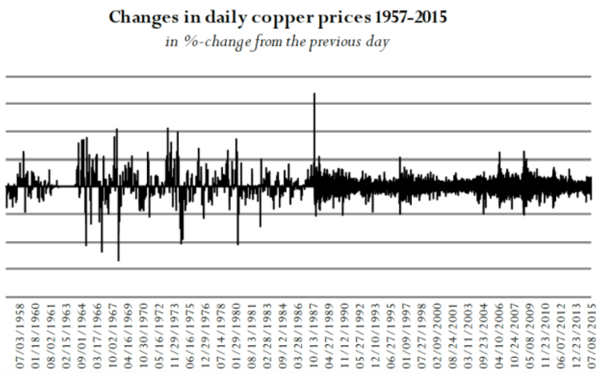
Notes: Monthly Industrial Input Price Index includes Agricultural Raw Materials and Metals Price Indices (based on Copper, Aluminium, Iron Ore, Tin, Nickel, Zinc, Lead, and Uranium Price Indices). Prices are non-seasonally adjusted nominal USD and range from 1980 to 2015. The base year for both indices is 2005. Source: IMF.

Figure 5: Daily Copper Grade A Cash prices.



Notes: Daily LME-Copper Grade A Cash prices between January 1957 and July 2015. Source: SNL database.

Figure 6: Daily %-changes in copper prices.



Notes: Daily %-changes compared to previous day of LME-Copper Grade A Cash between January 1957 and July 2015. Source: SNL database.

Figure 3 illustrates how smooth consumption develops over time, this is reflected in relatively stable demand and supply cycles. Valiante and Egenhofer (2013) consider eleven commodity markets (among them fossil fuels, metals, and biomass) and conclude that material price formation occurs through links between what the authors call *idiosyncratic factors* (e.g. substitutability, properties etc.), *fundamentals* (supply and demand), and *exogenous factors* (public subsidies, access to finance etc.). According to the authors' analysis, the increase in material use, especially in China, has led to a structure shift in prices, and to a lower extent to an increase in material price volatility.

While it is essential to differentiate between those materials that are locally traded, e.g. construction minerals, and those that are traded globally, e.g. metals, fossil fuels, changes in supply or demand are typically associated with structural shifts in prices, but not *per se* with price volatility (Valiante and Egenhofer 2013; Cuddington and Nülle 2014). Since there is no structured information available for local markets, this discussion relies on globally traded materials.

What becomes apparent from Figures 5 and 6 is that material price volatility, exemplified by copper prices, has increased in the magnitude of changes in levels (but not for price changes) and occurs much more frequently since the late 1980s. Similar conclusions can be drawn for the prices of aluminium and other materials. Thus, changes within short time periods have become 'the new normal', in line with energy price volatility (World Energy Council 2015).

To bring forward some of the reasons for these changes, Table 7 summarises potential drivers of material price volatility based on Valiante and Egenhofer (2013). The authors' focus lies on the connection of commodity prices with the financial system, which may have increased the pro-cyclicality of price changes and thus the extent to which prices fluctuate in response to shocks. Bouri et al. (2017) find a co-integrational relationship between the price volatility of gold and oil and volatility in the Indian stock market.

Table 7: Drivers of material price volatility based on Valiante and Egenhofer (2013).

- *Financialisation, i.e. the increasing interaction between commodity markets and the financial system (for most commodities since the early 2000s)*
- *Short-term costs fluctuations of interrelated resources (i.e. energy)*
- *Shocks to the business cycle*
- *Information shocks*
- *Close connection between futures and spot markets (i.e. high-frequency trading) increases the response to shocks*
- *Short-term production interruptions (i.e. strikes, natural disasters, water and electricity shortages, conflicts)*

To this end, Ecorys (2012) statistically analyses price levels and volatility using standard deviations for different time frames of 22 materials. The authors argue for similar drivers as Valiante and Egenhofer (2013) and add market power as well as speculation to the list. Following their analysis, the authors show that sand and gravel prices are less volatile compared to other materials, possibly because they are locally traded. Ma (2013) provides empirical evidence that changing the iron ore price formation framework from an annual to a quarterly benchmark pricing mechanism decreased iron ore spot price volatility using an autoregressive conditional heteroscedastic model, confirming information shocks as changing material price volatility.

A report by the United States Commodity Futures Trading Commission confirms most of the drivers from Table 7, emphasising that raw materials are increasingly seen as financial instruments, hence, financial and commodity markets become interlinked (CFTC 2008). Since price volatility incentivises firms to hedge against price fluctuations, for instance by engaging in the derivative market for commodity futures, such practices are likely to further increase the volatility of prices once there are shocks in the financial markets. While acknowledging that the causal effect between financial and commodity market is not clear, the report clearly shows that the financialisation of materials is correlated with higher material price volatility.

Generally, material price volatility is unlikely to be reduced in the future and already has negative impacts on the economy. For instance, Cavalcanti et al. (2011) find that commodity price volatility has a negative effect on economic growth due to lower capital accumulation using annual panel data from 1970-2007 for 118 countries and 32 primary commodities. Material price volatility is also associated with longer periods to develop new mining activity, thus delaying the potential economic benefits arising from commodity exports for resource-rich countries (Khan et al. 2016).

After briefly discussing the trends and determinants of material price volatility, two important connections to material use and material productivity can be drawn (Flachenecker and Rentschler 2015). First, material price volatility can incentivise firms and economies (especially those importing materials) to reduce their material use or increase their material productivity in order to decrease their exposure to the negative impacts of volatile prices. According to this argument, increases in material productivity could be result of increased material price volatility. However, at the same time, material price volatility can disincentive such investments in material productivity increases or material use reductions, because the returns of such undertakings are likely to be uncertain. Thus, material price volatility both incentivises as well as disincentives measures to reduce material use and increase material productivity, a paradox that will be discussed further in Chapter 4.

2.3.2 The criticality of materials

Given the substantial increase in material use over time, the question arises whether this growth could be sustained indefinitely. Concerns about limits to growth (Meadows et al. 1972), especially an increase in per capita use (i.e. *intensive growth*) became famous through the work by Thomas Robert Malthus. He argued that there is a binding constraint on the availability of natural resources such as fertile land for food production for an ever-increasing population size (Malthus 1798). Such references to resource scarcity can also be found in David Riccardo's work on the law of diminishing returns (Ricardo 1817).

Later work acknowledged that technology-induced productivity gains and substitution could counterbalance increasing demand and thus sustain growth over time (Solow 1957; Ayres and van den Bergh 2005). Nevertheless, concerns about possible supply restrictions of important materials have not disappeared, caused by specific events such as political conflicts and the oil price shocks in the 1970s and 1980s. Even if there is a broad consensus that most materials are physically abundant (Tilton 2001), the issue of criticality seems more urgent than ever, in particular since low-carbon technologies often require specific materials that might become critical over time (Busch et al. 2013; Bleischwitz et al. 2013; Roelich et al. 2014).

The term criticality goes beyond solely physical availability and also considers the constant and short-term access to individual materials for single countries, sectors, or firms. There is a particular focus on 'critical materials' since those materials are without immediate substitution, economically important, and under possible supply risk (EC 2014a). Materials may be classified by the EU as critical under the following situations:

- ***Importance:*** The material is economically important, which means it is relevant in terms of its relative use within a market (EC 2014a). The EU's methodology does not take the market size itself into account.
- ***Lack of substitution:*** No short-term substitution to a 'critical material' exists or can be accessed or the possibility to recycle is insufficiently low (EC 2014a). Strategies to recycle 'critical materials' appear to be unsuccessful so far (Graedel et al. 2011) and often lack the necessary infrastructure for effective collection, and fail to be economically viable (Allwood et al. 2013).

- ***Abuse of power:*** Suppliers (or supplying nations) may abuse their market power, thus not only increasing material prices but also limit supply causing disruption. Achzet and Helbig (2013) show that country concentration measured by the Herfindahl–Hirschman index is one of the main supply risks of certain materials such as Indium.
- ***Conflict risks:*** As already discussed above, materials are linked to other resources. Thus, geopolitical conflicts about materials may trigger direct supply restrictions of that materials or interlinked materials (Bleischwitz et al. 2013).
- ***Ore grade risk:*** Declining ore grades may make extraction of materials costlier in the future and thus decrease the quantity supplied (Tilton 2001). However, in perfectly competitive markets, this development would be anticipated by market participants and result in increasing prices, which incentivise innovations to reduce demand, increase technological capabilities, or trigger substitution.

The definition of what can be considered critical is important but often overlooked. Erdmann and Graedel (2011) and Achzet and Helbig (2013) show that depending on the methodology used to assess criticality (time horizons, substitutability, aggregation of indicators etc.) different materials are classified as critical. Moreover, Lapko et al. (2016) argue that the level on which criticality is assessed results in different outcomes. The authors propose to have criticality assessments not on individual industry levels, but rather take interdependencies within and between supply chains into account.

The criticality of materials is thus an important and strategic issue. However, given the definition of materials in this dissertation, the following discussion indicated that criticality is only indirectly or partly accounted for. The EU has currently declared 20 materials as critical, mostly metals. According to the European Commission's compilation guide for EW-MFA accounting (EC 2013a), such critical materials are either not accounted for (cooking coal, Gallium, Indium, Magnesite, Niobium, and heavy and light rare earth metals) or account for a negligible part of material flow indicators (Antimony, Beryllium, Borates, Chromium, Cobalt, Fluorspar, Germanium, Magnesium, Natural Graphite, Platinum group metals, Phosphate rocks, Silicon metal, and Tungsten).

Therefore, the bulk of materials are not in danger of being or becoming critical since they are distributed across countries (see Bleischwitz et al. 2009, p.6/7 for an overview). Nevertheless, supply restrictions of critical materials can have repercussions on other materials in the production of products, also those possibly enabling a reduction of material use (Roelich et al.

2014). This dependency on certain materials could hence incentivise efforts to increase material productivity or reduce material use to lower the exposure to the supply of such materials, similarly to material price volatility. Still, the great majority of how materials are defined and measured in this dissertation is not 'critical'. This is why the issue of criticality, while being important, is not directly considered in the empirical analyses but is discussed in Chapter 4.

2.3.3 Materials and eco-innovations

Materials are an input in the production function of economies, but as mentioned previously, the value creation associated with materials also depends on the way they are converted into economic goods and services. Regardless of the growth model in mind, the efficiency by which materials (or any other input) are used in the production process is directly connected to technological advancements and thus to innovations (Acemoglu 2008). This subsection will briefly discuss a specific kind of innovation, an 'eco-innovation', because it is best aligned with the economic and environmental components of materials.

An eco-innovation is defined as "the introduction of a new or significantly improved product (good or service), process, organisational change, or marketing solution that reduces the use of natural resources (including materials, energy, water, and land) and decreases the release of harmful substances across the whole life-cycle." (Eco-Innovation Observatory 2012). As such, eco-innovations are often used synonymously with related terms such as green innovations, environmental innovations, or environmentally sustainable innovations (Buhl et al. 2016).

Following the definition above, there are two conditions attached for a particular innovation to be defined as an eco-innovation, also referred to as 'double externalities' (Rennings 2000).

1) ***Reduction of material use:*** An eco-innovation has to result in a reduction of the use of one or several natural resources such as materials. However, it is not clear from the definition whether the decrease in material use has to be in absolute terms or relative to output, thus an increase in material productivity. Irrespectively of the terms of material reduction, this change in how materials are used in the production process is the result of (technological) advancements. In line with conventional innovations, the know-how may not only benefit a particular economic agent but could also spill-over and diffuse in the market, hence generating a positive externality (first externality).
2) ***Reduction of environmental pressures:*** An eco-innovation needs to reduce negative environmental pressures across the material life cycle. This reduction in environmental pressure, often a negative externality (second externality), can occur at any stage of the

life cycle which extends the definition of conventional innovations (Eco-Innovation Observatory 2011). Hence, eco-innovations should generate positive externalities and also decrease negative externalities on the environment, i.e. 'double externality'. Assuming that GHG emissions are being reduced, eco-innovations can be considered one strategy to align competitiveness and climate change mitigation.

In addition to the second condition which separates eco-innovations from conventional innovations, there are further differences. Comparable to conventional concepts of innovations, eco-innovations also comprise various types of innovations (product, process, organisational). However, eco-innovations are more substantive in their nature and are not only generated by profit-maximising firms but also non-profit organisation, thus requiring a broader understanding of the concept which includes social (e.g. social media, sharing-economy) and institutional innovations (e.g. environmental labelling) (Rennings 2000; Machiba 2010). Ekins (2010) argues that technological change triggered by eco-innovations cannot be seen in isolation from non-technical issues, such as organisational, marketing, societal, and institutional aspects, but are rather an integral part of socio-economic and institutional settings.

Whether material productivity increases resulting from eco-innovations result in a reduction of environmental pressures, thereby complying with the second externality condition previously outlined, will be investigated in Chapter 8. The results will show that for specific firms, sectors, and countries, eco-innovations leading to greater material productivity can reduce environmental pressures along the material life-cycle, thus contributing to climate change mitigation.

Moreover, the role of eco-innovations in reducing the potential for rebound effects resulting from material productivity improvements are discussed in greater detail in Chapter 7. The rationale is that instead of passing on the benefits of such productivity increases to individuals, which may choose to increase their consumption possibly leading to rebound effects, firms could be incentivised to channel the gains towards eco-innovations. Font Vivanco et al. (2016) suggest that this could reduce the likelihood of rebound effects.

After discussing the definition of eco-innovations, it is important to introduce the factors creating such innovations. To this end, a strand of the innovation literature is dedicated to the determinants of eco-innovations (Schiederig et al. 2012). The literature appears to converge on three main groups (and their interaction) that determine eco-innovations (Ghisetti and Pontoni 2015).

1) ***Technological push factors*** which enable eco-innovations by advancements in technology triggered by research and development (R&D). For example, cost savings due to high material prices and market share expansion are often cited as technological push factors, but also spontaneous, undirected, and basic research can result in technological progress (Demirel and Kesidou 2011; Horbach et al. 2012; Triguero et al. 2013).
2) ***Demand pull factors*** which trigger eco-innovations when consumers and specific market conditions require economic agents to engage in (eco-)innovative processes, for instance, by demanding eco-products, high material productivity, or fierce competition along the environmental branding of firms (Rehfeld et al. 2007).
3) ***Policy push factors*** are driven by policies and regulation which can have a *direct* effect on eco-innovations, e.g. through the introduction of standards or market-based instruments incentivising firms to develop eco-innovations to reduce their environmental externalities, or an *indirect* effect through strengthening the demand pull factors of consumers (Rennings and Rammer 2009; Rennings and Rexhauser 2011). The empirical analysis in Chapter 8 assesses eco-innovations that are motivated the availability of public financial support, i.e. government grants, subsidies, or other financial incentives.

Given the multifaceted nature of eco-innovations, a major challenge is how to adequately measure them (Machiba 2010). Some scholars argue that eco-innovations cannot be measured directly, but through finding proxies, for instance, the number of patents with environmental benefits or economic activity in innovative 'green' sectors (ILO 2013; Kemp et al. 2013; OECD 2014). Such 'outcome indicators' sometimes include material productivity (Bleischwitz et al. 2009a). Since this approach is based on existing data, eco-innovation could be measured on country or firm level. Other scholars additionally propose indicators measuring different types of products, attitudes of firms, and 'green' policies (Kemp and Pearson 2008).

The approach to rely on 'outcome indicators' faces some obvious challenges. For instance, patents with environmental benefits might not lead to an innovation, and even if they do, they might not be diffused through the market, and even if they are, they might not reduce environmental pressures. Given the lack of comprehensive data and measurement concepts, this approach needs to rely on approximations. The generally problem is that there is a very limited amount of comprehensive and adequate environmental performance indicators available (Ekins 2010).

Therefore, more recent attempts to measure eco-innovations rely on a scoreboard of indicators which are aggregated into one single output number. For example, the EU's Eco-Innovation Observatory covers 13 indicators, including eco-innovation inputs (governmental R&D spending, research personnel as share of total employment etc.), eco-innovation activities (firm's participation in eco-innovations etc.), eco-innovation outputs (eco-patents), environmental outcomes (material productivity, GHG emission intensity etc.), and socio-economic outcomes (employment in eco-industries, exports from eco-industry etc.) (Eco-Innovation Observatory 2011).

While the theoretical benefit of eco-innovations is obvious given their 'double externality' approach, there is limited empirical evidence on the determinants of eco-innovations and whether they are beneficial to the economy and the environment (Del Rio et al. 2016). This might also be linked to existing barriers to realise eco-innovations on a broad scale, thus making it possible to be studied in detail (Jordan et al. 2014; Ghisetti et al. 2016). Nevertheless, Horbach (2014) finds that eco-innovations triggering a reduction in material use in 19 European countries are mainly driven by the customers' demand for eco-friendly products and cost saving considerations. The author investigates the Community Innovation Survey of the European Commission in 2008.

Fischer and Brien (2012) summarise the yearly savings potentials for firms in the German manufacturing sector using data from the German Material Efficiency Agency. The authors conclude that almost €200,000 could be saved annually which accounts for 2.3% of yearly turnover in the sector. However, such results are based on 92 observations of those firms that had a publically financed assessment, thus limiting their explanatory power.

Arguably most short term gains can be achieved in process eco-innovations (Eco-Innovation Observatory 2011; Eco-Innovation Observatory 2012). Related research efforts focusing on systemic eco-innovations defined as "a series of connected changes improving or creating novel functional systems that reduce use of natural resources and decreases the release of harmful substances across the whole life cycle" conclude that the markets for such fundamental changes is currently still rather 'niche' (EC 2015b).

Besides the lack of available data and thus empirical evidence on the effects of eco-innovations on economic and environmental performance, the concept of eco-innovations is an important contribution in understanding, for instance, the link between materials and value creation in the economic system as well as a strategy to simultaneously reduce negative environmental externalities such as GHG emissions. Therefore, and given the limited empirical research on the issue, the effect of eco-innovations on material productivity, competitiveness, and GHG emissions of firms in the EU will be investigated in Chapter 8.

2.4 Materials and policy

Materials cover a wide range of multifaceted, interdisciplinary, and interrelated topics, thus affecting multiple policy domains, including economic growth, trade, environmental, competitiveness, climate, investment, education, research, and innovation. This breadth is what makes materials an important and complex policy area. The focus of this section is on material use and material productivity policies. After a brief overview on the global level, the material policy agenda of the EU will be outlined and discussed in greater detail.

Materials have long been an explicit policy issue (Malthus 1798; European Coal and Steel Community 1951; US Government 1952). However, linking the economic and the environmental dimension of materials is only a more recent consideration in global policymaking. Most notably since the Stockholm Declaration of the United Nations in 1972, in which materials were declared "essential to environmental management since economic factors as well as ecological processes must be taken into account" (UN 1972), the framing that materials comprise an economic and environmental dimension has reached global policy forums.

This notion was confirmed at the beginning of the sustainable development agenda with the Agenda 21 in Rio de Janeiro in 1992 (UN 1992). At this initial stage of contemporary material policies, the focus rested (and still rests) on supporting research, establishing material databases, monitoring developments, and trying to better understand the links between materials, the economy, and the environment. Additionally, increasing resource efficiency (and thus material productivity), decreasing the amount of waste, and increasing recycling were already then prominent policy recommendations.

However, what has to be kept in mind is that all measures outlined in the Agenda 21 document were voluntary, thus each country was sovereign in implementing policies according to its preferences. This lack of a binding nature of this and comparable initiatives, even today, is argued to have contributed to the heterogeneity of definitions on material indicators as discussed in this chapter, diverging political as well as administration efforts on implementing material policies, and a lack of transparency on material value-chains (Bahn-Walkowiak and Steger 2015).

One important follow-up to the Agenda 21 was the Organisation for Economic Cooperation and Development (OECD) Environmental Strategy for the First Decade of the 21st Century (OECD 2001). A core objective was to decouple material use, economic growth, and environmental pressures through "economic instruments, such as removal of environmentally harmful subsidies, green tax reform, and other market-based instruments, consumer and product information based instruments, as well as regulatory instruments and voluntary approaches" (OECD 2001). Businesses and industry are thought to have a "special responsibility" in achieving decoupling. Accordingly, the role of policy is to provide the framework conditions for private actors to increase their material productivity and to break the link between economic activity, material use, and environmental pressures. The quantitative underpinning of achieving (relative) decoupling between material use and economic growth, i.e. increasing material productivity, was decided during the World Economic Summit in Evian in 2003 (G8 2003).

Ever since these 'pioneer initiatives', among other initiatives (Bahn-Walkowiak and Steger 2015), material policies have been taken up by numerous stakeholders. International organisations have worked extensively on the issue and established high-level expert groups, such as the UNEP IRP in 2007 (e.g. UN 2015; UNEP IRP 2011, 2014; OECD 2015). Additionally, the intergovernmental group G8 committed itself to reducing waste in its Kobe 3R Action Plan (i.e. 3R stands for reduce, reuse, and recycle) under Japan's presidency in 2008 (G8 2008). The G7 institutionalised discussions on resource efficiency by establishing an Alliance on Resource Efficiency in 2015, a platform to exchange views and promote best practice examples for resource efficiency policies (G7 2015). Such initiatives resulted in comprehensive reports collecting the current evidence base, supporting policymakers in designing material policies, and informing the broader public on material-related matters (OECD 2016; UNEP IRP 2017)

The link between materials and policy has recently become even more evident on the global level, exemplified by three important agreements in 2015.

1) ***The Paris Climate Agreement*** comprises the goal to reduce global GHG emissions to keep the average surface temperature in this century well below 2 and close to 1.5 degrees Celsius compared to pre-industrial levels (UN 2015a). As discussed in a previous section, materials directly and indirectly generate GHG emissions across their life cycles (UNEP IRP 2010a). Therefore, the reduction of material use – and thus

their embodied GHG emissions – contributes to mitigating climate change (Barrett and Scott 2012).

2) ***Sustainable Development Goals***: The international community agreed on 17 SGDs as part of a renewed sustainable development agenda (UN 2015b). Materials play a key role in achieving the SDGs, in particular for improving access to food (Goal 2), ensuring access to sanitation (Goal 6), sustainable energy (Goal 7), building sustainable infrastructure (Goal 9), ensuring sustainable production and consumption patterns (Goal 12), and mitigating climate change (Goal 13) (Bleischwitz and Flachenecker 2017).
3) ***Addis Ababa Action Agenda***: The world agreed on the Addis Ababa Action Agenda which aims to increase development finance to make progress on the Paris Climate Agreement as well as the SDGs (UN 2015c). To achieve a reduction of GHG emissions and achieve the SDGs, substantial investments are required, including in material-intensive infrastructure projects (Peake and Ekins 2016).

The link between materials and policies is also reflected by national governments that developed strategies, targets, and platforms (e.g. BMUB 2015; Finish Ministry of Employment and the Economy 2014). For example, Sweden introduced a natural gravel tax of around €1.44 per tonne (see Bahn-Walkowiak and Steger 2015 and EEA (2011b) for an overview on material taxation). Furthermore, national governments promote and incentivise private and public investments in material productivity through multilateral development banks (EIB 2015; World Bank 2015; EBRD 2015b) and their national development banks (e.g. KfW 2009). Lastly, the private sector has also developed strategies to reduce material use and increase material productivity (e.g. WBCSD 2010; McKinsey Global Institute 2011).

Bahn-Walkowiak and Steger (2015) review international and national material policies using a range of criteria and conclude that in particular material use or material productivity targets often lack a time frame as well as a concrete vision on how to achieve them. Additionally, material productivity objectives focus on the supply side of material use, often not accounting for the demand side. The authors further argue that mainstreaming material policies is needed to overcome policy silos and consider the interlinkages between policies to identify effective policy-mixes.

2.4.1 An overview of the material policy agenda in the European Union

Policies focusing or relating to materials are particularly visible in the EU. This goes back to the fact that the EU depends on material imports, as it has one of the highest net imports per capita of materials worldwide (EC 2017a). Furthermore, the EU attempts to re-industrialise its economy by increasing the contribution of the manufacturing industry from around 15% in 2013 (depending on the definition of industry) to 20 percent by 2020 which is likely to lead to more material use (EC 2014b). At the same time, the EU pledged to reduce its GHG emissions by at least 20% in 2020, 40% in 2030, and 80% in 2050 compared to the level in 1990 (EC 2011c).

Additionally, the EU signed up to the SGDs which includes the aim to use natural resources sustainably (UN 2015b). Given that the manufacturing industry alone accounts for 27% of all direct GHG emissions in the EU (EEA 2013), there might be a trade-off between increasing the material-intensive industrial base of the EU economy, reduce the dependency of material imports, and reducing GHG emissions.

These considerations have led the EU to bring forward numerous policy initiatives, mainly aiming to enhance its material productivity, whereas reducing material use in absolute terms is not an explicit objective (Bahn-Walkowiak and Steger 2015). Important material policy initiatives in the EU are summarised in Table 8.

Roadmap to a Resource Efficient Europe

In 2011, the EU declared resource efficiency as one of seven flagship initiatives in the framework of its Europe 2020 Strategy with the objective to create the conditions for smart, sustainable, and inclusive growth (EC 2011a). Europe 2020 is the ten-year growth strategy proposed by the European Commission to guide EU policymaking between 2010 and 2020 (EC 2010a). Since the EU measures resource efficiency with the lead indicator material productivity, any resource efficiency policy is thus implicitly also a policy to increase material productivity (EC 2011b). Attributing resource efficiency, and thus material productivity, with such importance by making it an explicit objective of the EU's growth strategy, material policies have become an important domain for the EU.

Table 8: Key initiatives of the EU material policy agenda.

Name of initiative	*Year of introduction*	*Main purpose*
Europe 2020 Strategy	2011	– Ten-year strategy to create the conditions for smart, sustainable, and inclusive growth – Resource efficiency is one flagship initiative of this strategy
Roadmap to a Resource Efficient Europe	2011	– Part of the Europe 2020 Strategy's flagship initiative on resource efficiency – Sets out the vision of increasing resource efficiency to achieve the decoupling of natural resource use from economic growth – Proposes material productivity as a lead indicator to measure progress on resource efficiency
Circular Economy Package	2015	– An initiative to increase the circularity with which natural resources are used in the economic system – Includes, for example, revising waste and recycling targets as well as the eco-design legislation
Circular Economy Action Plan	2015	– Part of the Circular Economy Package – Emphasis on financing material productivity, resource efficiency, and circular economy investments
Raw Materials Initiative	2008	– Focus on securing foreign and domestic supply of raw materials through strategic trade deals and increasing domestic recycling
European Innovation Partnership on Raw Materials	2012	– Part of the Raw Materials Initiative – Platform that brings together stakeholders across industry, public services, academia, and civil society with the aim to exchange experiences and promote innovation activities
7th Framework Programme for Research and Technological Development	2007	– A funding programme of the EU for research and innovation projects for the period 2007-2013
Horizon 2020 (or 8th Framework Programme for Research and Technological Development)	2014	– The EU funding programme succeeding the 7th Framework Programme for the period 2014-2020 – Includes the investment programme 'Industry 2020 in the Circular Economy' which funds pilot innovations for a resource efficient and circular economy
European Fund for Strategic Investments	2015	– An initiative of the European Commission and European Investment Bank to increase economic growth by mobilising private capital for investments – Supports material productivity, resource efficiency, and circular economy investment projects
Ecodesign Working Plan	2016	– An initiative to identify, report, and set standards for designing products to improve their material productivity, energy efficiency, and circularity – Attempts to reduce obstacles to innovation through multi-stakeholder innovation deals and promoting products that are easy to repair, reuse, and recycle while saving resources

In order to structure the cross-cutting nature of the this policy agenda, define common goals, and coordinate initiatives between those on the EU-level and those from the EU member states or the regional level, the Roadmap to a Resource Efficient Europe was introduced in 2011 (EC

2011b). It sets out the vision of increasing resource efficiency to achieve the decoupling of natural resource use (and its associated environmental pressures) from economic growth. Specific areas are identified for which resource efficiency is expected to yield the highest benefits, namely nutrition/food waste, housing, and mobility – all material-intensive areas.

Implementing the resource efficiency agenda set out in the Roadmap requires the participation of various stakeholders, including academia, national and regional policymakers, the private sector, and civil society. To this end, the European Resource Efficiency Platform was established in 2012. The platform calls for coherent and stringent material policies, including a quantitative target to increase material productivity by 30% by 2030 compared to its level in 2014 (European Resource Efficiency Platform 2014). This platform's recommendation was considered far reaching and ambitious at the time, but the European Commission did not follow it and consequently did not propose the implementation of any quantitative target. With the end of the European Commission lead by José Manuel Barroso, the platform presented its final report and recommendations in 2014.

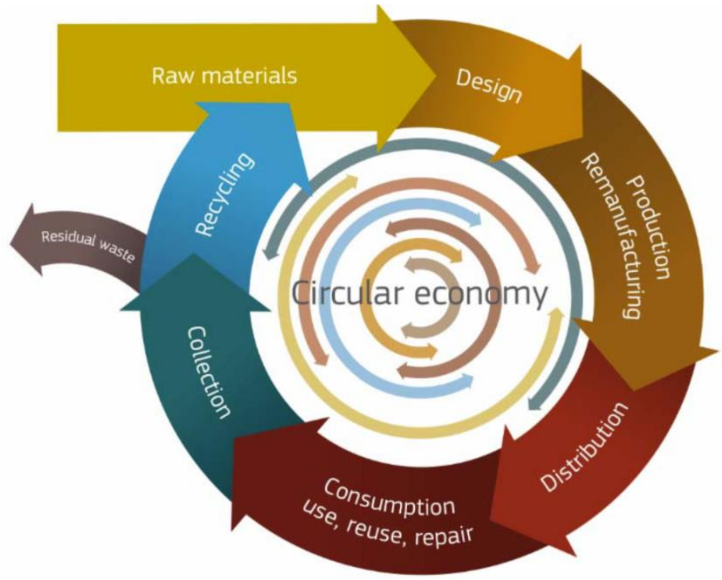
Circular Economy Package

First of all, it is crucial to understand the link between the circular economy and material productivity. Increasing the circularity of materials typically increases material productivity. For instance, domestic recycling steel allows recycled steel to become an input in the production function, *ceteris paribus* increasing output, while not affecting material use indicators, assuming steel is recycled and used domestically, i.e. it is not traded. In short, increasing the circularity of steel increases output while leaving conventional material use indicators unchanged, thus increasing material productivity.

However, increasing material productivity might not necessarily result in higher circularity. For example, reducing the steel input of a product might simply lead to a reduction in the demand of steel, thus not necessarily affecting the circularity of steel. In summary, a policy aiming to increase the circularity of materials is implicitly also a policy aiming to improve material productivity, but merely focusing on a specific aspect of material use. Therefore, the emphasis on a circular economy might impede the unfolding of the more comprehensive goal of increasing material productivity.

In 2014, the EU material policy agenda was complemented by the declared aim of increasing the circularity with which materials (and other resources) are used in the economic system. Even though the objectives of the resource efficiency agenda remain fairly similar, the narrowing down of this agenda to a circular economy (sometimes also referred to as a resource efficient and circular economy) was also linked to the change in the leadership of the European Commission at that time. Figure 7 illustrates the EU's understanding of the circular economy.

Figure 7: An illustration of the concept of a circular economy (Source: EC 2014c).



The initial Circular Economy Communication developed under the previous leadership of the European Commission was withdrawn under the leadership of Jean-Claude Juncker since it was considered to be 'red-tape' for businesses. The withdrawal followed the pressures of pro-business interest groups and resulted in a public discussion between proponents and opponents of the resource efficiency agenda. The European Commission's First Vice President Frans Timmermans then announced to propose a revised Circular Economy Package, including a Circular Economy Action Plan which was introduced in 2015 (EC 2014c; EC 2015a; Flachenecker 2015a).

The Action Plan claims to put more emphasis on the issue of financing material productivity, resource efficiency, and circular economy investments compared to the withdrawn Communication. Accordingly, it suggests a more prominent role of the European Investment Bank in this context. The rationale behind the Action Plan is stated to be the focus on concrete steps across the entire life cycles and supply chains of materials to incentivise the reuse, recycling, or remanufacturing of otherwise *wasted* materials and other natural resources.

As part of this agenda, revised EU targets on waste and recycling have been proposed and are currently in the legislative process (EC 2017b). For instance, it is aimed to recycle 65% of municipal waste by 2030 and 75% of packaging waste by 2030. Landfilling waste leads to the loss of all resources that are considered waste and is thus contrary to the concept of a circular economy. Therefore, the proposed objective is to reduce landfilling to below 10% of municipal waste by 2030. Moreover, through its Ecodesign Working Plan, the European Commission is also seeking to reduce obstacles to innovation through multi-stakeholder innovation deals and promoting products that are easy to repair, reuse, and recycle and that save material use (EC 2016a).

Compared to the first Circular Economy Communication, the new Circular Economy Package completely drops the idea of a comprehensive material productivity target based on one synthetic indicator. Instead, a monitoring framework with a number of specific indicators is expected to be presented by the end of 2017 (EC 2015a). However, setting quantitative targets, even of non-binding nature, appears to be very unlikely.

Additional initiatives

Simultaneously, other policies covering (raw) materials, defined as metals, minerals, and forest-based materials, have been developed. In 2008, the Raw Materials Initiative was introduced focusing mainly on securing foreign and domestic supply of materials through strategic trade deals and increasing domestic recycling (EC 2008). Crucially, the EU has no competencies for subsoil materials, thus relying on the trade and environmental angle on materials, in which the EU has either exclusive competences (trade) or shared competences with the member state (environment) (EU 2017).

As part of the Raw Materials Initiative, the European Innovation Partnership on Raw Materials was created, which is a platform that tries to bring together stakeholders across industry, public services, academia, and civil society with the aim to exchange best practice examples and promote innovation activities (EC 2012b). Additionally, the EU material policy agenda is supported by regular assessments on the criticality of raw materials and commodity markets to identify possible dependencies and recommend measures to ensure a secure access to those materials (EC 2014a). Such assessments became particularly important during the peak of material prices between 2006 and 2011.

Innovation and investment focus

Across all initiatives mentioned above, common themes to achieve an increase in material productivity are (i) *innovations*, in particular eco-innovations, and (ii) *investments*, especially on the firm-level and in technology as well as research. More specifically, the idea behind the general policies outlined above is to create the right environment for innovations and investments to take place, thus enabling the potential gains from increasing material productivity to unfold.

For example, an initiative in the Horizon 2020 framework, a funding programme of the EU for research and innovation projects, was launched on Industry 2020 in the Circular Economy (EC 2015c). This initiative has a budget of €650 million to fund pilot innovations with the aim to identify and address potential regulatory obstacles for innovators. Furthermore, the outreach of general EU funding (e.g. Cohesion Policy Funds and support for SMEs) has been directly linked to the material policy agenda. This has led to the inclusion of circular economy related priorities into the EU Cohesion Policy Funds which promote investment in research and innovation. In general, about €150 billion from the Cohesion Policy Funds support investment in innovation, SMEs, low-carbon economy, and environmental protection over the 2014-2020 funding period (EC 2016b). However, there is no systematic assessment on whether these funds and programmes have significantly improved the resource efficiency or circularity of firms, sectors, regions, or countries.

A new platform, the Circular Economy Finance Support Platform, for financing material productivity, resource efficiency, and the circular economy has recently been created on the EU level. Its initial task is to raise awareness and share best practice examples through the means of analyses, advice, and coordination activities across investors (EC 2017c). Investments in material productivity, resource efficiency, and the circular economy by the European Investment Bank sum up to €14.9 billion between 2005-2014 (EIB 2015) and by the European Bank for Reconstruction and Development to €18.3 billion between 2006-2015 (EBRD 2015a). This reflects the importance the public sector gives to mobilising investments for incentivising eco-innovations and technological updates to achieve progress on the EU's material policy agenda.

Nevertheless, one important shortcoming remains. While the economic viability of these publically supported investments is often a necessary requirement for the projects to be approved, their environment effects are either not assessed at all or only through *ex ante* predictions of their possible implications without systematic *ex post* evaluations. This has prompted research on developing firm level indicators allowing to measure GHG emission savings from resource efficiency projects (Rentschler et al. 2016).

As part of the European Commission's goal to create a Capital Markets Union, an initiative to further integrate the capital markets of EU member states, private investments supporting material productivity are explicitly mentioned (EC 2016c). The aim is to increase the availability of *green funds* to at least 20% of the EU budget for the period 2014-2020. Moreover, a high-level expert group on sustainable finance was set up in 2016 to recommend key elements for a strategy facilitating public and private investments towards sustainable investments, including material productivity investments. The high-level expert group is expected to deliver its report by the end of 2017.

Such measures at EU level are complemented by country-specific material policies. For instance, 9 out of 28 EU member states (Austria, Denmark, Estonia, Germany, United Kingdom, Hungary, Italy, Romania, and Sweden) have a quantitative target for increasing material productivity or decreasing material use (Bahn-Walkowiak and Steger 2015).

Interestingly, such initiatives on the EU and national level are correlated with tangible progress towards greater material productivity (EC 2017a). For instance, absolute material use, measured as DMC, in the EU has declined by 9% in 2015 compared to 2011 when the Roadmap to a Resource Efficient Europe was introduced. Also, material productivity in the EU, measured as the ratio between GDP in DMC, has increased by 22% between 2011 and 2015. Lastly, absolute GHG emissions in the EU have decreased by 23% in 2014 compared to 1990 (7% between 2011 to 2014).

However, it is not at all clear whether the such policies have any causal relationship with these improvements. In order to more thoroughly investigate the link between policies, materials, and environmental pressures, Chapter 8 will investigate whether public financial support for eco-innovations have caused a reduction in GHG emissions through increased in material productivity.

2.4.2 The status quo and future of the material policy agenda in the European Union

After introducing the EU material policy agenda, current circumstances and future challenges relevant to its political economy are discussed.

- On the one hand, the EU is currently facing multiple and existential challenges. The financial crisis starting in 2008 and followed by a sovereign-debt crisis has tied up considerable political attention to addressing these challenges. The peak of the migration movements in 2015, the increasing demands for a coordinated foreign and security policy, the decision of the United Kingdom to leave the EU, and a growing scepticism about the EU in general shifted the public and political focus to these policy areas (Baldock et al. 2016; Juncker 2016). These are some of the reasons that may have led the EU to focus on *jobs and growth* (Juncker 2014). This shift facilitated the initial withdrawal of the legislative proposals for a circular economy as well as a postponed discussion on material indicators (EC 2011b; EC 2014c; EC 2015a).
- On the other hand, the revised Circular Economy Action Plan is explicitly mentioned as a top priority in the work programme of the European Commission for 2017 (EC 2016d). Also, the announcement to extend and increase the funding capacity of the European Fund for Strategic Investments that also invests in material productivity projects is in line with the continuation of the material policy agenda (EC 2016e). These developments might be linked to the global commitments the EU has subscribed to such as the Paris Agreement and the SDGs discussed above. Additionally, various EU research projects supported by the EU Framework Programmes for Research and Technological Development might indicate the continued commitment towards the material policy agenda (e.g. Distelkamp and Meyer 2016).

While the *status quo* shows two opposing forces, the future of the EU material policy agenda also depends (besides political cycles) on more fundamental matters. The following five issues currently being underrepresented in the political and academic debates can be identified.

1) ***Implementation of the existing agenda***: The first Environmental Implementation Review of the European Commission states that ineffective coordination among government entities and hierarchies as well as lack of administrative capacity and knowledge often prevent the successful implementation of existing regulation, including on material productivity, resource efficiency, and the circular economy (EC 2017d). Implementing material policies can be cumbersome, in particular if governments fail to actively engage with relevant actors in the implementation phases of such measures (Cramer 2013). Therefore, the EU material policy agenda could put more emphasis on the successful implementation of existing legislation.

2) ***Monitoring progress***: Currently, the progress towards greater material productivity is measured by the Resource Efficiency Scoreboard, analysing data on materials, water, land, and CO_2 (EC 2016f). The lead indicator is material productivity based on GDP and DMC. Additionally, the Raw Material Scoreboard monitors developments concerning raw materials in 24 indicators (EC 2016g).

   The adoption of a material productivity target was advocated by the European Resource Efficiency Platform (2014) including the measurement of indirect resource flows, i.e. RMC. This recommendation was debated in the European Council of Environmental Ministers in the framework of the mid-term review of the Europe 2020 strategy, however, reaching no agreement (Council of the European Union 2014). Subsequently, the European Parliament published a report calling for lead indicators on material productivity by 2019 (EP 2015). As set out in the European Commission's work programme for 2017, a monitoring framework is currently under development (EC 2016d).

   As identified by the Environmental Implementation Review a lack of quality data hinders the monitoring and academic research of the effects of certain policies as outlined previously (EC 2016h). Therefore, the development of consistent, comprehensive, and robust indicators could support the political process in developing, implementing, and monitoring the EU material policy agenda.

3) ***Evidence base***: Unlike energy efficiency, estimating the impacts of material productivity on the macroeconomy and firms is a relatively recent research area. For instance, the majority of empirical studies on the effects of material productivity on competitiveness and GHG emissions either rely on case studies or have methodological shortcomings (which will be discussed in detail in Chapter 3). Such limitations in the current evidence base, which is at the centre of this dissertation, may prevent stakeholders from significantly engaging in becoming more material productive in the first place.

4) ***Investment focus***: In times of efforts to consolidate state and regional budgets across the EU, incentivising private participation is often argued (yet disputed) to be an efficient and effective strategy (Hodge and Greve 2007). Accordingly, the announced extension and increase of the European Fund for Strategic Investments can be mentioned here, as it incentivises material productivity increases through co-financing investment projects. An increased public investment focus can showcase that by

internalising externalities and taking into account the cost of inaction material productivity investments can be beneficial (Flachenecker et al. 2017).

5) ***Political will***: As outlined previously, the Circular Economy Action Plan and the explicit mentioning of the material policy agenda in the work programme of the European Commission for 2017 can be interpreted as a political commitment to this agenda. However, maintaining political focus is particularly important during times of low material prices, because they dis-incentivise the urgency of reducing the import dependency to becomes less vulnerable to supply disruptions as well as to increase productivity (Rout et al. 2008). However, this poses the risk that once material prices rise again, vulnerabilities increases with little time to react (WEF 2017). The strength of the political commitment towards the material policy agenda might be an important factor for the future development of this agenda – and possibly even whether it can establish itself as a priority beyond political cycles.

In summary, as part of the EU material policy agenda, numerous initiatives have been introduced. However, currently other policy domains might dominate political discussions, also due to the relatively low levels of material prices. Nevertheless, recent signs might indicate a revitalisation of the material policy agenda.

Chapter 3

Literature Review

3 Literature Review

This chapter serves as an overview of the current academic discussions and evidence base of the most relevant bodies of literature related to this dissertation. The aim of this chapter is to review the various strands of the literature, identify research gaps, and thus motivate the empirical chapters in this dissertation (Chapters 5-8).

As part of this chapter, the current evidence base on the drivers of material use is reviewed (Chapter 3.1), finding that economic growth is considered one (if not the most) important driver, but empirical studies often fail to adequately address the potential problem of endogeneity and account for heterogeneity across firms, sectors, countries, material subgroups, and material indicators. Researching the effects of material productivity on competitiveness and GHG emissions, in addition to the literature on drivers, is embedded in the strand of literature on material productivity and decoupling (Chapter 3.2), identifying similar shortcomings. Moreover, studies on the effects of material productivity on competitiveness not only face the limitations with regards to endogeneity and heterogeneity, but also frequently rely on case studies and do not discuss in detail the concept of competitiveness. To this end, this chapter comprises an in-depth review of competitiveness on the macroeconomic and microeconomic level as well as its link to material productivity (Chapter 3.3).

While investigating the effects of material use and material productivity on competitiveness and GHG emissions is not a novel research topic, the existing literature on these issues shows some specific limitations (Chapter 3.4) that this dissertation attempts to address (Chapter 3.5).[1]

3.1 Drivers of material use and material productivity

Several contributions in the literature have tried to identify the factors determining material use and productivity in the economy. The term driver is sometimes used with fairly specific meanings. In the *Driving Forces-Pressure-State-Impact-Response* (DPSIR) framework of the European Environmental Agency (EEA), for example, (environmental) indicators for driving forces "describe the social, demographic, and economic developments in societies and the corresponding changes in life styles, overall levels of consumption and production patterns [...]

[1] As already discussed in Chapter 2, the relationship between material use indicators and environmental pressures such as GHG emissions might be more complex than a straight forward positive link (Voet et al. 2003). Therefore, this topic will not further be discussed in this review chapter, but empirically investigated in Chapter 5.

Driving forces provoke changes in the overall levels of production and consumption. Through these changes in production and consumption, the driving forces exert pressure on the environment." (EEA 1999). While this definition is coined to environmental issues, in most parts of the literature, however, the term is used without an explicit definition in mind. It is often rather used to indicate factors influencing or determining the level or the composition of material use and productivity.

Not surprisingly, different disciplinary and methodological approaches adopted in studies have resulted in an extensive list of heterogeneous drivers. Some scholars divide drivers of material use and productivity based on whether they are *extensive* or *intensive*; the former representing population, geographical area, or economic activity, and the latter including normalised variable such as income per capita, population density, and the sectoral composition of an economy (Weisz et al. 2006).

More specifically, in addition to economic activity, which is one of the most cited drivers of material use and productivity (Voet et al. 2005b; Weisz et al. 2006; UNEP IRP 2014; West et al. 2014; Pothen 2015; Pothen and Schymura 2015), it has been found that (i) material prices, (ii) the structure of the economy and material use, (iii) technological factors, (iv) social factors, (v) material policies, (vi) the use of other inputs, and (vii) natural endowments drive material use and productivity.

- ***Prices of materials***: Only a limited number of studies empirically investigate the link between material prices and material use or productivity. Dahmus (2014) investigates ten case studies and argues that high resource prices can incentivise efficiency increases to the extent that they can contribute to outweighing the increasing trend in resource use. While it is generally argued that higher prices are expected to reduce demand, the price elasticity of demand crucially depends on the substitutability of materials, the possibility to increase efficiency, and the dynamics of the adjustment to the new input mix (Pindyck and Rotemberg 1983; Brons et al. 2008; Hughes et al. 2008). As outlined in Chapter 2, material price volatility can both incentivises as well as dis-incentivises material productivity improvements (Flachenecker and Rentschler 2015).
- ***Structural factors***: The literature considers the sectoral composition of the economy and thus indirectly the types of materials used in an economy as an important driver of material use. It is argued that transforming the economy from an agricultural to an industry-based economy is likely to increase material use, while the shift to a service-

based economy would reduce it (Schandl and West 2010; Giljum et al. 2012; Steinberger et al. 2013; Pothen and Schymura 2015; Bleischwitz and Nechifor 2016). This goes back to the theoretical concept of an inverted U-shaped relationship between economic growth and material use. The famous 'Environmental Kuznets Curve', or alternative concepts such as the saturation effect, would predict the initial increase in material use, followed by a decline or levelling out once the economy develops by predominantly relying on the less-material intensive service sector. Empirical research on the issue is often limited by the short time span of available data (Bleischwitz and Nechifor 2016). However, structural change towards a service oriented economy might not necessarily result in a less material-intensive economy, especially when the indirect material use of services is accounted for such as the infrastructure for service providers, hardware for information and communication technologies, energy use etc. (Kander 2005; Schoer et al. 2012).

- ***Technological factors***: Technological features in production (and consumption) can influence material use, both positively and negatively. The concept of eco-innovations, an issue closely related to technological advancements, by definition requires a reduction in material use (Eco-Innovation Observatory 2012). New technologies could reduce the use of materials or substitute them with other production inputs, i.e. increase material productivity (Söderholm and Tilton 2012; Allwood et al. 2013). However, technological advancements are argued to also result in new demand for specific materials (e.g. critical raw materials for smartphones) or enable economic development which in turn could require more materials (Allwood et al. 2011; Bleischwitz and Flachenecker 2017).

- ***Social factors***: Social indicators are also considered as factors influencing material use. Examples include road density, car possession, meat consumption, household size, urbanisation, population, life style choices, and waste recycling. Parts of the literature argues that such indicators have a positive but decreasing effect on material use (Müller et al. 2011; Steger and Bleischwitz 2011). This points to a saturation effect of developed economies which could be the result of having sufficient infrastructure stocks, technological shifts, or structural changes in the economy as well as society (Bleischwitz and Nechifor 2016).

Steinberger et al. (2010) argue that countries "with uninhabited areas tend to have more mineral extraction per capita, and be net exporters. Since exported ores/industrial minerals are a small fraction of the extracted material, these countries have large apparent consumptions in comparison to their customers with lower available area and less ore extraction". The authors conclude that available area per capita explains a significantly part of material use using a simple regression analysis of 143 countries. Furthermore, socio-economic drivers are argued to explain most of the international distribution of material use, whereas demographic characteristics are more associated with domestic extraction (Teixidó-Figueras et al. 2016).

Besides such findings, the direction of the effect is not always clear. For instance, increasing the share of the urban population might decrease material use per capita due to economies of scale, similarly to GHG emissions (Satterthwaite 2008; Dodman 2009), but whether urban areas can benefit from economies of scale in practice depends on local factors, including geophysical and technical circumstances (Kennedy et al. 2009).

- ***Policy factors***: The productivity and use of materials, comparable to other production inputs such as energy and labour, can be influenced by policy interventions. As outlined in the previous chapter, material policies aim to provide guidance and incentives to economic actors to increase material productivity. Also because materials cover a wide range of policy domains, it is argued to take the interactions between various policy measured in account, thus considering policy-mixes (POLFREE 2014; Fedrigo-Fazio et al. 2016; Watkins et al. 2016). While policy measures are often difficult to be included in empirical analyses, especially because they are not directly comparable (EEA 2011a; POLFREE 2014), theoretical investigations caution against unintended consequences of policies trying to influence materials prices, including distortions of markets as well as negative distributional effects (Aidt et al. 2017).
- ***The use of other production inputs***: This reflects the substitution or complementary patterns between materials and other inputs such as energy, labour, and capital. For instance, if labour was a substitute to materials, which is argued by some scholars (Bruyn et al. 2009; Allwood et al. 2011; Bleischwitz 2012), an increase in the demand for the former would be observed alongside a decrease in materials. If energy was complementary to materials (Nordic Council of Ministers 2001; Hannon 2013), an increase in energy use would result in an increase in material use. Though, it is not clear whether materials are substitutes or complements to other inputs (Baptist and Hepburn 2013), the use of other inputs is argued to be one determinant of material use

which is referred to as the *resource nexus* (Andrews-Speed et al. 2012; Bleischwitz and Corey 2012; Andrews-Speed et al. 2014).

- ***Natural endowments***: Practically every country possess natural endowments of materials. Since minerals, especially sand and gravel, are available across most of the world and their transportation costs are relatively high due to their weight, such materials are often extracted locally (Ecorys 2012; EEA 2012). For the EU, domestic extraction explains a significant part of the variation in material use between 2000-2013 ($R^2 = 0.81$) (EC 2017a). Weisz et al. (2006) states that high per capita resource availability in a country not only favours the establishment of material-intensive industries such as agriculture, wood production, mining, and construction, but also a high per capita use of that abundant resource. One example would be the use and extraction of wood resources in the Nordic and Baltic countries which rank among the highest in Europe (EC 2017a).

This list of potential drivers of material use is one way of analysing the literature. Some scholars identify a fairly large list of drivers of material use, comprising determinant across the above-mentioned groups. For instance, Steger and Bleischwitz (2011) list 68 variables as possible drivers, although the authors reduce their variable considerably for the empirical analysis. Other scholars limiting their analysis to only a few drivers for material use (e.g. Weisz et al. 2006; Krausmann et al. 2009; Steinberger et al. 2010). However, Steger and Bleischwitz (2011) are not the exception. Voet et al. (2005b) consider 30 different variables and Hirschnitz-Garbers et al. (2015) 47 as drivers of material use.

In models containing a considerable number of independent variables, it is sometimes challenging to distinguish among the contribution of the variables and decide on those which should be retained. Data-driven procedures, like the general-to-specific approach can be used, but there is a risk of ending up with the 'incorrect' set of explanatory variables (Hoover and Perez 1999). Thus, the empirical analysis in Chapter 6 will only investigate one particular driver material use which is most frequently found to be a relevant determinant – economic growth.

Another approach to review the existing literature is to distinguish it according to the methodology applied. This supports the understanding of limitations and research gaps. The following three methodologies are frequently found in the literature.

1) ***Econometric models***: The fast majority of the studies are based on simple regression analyses, possibly failing to identify a causal relationship, because most drivers of material use and productivity are simultaneously determined (Angrist and Pischke 2009).

   i. *Panel data*: Voet et al. (2005b) identify 27 potential drivers and conduct a panel data regression on material intensity of the EU-28 countries between 1992 and 2000. The authors regress GDP on material intensity which is problematic since GDP is endogenously determines material intensity. The authors find that increasing GDP by 1% reduces material intensity by less than 1%, depending on the model used. In line with the previous results, the authors estimate that a 1% increase in the share of the construction sector (NACE F) increases material intensity by 1.63%, while higher recycling rates are associated with a reduction in material intensity. This study identifies car possession, railway density, dwellings per capita, renewable energy production, motor fuel price, education spending, and patents per capita to significantly drive material intensity.

      Bringezu et al. (2004) study the relationship between GDP and DMC as well as TMR. The authors analyse 24 countries between 1980 and 1997 and find that income per capita increases material use per capita (measured in DMI). Furthermore, the authors provide evidence for a quadratic relationship between economic activity and material use which suggests an Environmental Kuznets Curve for material use.

      Yang and Managi (2015) investigate the relationship between economic growth and material productivity (based on DMC) using a panel data set of 130 countries and their average values of the 1990s and 2000s, i.e. two time periods. The authors find that population size is negatively correlated with material productivity across all material group, whereas most other factors (economic development, investments, patents, trade, renewables etc.) are not significantly correlated with material productivity.

   ii. *Time-series data*: Steger and Bleischwitz (2011) analyse 33 potential drivers and identify the share of employment in the manufacturing sector of total employment, imports per capita, labour productivity in the industrial sector, the share of the construction sector of GDP, population density, primary energy generation per capita, dwelling stock, and the share of employees in the construction sector of total employment as the main drivers for material intensity in the EU-15 from 1980-2000 (having excluded GDP). For the EU-27 from 1992-2000, they find evidence for the share of employment in the manufacturing sector of total employment, share of the service sector of GDP, imports per capita, number of completed dwellings per 1 million inhabitants, the length of the railway network, labour productivity in the industrial sector, and per capita primary energy generation as the main drivers for material intensity.

Wang et al. (2016) analyse the socioeconomic drivers of material productivity in China between 1980-2010 using an autoregressive distributed lag model. The authors' findings suggest that energy intensity for the secondary industry is the main driver of material productivity, both in the short and long term. Additionally, the productivity of the service sector is also linked to material productivity, in particular in the long run, while trade openness only plays a minor role. Domestic extraction shows significant effects on material productivity in the short term.

Some analyses are specific to individual materials. For example, Jaunky (2013) uses 16 countries between 1966 and 2010 and tests for co-integration between economic growth and copper consumption. The findings suggest a unidirectional link from an increase in economic activity to copper consumption in Finland, France, and the United Kingdom in the long-run estimating an error-correction-model.

iii. *Cross-section data*: Steinberger et al. (2010) analyse material productivity of 175 countries for the year 2000. The authors find that material productivity is strongly correlated with income. However, this is not the case for fossil fuels and metal ores or industrial minerals, thus identifying substantial heterogeneity across material groups. The authors argue that biomass is inelastic to income and equitably spread throughout the world by comparing the Gini-coefficient across material groups. Accordingly, biomass has a coefficient of 0.29, construction minerals of 0.38, fossil fuels of 0.58, metals and minerals of 0.60, compared with overall DMC of 0.35 and GDP of 0.55. Biomass and minerals are linked to changes in population, whereas fossil fuels, metals, and minerals strongly correlate with GDP.

Wiedmann et al. (2013) use a cross-section for 137 countries in 2008 in a multivariate regression analysis. Using material footprint data, the authors find that GDP per capita mainly drives the use of materials, both measured by footprint data as well as the more conventional material indicator DMC. However, the authors find that the relationship between GDP in DMC is lower in magnitude (an elasticity of 0.15) compared to the material footprint (an elasticity of 0.60).

2) ***Descriptive and trend analysis***: These methods can identify correlations and trends but not the direction of impact between two variables. Weisz et al. (2006) assess the material use for the EU-15 member states between 1970 and 2001. By considering each material category separately, the authors find that the economic structure is higher correlated with material use than economic growth. The authors also point to additional drivers such as trade activity, stage of economic development, standard of living, resource endowments, population density, climatic conditions, and the structure of the energy system being drivers of material use.

   Bleischwitz and Nechifor (2016) analyse data on four materials (steel, cement, aluminium, and copper) for Germany, Japan, the United States of America, and China between 1900 and 2013. The authors provide evidence for a saturation effect, i.e. the impact of GDP on material use levels out at a later stage of development. For instance, the saturation effect for copper kicks in at around $20,000 per capita.

   The *Impact-Population-Affluence-Technology* (IPAT) identity is sometimes used to constrain the number of drivers being used in the analysis which assumes that changes occur only due to the selected drivers. West et al. (2014) study trends in material use for 12 countries formerly part of the Soviet Union. The authors apply a logarithmic IPAT framework from 1992-2008 using DMC as a proxy for environmental impact (I), population (P), GDP per capita for affluence (A), and material intensity as a proxy for technology (T). The authors conclude that DMC is predominantly driven by an increase in GDP per capita.

   Schandl and West (2012) also apply the IPAT identity and find that economic growth is the main driver behind China's and Japan's increase in material use, while in Australia (and more recently also in Japan) material productivity has had a substantial downwards effect on the overall increasing trend of material use. The authors investigate materials flows in China, Australia, and Japan between 1970 to 2005.

   An adoption of the IPAT approach is also used by Dahmus (2014) to empirically assess how effective efficiency improvements have been in counterbalancing the increase in material use. Efficiency is measured as the ratio between quantity of goods and services provided and amount of materials used. Considering ten case studies[2] suggests efficiency improvements have failed to counterbalanced increases in material consumption. The only time during which absolute material use has decreased was marked by periods of industry upheaval, high material prices, and strong policy commitments.

3) ***Decomposition analysis***: Similar to the IPAT identity, decomposition analyses look into the relevance of certain drivers changing material productivity or material use. However, such methods cannot identify in which direction the variables influence each other and also restricts the possible drivers to the ones selected.

   Pothen (2015) applies a structural decomposition analysis on how changing investment and consumption patterns affect RMC between 1995-2008 for 38 industrialised countries using the World Input-Output Database (WIOD). The results suggest that RMC is mainly driven by an increase in final demand. Similarly, Pothen and Schymura (2014) apply an index decomposition analysis using the WIOD database to identify the drivers of material use for 40 countries from 1995-2008. The authors find that economic growth and structural changes within economies are the main drivers of material use, with substantial heterogeneity across countries.

   Hashimoto et al. (2008) study drivers of a decreasing trend in material intensity (based on DMI) in Japan between 1995-2002. The authors conclude that changes in the demand structure (especially for machinery and services) predominantly increase material intensity, while recycling contributed to its decrease. Wood et al. (2009) identify drivers of material use (based on DMI and TMR) in Australia using input-output data for 344 industries between 1975-2005 applying a structural decomposition analysis. The authors find that levels of exports, the composition of exports, industrial structure, affluence, and population drive material use. Hoffren et al. (2001) use an index decomposition analysis for Finland's direct material flows between 1960-1996. The authors conclude that economic activity has contributed most to the increase in material use, especially those used in infrastructure such as roads, waterways, and electricity.

[2] The ten case studies comprise pig iron production, aluminium production, nitrogen fertilizer production, electricity generation from coal, electricity generation from oil, electricity generation from natural gas, freight rail travel, passenger air travel, motor vehicle travels, and residential refrigeration.

Wenzlik et al. (2015) use a structural decomposition analysis of RMC data for Austria between 1995 and 2007. The authors find that while economic growth is positively associated with material use, the composition or material-intensity of economic activity is an important determinant often ignored by other studies. The authors show that material use increased in Austria also during times of low economic growth since the material-mix of economic activity had an adverse effect on overall material use.

To this end, it is important to note that irrespectively of the methods applied and discussed in detail above, the current empirical literature on the drivers of material use and productivity rely on methods that identify correlations but not necessarily causal effects. This goes back to the fact that most drivers and material use are simultaneously determined, resulting in endogeneity. In short, some of the estimated coefficients are likely to be biased and inconsistent (Angrist and Pischke 2009). Additionally, many studies do not explicitly investigate heterogeneity across firms, sectors, countries, material subgroups, and material indicators.

Both issues will be discussed in greater detail in Chapters 6-8. Given that the two issues have received relatively little attention in the existing literature, this dissertation attempts to shift the debate towards explicitly addressing these potential shortcomings by applying an instrumental variable approach and considering heterogeneity across firms, sectors, countries, material subgroups, and material indicators.

In summary, the literature has identified a wide range of possible drivers of material use using diverse methodologies. Economic activity is considered one of the most, if not the most, important driver of material use and productivity across disciplines and methodologies (Voet et al. 2005b; Weisz et al. 2006; UNEP IRP 2014; West et al. 2014; Pothen 2015; Pothen and Schymura 2015; Worrell et al. 2016). Therefore, an empirical analysis in this dissertation will investigate the relationship between economic growth and material use (Chapter 6). Additionally, as for any econometric method, the amount of dependent variables should be limited to only a few (Wooldridge 2008). This particularly relevant for the method applied for studying the causal effect of economic growth on material use – an instrumental variable approach.

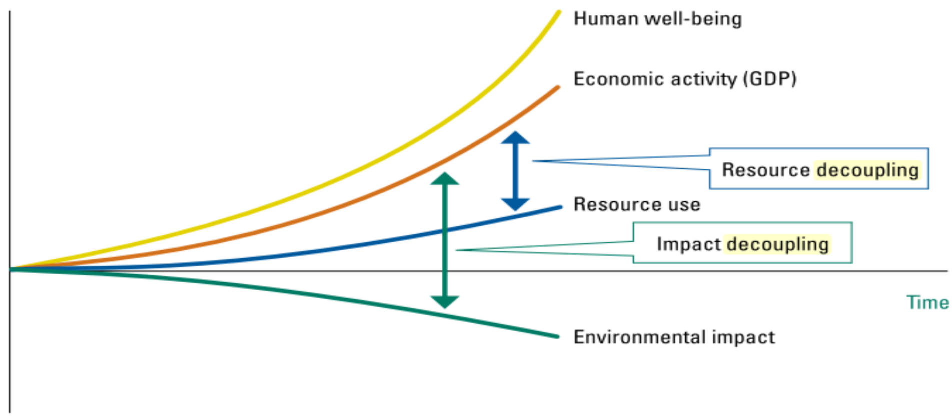
3.2 Material productivity and decoupling

This section will discuss the literature on material productivity and decoupling. Both concepts are directly linked with the empirical analyses in this dissertation on whether material use decoupled from economic growth (Chapter 6), and the effects of material productivity on competitiveness as well as GHG emissions (Chapters 7 and 8).

The broadly agreed definition of resource decoupling is breaking the link between economic activity (e.g. GDP) and resource use (e.g. DMC, RMC) (UNEP IRP 2011; UNEP IRP 2014). Decoupling is thus closely related to "using less resources per unit of economic output", i.e. increasing resource productivity (UNEP IRP 2011). The definition of resource decoupling can be applied to materials. The difference between material productivity and decoupling is that decoupling can occur either when economic activity grows faster than material use (*relative decoupling*), or the former increases while the latter decreases (*absolute decoupling*), while both cases are considered an increase in material productivity.

Furthermore, as shown in Figure 8, resource (or material) decoupling and impact decoupling can further be separated. The latter additionally requires to lower the environmental pressures (or impacts) of materials in absolute terms.

Figure 8: The concept of decoupling (source: UNEP IRP 2011).



3.2.1 Trends in material productivity and decoupling

There is a broad body of literature providing statistical evidence for changes in material productivity and materials decoupling around the world. The following compilation summarises the results of the main contributions according to their geographical coverage:

- ***Asian-Pacific region***: Schandl and West (2010) focus on 45 Asian-Pacific countries between 1970-2005. The authors analyse trends in material intensity concluding that material intensity remained relatively stable between 1970-1990 and substantially increased since then, contrarily to the rest of the world. Lee et al. (2014) calculate data on material productivity for South Korea between 2000-2010. The authors suggest that the increase in material productivity is mainly due to the increase in economic growth. Yu et al. (2017) use simple regression analysis to estimate the drivers of the increase in material productivity in China between 1980-2010. The results suggest that the reduction in energy intensity has contributed most to the material productivity increase. These findings are in line with a previous analysis on China using time-series econometrics (Wang et al. 2016).

- ***Latin America***: West and Schandl (2013) investigate the material intensity in Latin American countries between 1970-2008 and conclude that starting from 1993, when Latin America opened up to global markets and experienced a high inflow of foreign direct investments in the mining sector, material intensity substantially increased. The authors identify the mining sector (in Chile and Peru) and the agriculture sector (in Brazil) as the core drivers of the increase in material intensity.

- ***Central Asia***: Giljum et al. (2012) analyse patterns in material productivity in Central Asia, Eastern Europe, and the Newly Independent States (30 countries in total) in 1995, 2000, 2005, and 2008. The authors suggest that the structural transition towards market-based economies with higher shares of the service sector is likely to explain the increase in material productivity over time.

- ***Europe:*** Bringezu and Schütz (2001) calculate material productivity based on TMR data and find that material productivity increased by around 6% between 1988 and 1997 in the EU, compared to the increase in material productivity by 28% when calculating productivity using DMI data. Moll et al. (2005) present statistical evidence that material productivity in the EU-15 between 1980 and 2000 has increased by around 50%, independently of measuring materials in TMR, DMC, or DMI. Voet et al. (2005b) statistically show that the EU-28 relative decoupled GDP (increase by 20%) from DMC (increase by 4%) between 1992-2000, mainly driven by a decrease in the use of fossil fuels.

  Schandl et al. (2016) model various scenarios using a global general equilibrium model between 1990-2010. The authors find that if material productivity improvements were to increase between 3.5 and 4.5% annually, material use in the EU could decrease to 15 tonnes per capita by 2050, CO_2 emissions could be reduced by 50%, while economic activity could continue to increase (compared to a business-as-usual scenario), i.e. absolute decoupling is theoretically possible under such assumptions.

- ***Worldwide***: Giljum et al. (2014) provide statistical evidence for changes in material productivity between 1980 and 2009. The authors conclude that global material productivity has increased by 26.4% and all continents experienced a positive productivity growth. Krausmann et al. (2009) estimate changes in material intensity between 1900-2005, showing that material intensity decreased by 30%. This decrease mainly occurred due to a reduction in the biomass intensity, while the intensity of minerals increased during most of the 20th century. The authors state that productivity increases on average by about 1% per year.

  Behrens et al. (2007) compile global data on material extraction between 1980 and 2002. By means of statistical analysis, the authors provide evidence that material intensity decreased by approximately 25%. This decrease is heterogeneously distributed across countries. Not surprisingly, the sharpest decrease in material intensity occurred in the transition countries, while Latin America and the Caribbean almost remained at their levels of 1980. Western Europe is by far the least material intensive part of the world, whereas Africa has become the most material intensive continent.

  Yang and Managi (2015) find that all material subgroups, i.e. biomass, minerals, metals, and fossil fuel, have relatively decoupled from economic growth for developing and developed countries (in absolute and per capita terms), statistically analysing data of 130 countries between 1990 and 2010.

This body of literature predominantly relies on statistical analyses. What becomes apparent is that (i) there is substantial heterogeneity across countries, regions, and continents, and (ii) some results provide partly conflicting findings on developments of material productivity and material decoupling over time. While most studies argue that material productivity has increased over time and lead to relative decoupling of material use from economic growth (O'Rourke and Lollo 2015), in particular in Europe, some continents and countries (e.g. Africa, Asian-Pacific countries, Latin America) may have develop contrarily to this trend. There are three reasons why such results may differ but not necessarily contradict each other:

1) ***Choice of economic indicator***: Flachenecker and Rentschler (2015) show that choosing different methodologies for calculating economic activity may lead to different

conclusions. They consider global DMC between 1980 and 2009 and GDP in current international dollars based on purchasing power parity (PPP) and GDP in constant 2005 USD. Material productivity based on the former would suggest a significant increase in material productivity, whereas the latter shows only a minimal productivity increase. As suggested by the European Commission, when comparing material productivity over time, price changes need to be controlled for, and when comparing productivity across countries, PPP-based measures control for heterogeneous purchasing power across countries (EC 2015d).

2) ***Choice of material indicator***: Different material indicators cover different material flows. Thus, heterogeneous outcomes may occur when calculating material productivity using different material indicators. In fact, some studies use consumption indicators (DMC, RMC, TMR), other input or extraction-based measures as described above. However, as Moll et al. (2005) show, this may not necessarily change the conclusions drawn from using different material indicators.

3) ***Choice of timeframe and base year***: This is exemplified by Schandl and West (2010) showing that material intensity in the Asian-Pacific region remained relatively stable between 1970-1990 and substantially increased since then. This is somewhat divergent from Giljum et al. (2014) finding that material productivity has increased in all world regions between 1980-2009. However, it should be acknowledged that the two studies in addition to using different timeframes and base years, they also use different methods to measure GDP.

3.2.2 Non-linear relationships between economic growth and material use

Although the conclusion of many studies is that relative decoupling is unfolding, at least in developed countries, other studies have produced indicative evidence of N-shape correlations indicating at least a period of recoupling between material use and economic growth (Hüttler et al. 1999; Bruyn 2002). To this end, Canas et al. (2003) use panel data for 16 industrialised countries between 1960-1998 finding statistical support for both the quadratic and cubic Environmental Kuznets Curve hypothesis between DMI and GDP per capita.

Results from Bringezu et al. (2004) for 24 countries between 1980-1997 point to a quadratic relationship between per capita material use (measured in DMI) and income per capita, a finding giving some credit to the Environmental Kuznets Curve hypothesis and decoupling theory. Unfortunately, models estimated by the authors makes the choice between the quadratic and the cubic model virtually impossible.[3] This is of great relevance as the cubic models point at N-shape curve while the quadratic model would suggest an inverted U-shape relationship. The authors also test for non-linear relationships between income per capita and TMR per capita, concluding no statically significant evidence for a non-linear relationship.

Steinberger et al. (2013) estimate DMC and GDP for 39 developing and industrialised countries between 1970-2005 using an autoregressive pooled estimated general least squares (EGLS) estimator. The authors use a co-integration test to establish a 'causal' link between the two variables. The authors find that over the long term (i.e. 1970-2005), industrialised economies couple less compared to developing countries, while Germany, the Netherlands, and the United Kingdom experience absolute decoupling. Notably, Greece, Portugal, and Spain have coupling elasticities of above or close to 1. However, there is little evidence for the existence of an Environmental Kuznets Curve since the quadratic coefficients are either not significant or significant and positive. As Bleischwitz and Nechifor (2016) point out, finding evidence for non-linear relationships between material use and economic activity is often restricted by the relatively short time horizons for which adequate data are available.

3.2.3 Potential shortcomings

In summary, most evidence suggests that most parts of the world, in particular Europe, has experienced relative decoupling and thus an increase in material productivity. However, such evidence is based on statistical and trend analyses, thus not addressing whether the underlying causal link between economic growth and material use has in fact been broken or simply omitted variables have triggered material productivity to increase. Therefore, simply considering trends could be misleading in judging whether there is a link between economic growth and material use.

This will be discussed in greater detail in Chapter 6. What is important to take away from this section is that there is a considerable body of literature researching the trends and developments of material productivity and decoupling. However, the majority of studies do not explicitly address the potential problem of endogeneity or heterogeneity. In order to investigate whether endogeneity is indeed a problem for analysing material productivity and decoupling motivates the empirical studies in this dissertation.

[3] This applies to the case of feasible generalized least squares (FGLS) estimator with country fixed effect, heteroskedastic panel, and common AR(1) coefficients and the fixed effects and random effects models estimated by the authors. In all cases, the R^2 of the cubic and the quadratic model are virtually identical, log-likelihood of the cubic model, when reported is however higher. Although R^2 is bad model choice criterion, the authors present no additional information.

3.3 Material productivity and competitiveness

After reviewing the drivers of material use and productivity, and material productivity and decoupling, another specific body of literature dedicated to the effects of material productivity on competitiveness is discussed. This will serve as a basis for the later empirical analyses in Chapters 7 and 8.

In particular since the early 1990s, managing the economic as well as environmental implications of material productivity has become an explicit policy concern. "Reducing the amount of energy and materials used per unit in the production of goods and services can contribute both to the alleviation of environmental stress and to greater economic and industrial productivity and competitiveness." (UN 1992). To this end, understanding the effects of material productivity on competitiveness is essential.

This framing has contributed to the notion that increasing material productivity can lead to an increase in competitiveness. This link is at the centre stage of contemporary material, resource efficiency, and circular economy initiatives in the EU (EC 2011b; EC 2015a), the OECD (OECD 2012), the United Nations (UNEP IRP 2011; UNEP IRP 2014), the G7 (G7 2015a), multilateral development banks (EBRD 2015a; World Bank 2015), national governments (EEA 2016), and the private sector (WBCSD 2010; McKinsey Global Institute 2011), among others. Virtually all political and private stakeholders argue in favour of a positive link between material productivity and competitiveness.

In addition to numerous reports written by governmental agencies and consultancies, the growing academic literature has mostly found a positive correlation between material productivity and competitiveness (Bleischwitz et al. 2009b; Ecorys 2011). However, the vast majority of the literature puts relatively little scrutiny on the following three issues:

1) ***Endogeneity:*** Most empirical studies rely on statistical methods, not explicitly addressing the issue of endogeneity. Endogeneity can arise since material productivity could potentially increase competitiveness by reducing unit production costs, while more competitive firms are likely to increase their material productivity (Bringezu et al. 2004; Bleischwitz et al. 2007).
2) ***Heterogeneity***: Several studies only cover specific firms or countries, hence not taking the heterogeneity across firms, sectors, countries, material subgroups, or material indicators into account (Flachenecker 2017).

3) ***Definition of competitiveness***: Hardly any study on the effects of material productivity on competitiveness reviews and defines the concept of competitiveness. To this end, this section discusses the concept of competitiveness on the macroeconomic and microeconomic level in detail.

How this dissertation attempts to address these limitations is outlined in detail in Chapters 7 and 8. This section provides the conceptual basis for the empirical investigations on the effects of material productivity on competitiveness, both on the macroeconomic (Chapter 7) and microeconomic level (Chapter 8).

The concept of competitiveness has received considerable attention in the literature and policy circles (Odendahl 2016). Since there are fundamental differences between competitiveness on the country or firm level, the following reviews of the concept, distinguishing it according to the macroeconomic and microeconomic level, followed by the identification of channels linking material productivity and competitiveness.

3.3.1 Microeconomic competitiveness

According to the Oxford Dictionary of Economics, competitiveness on the microeconomic level is defined as "the ability to compete in markets for goods or services." (Black et al. 2013). According to economic theory, *ceteris paribus*, a firm is competitive in a perfectly competitive market if it is able to sell homogeneous products or services at a price that is equal to its marginal costs. This can be referred to as 'price competitiveness', as firms directly compete with other firms on prices. The precondition for price competition is perfectly competitive market conditions, i.e. the assumptions underlying the first fundamental theorem of welfare economics (Varian 2010). This set of assumptions includes perfect information, no market power, no barriers to entry or exit, homogeneous goods, no externalities, perfect factor mobility, among others.

This definition of competitiveness above, however, may be unrealistic in practice. Once any assumption underlying perfectly competitive markets is violated, the modus of competition and factors determining competitiveness are likely to change (Aiginger 2006).

- ***Heterogeneity:*** If goods or services are heterogeneous, quality may become a determining factor. Accordingly, a firm would be more competitive compared to another if it offers a higher quality product at an equal (or lower) price compared to its competitors in a given market (Ekins and Speck 2010).

- ***Imperfect information:*** In market settings with imperfect information, information networks, continuous learning, and the rate of information diffusion within and across firms may shape competitiveness (Maskell and Malmberg 1999).
- ***Market power:*** If firms have market power or markets are otherwise distorted (e.g. through subsidies), even uncompetitive firms can sell their goods and services at prices which equal to the marginal costs of competitive firms.

These examples illustrate that prices in imperfect market settings are only one determinant of competitiveness, thus a wider range of factors need to be considered. Such factors can be grouped into *internal* (e.g. ability to reduce costs, innovate etc.) and *external* determinants (e.g. market prices, cost structure of competitors, subsidies etc.) (Aiginger 2006).

Depending on market conditions, a combination of market failures can occur making it difficult to select a single factor determining competitiveness. Additionally, those factors are often difficult to objectively be measured (e.g. product quality). Therefore, instead of studying factors shaping competitiveness, the literature frequently refers to 'outcome factors' which result from being competitive.

Krugman (1994) argues that the outcome of microeconomic competitiveness is the ability to stay in business. Others claim that firms are competitive if they generate *high* revenues and profits (Lehner et al. 1999; Siggel 2006; Ekins and Speck 2010). Alternative outcomes of competitiveness range from expanding and growing firms (Reinert 1995), increasing productivity (Aiginger and Vogel 2015), increasing employment (Chan et al. 2013), positive returns on invested capital (Snowdon and Stonehouse 2006), and exporting goods and services to foreign markets (Siggel 2006; Dosi et al. 2015; EC 2015e).

The advantage of considering 'outcome factors' is their measurability and often their data availability, making them suitable for empirical analyses. However, three issues need be considered when using these factors as indicators for competitiveness:

1) ***The sign of direction is unclear***, i.e. such factors may either cause competitiveness or be the result of it. For example, high productivity could either be the result of being competitive or enable firms to successfully compete in the market. Thus, the direction of impact needs to be considered.

2) ***Omitted effects:*** Despite being closely associated with competitiveness, such factors may not necessarily directly represent it. For instance, staying in business over a long period or generating profits might be an indication for competitiveness, but it might

also be the result of market failures and distortions allowing un-competitive firms to falsely appear competitive (Aiginger 2006).

3) ***Relative concept:*** Most factors mentioned above lack to consider the relative dimension of competitiveness, i.e. firms are more or less competitive compared to competitors (Siggel 2006). Therefore, Krugman (1994) describes competitiveness in a zero-sum world with a fixed market size. One firm increases its competitiveness at the expense of another. Using a styalized example, if Coca Cola supplies a customer, Pepsi cannot supply the same customer anymore (unless the market expands). Against this backdrop, competitiveness is a direct reflection of the market share. To this end, Siggel (2006) argues that competitiveness indicators need to be benchmarked, for example against other participants in the market they are engaged in.

In conclusion, even if the specific factors determining competitiveness may differ from market to market and over time, the concept of competitiveness on the microeconomic level is best described as the relative performance of firms compared to their competitors within their respective markets. While it is challenging to address 1) and 2), the empirical analysis in Chapter 8 will take these considerations into account, in particular 3) with regards to the relative nature of competitiveness. The details on which specific indicators and data used in the empirical analysis are provided and discussed in Chapter 8.

3.3.2 Macroeconomic competitiveness

There is no consensus in the literature on the definition of competitiveness on the macroeconomic level. As Lawrence (1993) describes it: "Competitiveness, particularly with reference to an entire economy, is hard to define. Indeed, competitiveness, like love or democracy, actually has several meanings." The lowest common denominator appears to be that it is frequently ill-defined, while conclusions about macroeconomic competitiveness range from being "a dangerous obsession" (Krugman 1994) to "a welfare creating ability with positive externalities" (Aiginger 2006) and being "central in public policy for at least 500 years." (Reinert 1995). Such opposing views indicate the controversy with which the debate in the literature has been taking place.

Four related understandings of competitiveness on the macroeconomic level can be differentiated as shown in Table 9 which are subsequently discussed.

Table 9: Four interpretations of macroeconomic competitiveness.

Macroeconomic competitiveness	*Details*	*Conclusions*
Krugman's critique	– Countries are not firms – Productivity is a better measure of welfare – Dangerous conclusions (protectionism)	– Elusive concept on the macroeconomic level – Once market failures are present, macroeconomic competitiveness can become 'meaningful'
Price competitiveness	– Competition is along prices – The competitiveness of countries is constituted by low unit labour costs, a high real effective exchange rate, a trade surplus, etc.	– Such measures might be misleading – Competitiveness is more than price measures in imperfect market settings – Macroeconomic competitiveness should be complemented by non-price measures, including welfare, standard of living, and human development
Microeconomic foundation	– Firms generate a competitive advantage, but they operate within the macroeconomic environment – Macroeconomic competitiveness is about enabling firms to be competitive	– Porter's competitiveness triangle (factor, demand, supporting industry, firm strategy, and structure and rivalry) – Macroeconomic competitiveness may need to be complemented by a microeconomic foundation
Institutions	– Competitiveness among institutions – Since institutions shape the environment in which firms operate, they shape the 'rules of the game' and thus competitive outcomes	– Formal and informal institutions play an important role in enabling firms to be competitive

3.3.2.1 Krugman's critique

Paul Krugman criticises the concept of competitiveness on the country level in his two seminal contributions on the issue (Krugman 1994; Krugman 1996). The author puts forward three core arguments casting doubt on the meaningfulness of the concept on the macroeconomic level:

1) ***Countries are not firms***: Countries (unlike firms) do not compete with each other in supplying products and services on markets. As mentioned in the previous section on microeconomic competitiveness, Krugman argues that the outcome of firms being competitive is that they remain in business over time. Countries, however, are fundamentally different since they cannot go out of business, thus the "concept of national competitiveness is elusive" (Krugman 1994).

   At first sight, this seems plausible as countries mainly supply public goods and services which by definition are non-rival and non-excludable. However, as the sovereign debt crisis in the Euro area and historic examples illustrated, countries can default on their debt. Nevertheless, they generally do not go out of business in the sense that they close down or disappear. Krugman further argues that countries (unlike firms) are not in a zero-sum world, i.e. an increase in productivity or exports in one country does not harm another. Quite contrarily, trade theory concludes that trade among countries makes everyone – on average – better off. Countries are therefore in a mutually beneficial arrangement contradicting the very nature of competitiveness, i.e. competing in or for markets.

2) ***Competitiveness or productivity***: Krugman argues that competitiveness, by some scholars defined as increasing the standard of living, is essentially about increasing productivity. He argues that leaving trade aside, competitiveness could be described as domestic productivity growth relative to other countries. He reasons that trade only matters for the standard of living if the purchasing power grows slower compared to output, which he argues has not been the case in the United States of America, EU, and Japan in the 1980s. Therefore, he claims that relative domestic productivity growth determines the standard of living in a country, not competition among countries.

3) ***Dangerous conclusions***: Krugman warns that pursuing policies for macroeconomic competitiveness is not only meaningless from an economics perspective but dangerous. He describes different schools of trade theory and concludes that *mercantilists* are most receptive to the concept of competitiveness since *mercantilists* believe trade takes place in a zero-sum world. Contrarily, *classicists* argue that imports are beneficial, because they are more efficient than home production, making consumer better off.

   Strategists, who are supporters of the new trade theory, acknowledge market imperfections such as economies of scale and spill-overs, thus arguing to address or take advantage of these failures in order to create a temporary competitive advantage. Lastly, *realists* are aware of market imperfection but do not believe policy can adequately address them. Thus, Krugman concludes, that those arguing in favour of competitiveness policies follow the thoughts of *mercantilists* in pursuing protectionism and introduce trade barriers.

In summary, Krugman argues that countries unlike firms do not compete on markets, competitiveness may simply be “a poetic way of saying productivity” (Krugman 1996), and the competitiveness rhetoric may potentially lead to protectionist tendencies. However, Krugman mentions one scenario in which competitiveness on the macroeconomic level might be a ‘meaningful’ concept: “[…] people who talk about competitiveness must understand the basics [of trade theory] and have in mind some sophisticated departure from standard economic models, involving imperfect competition, external economies, or both." (Krugman 1996). This statement indicates that Krugman has a standard economic model in mind which relies on perfect market conditions.

Response to Krugman's critique

However, there is also opposition to Krugman's critique. Some scholars argue that Krugman may be opposed to the concept of competitiveness, because it questions the assumption of perfectly competitive markets (Reinert 1995; Budzinski 2007). Assuming such markets, however, might not be applicable in practice (Fagerberg et al. 2007). If any assumption is violated and for instance path-dependencies and lock-in effects are present, competitiveness on the macroeconomic level might become a 'meaningful' concept.

Lall (2001a) argues that once markets fail across several countries, individual countries can temporarily generate a competitive advantage and grasp economic benefits generated by well-functioning markets by intervening to remedy such failures within their own territory. In doing so, they can momentarily become more competitive compared to those countries in which failures persist. This argument assumes that firm-level advantages within a given market but across countries can constitute a competitive advantage on the macroeconomic level. However, Lall (2001a) also argues that competitiveness analysis cannot fully address all market failures and bring about an equilibrium, but it can create factors, markets, institutions, and capabilities which lead a country to higher prosperity.

Aiginger (2006) reasons that competitiveness gains by one country occur not necessarily to the expense of another. If one understands competitiveness in a broader sense, positive externalities such as political stability, knowledge networks, industrial clusters, and increased purchasing power of foreign consumers are mutually beneficial to all parties involved.

Another 'response' the Krugman's critique addresses the channels through which welfare is generated in an economy. Reinert (1995) defines competitiveness as welfare, i.e. increasing the standard of living. The author makes the point that according to neoclassical theory, wealth is created through technological progress which reduces costs and thus increases the welfare of consumers worldwide. However, there is also a second way (the author calls it "collusive mode") that technological progress increases wealth which is then distributed among domestic workers through increased income. "Competitiveness in this way can be seen as the consequence on a national level of what labour economists refer to as 'industry rent'. The core of the competitiveness strategy is to locate industries where high industry rents exist [...].” (Reinert 1995).

Pursuing this strategy could secure that the generated welfare is not spread to all consumers globally, but directed to economic activities in certain countries. According to Reinert (1995), high-quality activities are characterised by a steep learning curve, rapid technological progress, high R&D content, high wages, and a high industry concentration. This ‘winner-picking’ strategy is considered either as “dangerous” since it might lead to inefficient protectionist tendencies (Krugman 1994) or as extremely difficult to judge in case of pursuing an ‘infant industry’ approach (Mulatu 2016).

Krugman’s argument that competitiveness might simply be a synonym of productivity is also challenged. Even though it might be an important aspect of competitiveness, productivity alone is not sufficient to explain the competitive position of a country:

> *“The definition of competitiveness as productivity is to some extent nested in the concept of ‘outcome competitiveness’: incomes will in general be higher if productivity is higher, but there are also exceptions. Productivity can be high at the price of unemployment, a low participation rate, social inequality, and ecological deprivation. And productivity can be intentionally lowered (1) to spread incomes, (2) to allow for leisure preferences, (3) to limit differences in incomes and (4) to promote social and environmental goals or leisure, health and cultural activities. In general, while productivity and increases in productivity are important to a wider assessment of outcome competitiveness, the concept of productivity seems to be too narrow for a knowledge-based society.” (Aiginger 2006).*

In summary, most ‘responses’ to Krugman’s take on competitiveness challenges his assumptions of perfectly competitive markets. The counter-argument to why productivity differs from competitiveness essentially reflects a measurement difference and is based on defining competitiveness as income growth. However, Krugman’s cautioning against protectionism seems to remain uncontested. So far, it can be concluded that the precondition for competitiveness to play a role on the macroeconomic level is the existence of market failures.

3.3.2.2 Complementing price competitiveness

Despite Krugman’s critique, the concept of macroeconomic competitiveness has remained in the academic and particularly in the political debate for many years. Among economists and policymakers, macroeconomic competitiveness is frequently measured by standard cost and trade indicators, including unit labour costs, the real effective exchange rate (REER), interest rates, or exports (Siggel 2006; Lommatzsch et al. 2016; OECD 2017). The rationale underlying such cost and trade measures might be the increased competition in a globalised world which often results in offshoring parts of production and employment from relatively high-cost to low-cost economies (Acemoglu et al. 2016). In order for relatively high-cost countries to remain competitive, it is argued to pursue a cost reduction strategy (Salvatore 2010).

Porter (1990) argues that such cost measures are insufficient to establish and explain a real and sustained competitive advantage. For instance, a fall in wages or the exchange rate does not make a country more competitive, if the objective of being competitive is to raise the standard of living – a definition share by several scholars (Snowdon and Stonehouse 2006). Aiginger (2006) argues that 'price competitiveness', which these measures essentially reflect, might be good in perfectly competitive markets and for low-income countries, as they are competing with relatively homogeneous goods, but not in imperfect markets and high-income countries, as they typically do not compete according to costs but rather according to innovation and quality. This is in line with the arguments brought forward for microeconomic competitiveness.

Lall (2001) adds that countries are not in competition with each other according to costs or prices which is implicitly suggested by using the costs measures. Cost measures are insufficient to measure the competitive stance of economies, especially in the long-term (Mulatu 2016). Rozmahel et al. (2014) point out that "the traditional approach of countries' competitiveness evaluation is oriented on cost-based measures such as unit labor costs, REER or unit labor productivity indices. Today's Europe seeks for sustainable, smart, inclusive and environmentally friendly economic growth. From that perspective, the traditional cost-based approach of productivity assessing provide a limited picture."

These conclusions are reflections of what has previously been discussed in the literature as the 'Kaldor paradox' which argues that relative unit labour costs are positively correlated with the relative market share of manufacturing exports that is considered a factor of international competitiveness (Kaldor 1978). Kaldor (1978) thus questioned "the relative importance of price (or cost?) competition, as against other 'non-price' factors, such as superiority of design or quality, length and reliability of delivery dates, after-sales service, etc."

More holistic approaches exist which comprise non-monetary factors. For instance, Aiginger (2006) defines competitiveness as "the ability of a country or location to create welfare". This definition is shared by several scholars (Reinert 1995; Lehner et al. 1999; Snowdon and Stonehouse 2006; Salvatore 2010; Voinescu and Moisoiu 2015). In order to measure welfare, Aiginer (2006) complements cost measures with additional non-cost factors determining or resulting from competitiveness. The author groups competitiveness into two categories.

1) ***'Outcome competitiveness'*** which are the observed results of being competitive. This is often measured by a high and rising standard of living, high GDP per capita, high levels of employment, a high human development index, and achieving sustainability goals. Such indicators aim to approximate welfare (Aiginger and Vogel 2015). This approach is similar to the one on microeconomic competitiveness which entails advantages (measurability, data availability etc.) and disadvantages (sign of direction unclear, omitted factors, relative nature of concept).

2) ***'Process competitiveness'*** which describes factors determining macroeconomic competitiveness. Measures include the inputs of production functions (capital, labour, materials), technology, capabilities, structure, and institutions. The latter are thought to be particularly important, as they support factor accumulation, innovation and the efficiency of resource allocation through incentives (Budzinski 2007; Lee 2010).

There are a few empirical assessments evaluating the factors underlying outcome and process competitiveness. Aiginger and Vogel (2015) use a panel of the EU economies between 2000-2010 to estimate the impact of different components of competitiveness (i.e. prices, economic structure, and capabilities) on beyond-GDP indicators including income, social, and ecological measures. Using simple regression analysis with year-fixed effects, the authors find significant results for the economic structure and capabilities indices but not for price measures.

Thompson (2004) find that institutional settings are more important compared to cost measures using a hierarchical regression analysis with primary data from Hong Kong. Fagerberg et al. (2007) use a panel of 90 countries between 1980-2002 to estimate the importance of technology, capacity, price, and demand indices in explaining GDP growth. The authors use simple regression analysis and provide evidence that technology, capacity, and demand positively affects GDP growth whereas prices negatively. However, the authors test for endogeneity and lack to provide a convincing justification for their instrumentation strategy that is based on selecting instruments according to their correlation significance with the dependent variable.

Fagerberg (1988) use a panel of 15 industrialised countries between 1961-1983 to estimate the impact of unit labour costs on growth and competitiveness. Using a two stage least square (2SLS) estimation, the author finds evidence supporting the 'Kaldor paradox'. Unit labour costs are insignificantly related to growth and competitiveness, whereas technology and capacity are not. Madzík et al. (2015) study correlations between various process competitiveness indicators and the standard of living and find "structural links" between them. The authors identify free-time as the trade-off between increasing competitiveness and the standard of living.

In summary, costs and price measures are important in determining competitiveness, but might need to be complemented with non-monetary factors. However, there is no clear understanding which specific factors should be chosen to measure outcome or process competitiveness, because empirical assessments evaluating individual factors are based on methodological limitations and the literature does not reach any consensus on the 'best' way to measure competitiveness on the macroeconomic level.

3.3.2.3 Macroeconomic competitiveness with a microeconomic foundation

There is an additional approach to macroeconomic competitiveness which somewhat seems to combine Krugman's argument that only firm level competition is meaningful with factors associated with macroeconomic competitiveness. This approach essentially argues that only firms compete with each other, but the country's environment is an important factor determining the type of competition taking place. In short, microeconomic and macroeconomic factors combined determine competitiveness (Thompson 2004).

Michael Porter in his seminal contribution argues that competitiveness can only be realised by firms through continuous innovation and upgrading, comprising both incremental and fundamental changes (Porter 1990). This competitive advantage can be sustained as long as competitors are slower in adopting to such changes, thus arguing for the existence of a first mover advantage for innovators. This is confirmed empirically for the most productive firms, but the first mover advantage lasts a relatively short period in the most industrialised economies (Albrizio et al. 2015).

Firms operate within a country's economic, social, and political environment which might support (or obstruct) firms to achieve a competitive advantage. Porter (1990) calls those preconditions for continuously innovating and upgrading the "diamond of national competitiveness". This set of determinants of competitiveness comprises four interrelated factors.

1) ***Factor conditions*** which comprise natural and 'created' factors of production, namely labour, capital, land, resources, highly-specialised skills, and infrastructure. The combination of such factors determines which goods and services a country specialises in and how competitive they can be supplied to markets.

2) ***Demand conditions*** which describe the sophistication of domestic demand. Despite claims that in a globalised world domestic demand becomes relatively less important, there is a home-bias of firms' strategic decisions towards domestic consumers. If domestic consumers are sophisticated and demanding, domestic firms are likely to be more competitive relative to foreign firms not facing this type of domestic consumer.

3) ***Related and supported industries***, including the strength, proximity, and specialisation of the domestic supplier industry. Once the supplier industry provides access to inputs more efficiently or increase the likelihood of innovation spill-overs (due to proximity, clusters, networks, preferential treatment), domestic firms are likely to be competitive.

4) ***Firm strategy, structure, and rivalry*** which emphasise the importance of the legislative environment, the creation, organisation, and management of firms as well as the level of competition in the market. All such factors determine competitiveness heterogeneously, depending on country and sector specific circumstances.

Porter (1990) argues that the combination of these factors ultimately determines a country's competitiveness. Parts of some factors are the responsibility of firms or consumers; others can be influenced by governments. Thus, Porter envisions a cautiously active government, i.e. a government that sets incentives for change, competition, and innovations while not creating dependencies of firms on public support.

Porter's approach to combine the macroeconomic environment with the microeconomic capabilities to explain competitiveness is shared by other scholars (Lehner et al. 1999; Önsel et al. 2008). Snowdon and Stonehouse (2006) argue that the macroeconomic environment, including political, economic, legal, and social stability with a strong anti-trust policy, is a necessary condition for firm level competitiveness. Rozmahel et al. (2014) complement traditional cost measures for competitiveness by introducing a microeconomic perspective capturing a country's potential to attract firms. As such, the authors use indicators that measure the broader environment in which firms operate, including the quantity and quality of infrastructure (airports, railways, internet access etc.) and the quality of human capital accumulation (education attainment, tertiary students etc.).

There is little empirical evidence on the importance of microeconomic factors in macroeconomic competitiveness. Delgado et al. (2012) estimate the impact of 120 macroeconomic and microeconomic indicators on expected prosperity. The authors measure expected prosperity by the expected level of output per working-age individual, thus capturing labour productivity and labour market participation. Using a panel of 130 countries between 2001-2008, the authors use simple regression analysis, controlling for country and year fixed-effects as well as endowments, finding that the microeconomic indicators are more robust in explaining expected prosperity compared to social and political institutions, or monetary and fiscal policy. However, the authors explicitly acknowledge that they have not dealt with the potential problem of endogeneity in their estimations. Jara (2017) uses a simple regression model to analyse the differences in country level competitiveness for the mining sector. The author finds that besides geographical factors, the investment climate for firms determines differences in macroeconomic competitiveness.

There is critique on Porter's initial concept of competitiveness with regards to not considering sustainability (e.g. Zhang and London 2013). Additionally, the relationship between microeconomic and macroeconomic factors of competitiveness remains unclear. As Reinert (1995) points out: "Competitiveness is in my view divorced from the issues of productivity or efficiency as such. Although it is difficult to be competitive if you are not efficient and have a high productivity, it is by no means obvious that being the most efficient producer of an internationally traded product makes a country competitive - i.e. enables it to raise the standard of living."

In summary, the concept of competitiveness on the macroeconomic level is argued to require a microeconomic foundation in order to meet the complexity of the concept. Firm level aspects need to be considered in analyses on macroeconomic competitiveness, for instance, by including indicators that reflect or a based on firm level determinants related to competitiveness. However, microeconomic considerations by themselves are insufficient to explain macroeconomic competitiveness.

3.3.2.4 Institutional competitiveness

Institutions are often defined as "humanly devised constraints that structure political, economic and social interaction [...] to create order and reduce uncertainty in exchange." (North 1991).

Institutions can be both of *formal* and *informal* nature. The former is typically represented by laws, constitutions, and property rights, whereas the latter are societal constraints, such as norms, traditions, ideas, and customs. This understanding of institutions is rooted within New Institutional Economics which attempts to explain the role of institutions in imperfect market conditions (North 1990; Coase 1998).[4] Besides various approaches to explaining institutions, there appears to be a consensus that institutions directly or indirectly can direct economic activity. Hence, they shape the 'rules of the game' which is an essential part in defining a country's economic, political, and social environment.

Another differentiation among institutions can be made along the lines of *extractive* and *inclusive* institutions (Acemoglu et al. 2014). According to this definition, *extractive* economic and political institutions only serve the interests of a small elite, depriving the broader society of adequate incentives to invest in economic activity and to engage in competitive markets. Thus, the authors conclude that *inclusive* economic and political institutions are a necessary condition for countries to prosper, and indirectly, for competitiveness to unfold.

Following Caplin and Nalebuff (1997), there are two views on how institutions and competitiveness are linked. The first one considers how institutions are shaped by their environments, i.e. competition among institutions, and the second one takes the impact of institutions on their environment into account, i.e. institutions as a determinant of competitiveness.

1) ***Competition among institutions***: Institutions are thought to be the result of a process driven by the societies they are embedded in. Accordingly, Hayek (1967) argues within an evolutionary approach towards institutions that the most successful institutions remain while other disappear over time. This evolutionary perspective sets competition among institutions in the centre of discussion. Competition takes place in attracting economic agents or economic activity to take place in the jurisdictions that institutions represent. Since it is *ex ante* not clear which institutions will be more successful than others, this process can be considered a knowledge-creating discovery process (Vanberg and Kerber 1994; Kerber 1999).

   Institutions can support the production of social surplus by providing hospital environments for economic agents in terms of stability, education systems, subsidies, infrastructure, bureaucracy, taxes, and other environmental and cultural benefits. How

[4] Other definitions of institutions exist and are summarised in Bleischwitz (2005).

efficiently surpluses are generated through setting rules, constitutes the factor among which institutions compete (Vanberg and Kerber 1994). This type of competition assumes that economic agents or economic activity can freely move throughout jurisdictions and therefore provide feedback to which set of institutions they prefer (Bleischwitz 2005). Not only economic agents are assumed to freely move between jurisdictions, but also capital, thus creating competition across institutional setting (taxation, public goods provision, stability etc.).

Competition according to the level of taxation on highly-mobile tax bases, for instance financial capital such as profits and savings, might not be desirable. This kind of competition can incentivise separating the location where profits and savings are generated, including through the use of public goods, from the jurisdiction in which those profits and savings are being taxed. While tax competitiveness can also incentivise governments to spend tax revenues efficiently, the practise of tax optimisation can ultimately undermine the provision of public goods, deteriorate trust in public institutions, and lead to free riding (Sinn 1997).

These considerations are particularly important in the context of the European Single Market, as it allows for the free movement of goods, capital, services, and labour, while having different institutional arrangements guaranteed by historic path dependency and the principle of subsidiarity (Kerber 1999). An institution that successfully attracts economic activity can be considered relatively more competitive, whereas the others jurisdictions with inferior institutions might fall behind, providing an incentive to change (Vanberg and Kerber 1994).

However, not all scholars share this approach towards institutions. "System competition" with the aim to overcome market failures by setting rules can result in government failures resulting in inefficiently low regulation, an under-provision of public goods, or too little redistribution (Sinn 1997). Thus, it is highly questionable whether the result of institutional competition is socially desirable (Kerber 1999).

2) ***Institutions as a determinant of competitiveness***: By shaping the environment in which economic activity takes place, institutions are argued to support factor accumulation, innovation, an efficient resource allocation, thus affecting economic activity (de Soto 2003; Lee 2010). Furthermore, institutions can incentivise the spread of knowledge by influencing its content, direction, and dynamic (Vanberg and Kerber 1994) which is at the very core of Schumpeterian competition (Budzinski 2007).

According to Caplin and Nalebuff (1997), institutions have an impact on their environment by shaping the *formal* and *informal*, *internal* and *external*, and *extractive* and *inclusive* settings in which firms operate, making institutions a determinant of competitiveness.

Bleischwitz (2005) argues that institutions face a trade-off. On the one hand, setting rules on economic activity can decrease transaction costs and lead to a more efficient allocation of resources. On the other hand, there is a cost of setting up and maintaining institutions (which in extreme cases can sum up to 80% of a country's GDP) as well as costs of 'over-regulation', for instance, when outdated regulation impedes technological progress.

Odendahl (2016) points out that an optimal mix of institutional settings define the environment for firms to operate is highly country-specific. Hence, there is no universally defined mix of policies applicable to all countries, but each country requires a different set of interlinked institutions to provide a competitive environment.

There is little empirical evidence on institutional competitiveness. Huemer et al. (2013) argue that the competitiveness of countries is not only determined by price factors, but also by discretionary policy decisions. The authors construct an index of institutional competitiveness for 36 industrialised countries between 1990-2009, comprising policy-induced factors of competitiveness, concluding that infrastructure and financial market regulation explain most of the between-country variation in institutional competitiveness. Changes over time are mostly explained by the taxation of production factors, such as labour and goods. This index will be used in the empirical analysis in Chapter 7. Thompson (2004) finds that institutional settings are more important compared to cost measures using a hierarchical regression analysis of survey data from Hong Kong.

In summary, institutions play an important role in the competitiveness debate since they shape the environment in which firms operate, both *internally* and *externally* (Bleischwitz 2003; Bleischwitz 2010). Even if the assumption of factor mobility might be limited in practice (e.g. only 2.5% of EU-citizen live in another EU member state (EC 2017e)), firms or capital are likely to choose a jurisdiction that best reflects their needs. From a normative perspective, this could either be beneficial (cluster building with positive externalities) or detrimental (corporate tax reductions leading to a 'race to the bottom'). What becomes apparent though is that institutions play an important role in the competitiveness debate.

3.3.2.5 Conclusions

After having considered four different yet related approaches to macroeconomic competitiveness, this section briefly outlines the conclusions that can now be drawn. These considerations will play a vital role in Chapter 7, when the effect of material productivity on competitiveness on the country level are being investigated empirically.

The following key issues could guide the understanding of macroeconomic competitiveness.

1) ***Market failures:*** Following the conclusions from Krugman's critique, the existence of market failures can be seen as a necessary condition for macroeconomic competitiveness to become a 'meaningful' concept.
2) ***Complementing price measures:*** Conventional price or cost measures, including unit labour costs, interest rates, the current account, among others, are helpful in understanding a country's competitive position according to prices. However, solely considering such measures is likely to be misleading, thus price and cost measures need to be complemented by non-price factors.
3) ***Microeconomic foundation:*** Assessing macroeconomic competitiveness using macroeconomic indicators provides a logical starting point. Nevertheless, as argued by Porter and other scholars, such country level indicators should either consist of or be complemented by indicators that capture firm (or industry) level aspects related to competitiveness.
4) ***Institutions:*** Measuring institutional quality and the conditions which are shaped by institutions plays an important role in assessing macroeconomic competitiveness. Therefore, including indicators related to institutions is necessary in empirically investigating the issue.
5) ***Welfare creation:*** While no single definition of macroeconomic competitiveness exists, the majority of scholars argues that the outcome of competitiveness is welfare creation. Accordingly, indicators reflecting welfare creation could measure the success of competitive countries.

The details on which specific indicators and data used in the empirical analysis are provided and discussed in Chapter 7.

3.3.2.6 A brief overview of competitiveness in the European Union

Since this dissertation's focus is on Europe, and in particular the EU, a brief overview of the definitions and concepts assesses the application of the previous discussion in practice. Given the various approaches to competitiveness, it is not surprising that the EU does not have a commonly agreed understanding of competitiveness. In the EU, there are essentially three publically available definitions of competitiveness.

1) ***Definition DG Eurostat:*** Competitiveness as defined by the Directorate-General (DG) Eurostat of the European Commission is "a measure of the comparative advantage or disadvantage of enterprises, industries, regions, countries or supranational economies like the European Union (EU) in selling its products in international markets. It refers to the ability to generate relatively high income and employment levels on a sustainable basis while competing internationally." (EC 2015e).

   This definition conflicts with Krugman since it suggests that countries, like firms, sell products and directly compete in international markets (Krugman 1994; Krugman 1996). Additionally, competitiveness is argued to be a measure of comparative (dis-)advantages. However, according to Snowdon and Stonehouse (2006), a comparative advantage considers existing factor endowments as the principle determinant of trade, whereas competitiveness is about the quality of factors and how they are being used within a firm. A comparative advantage compares equilibrium factor prices, whereas competitiveness considers the business environment in which firms operate (Siggel 2006).

   Nevertheless, the second part of the definition is in line with the concept of 'outcome competitiveness' which is high income, high employment levels, and sustainability, acknowledging the relative nature of the concept (Aiginger 2006).

2) ***Definition 'European Semester':*** As part of the surveillance of EU member states' state budgets and macroeconomic imbalances, competitiveness is referred to as price or export competitiveness, measured by unit labour costs, the REER, and the trade balance (EC 2015f). This approach to competitiveness was already discussed previously, concluding that neither firms nor countries compete solely according to prices (see 'Kaldor paradox') but also according to non-monetary factors.

3) ***Definition DG GROW:*** Former DG Enterprise and Industry (now DG for Internal Market, Industry, Entrepreneurship, and SMEs) used the following definition for the EU's growth strategy, the so-called 'Lisbon Strategy', between 2000 and 2010: "A competitive economy is an economy with a consistently high rate of productivity growth. Competitiveness depends on the performance of the economy's SME-fuelled

industry. To be competitive, the EU must outperform its competitors in terms of research and innovation, information and communication technologies, entrepreneurship, competition, education and training." (EC 2015g).

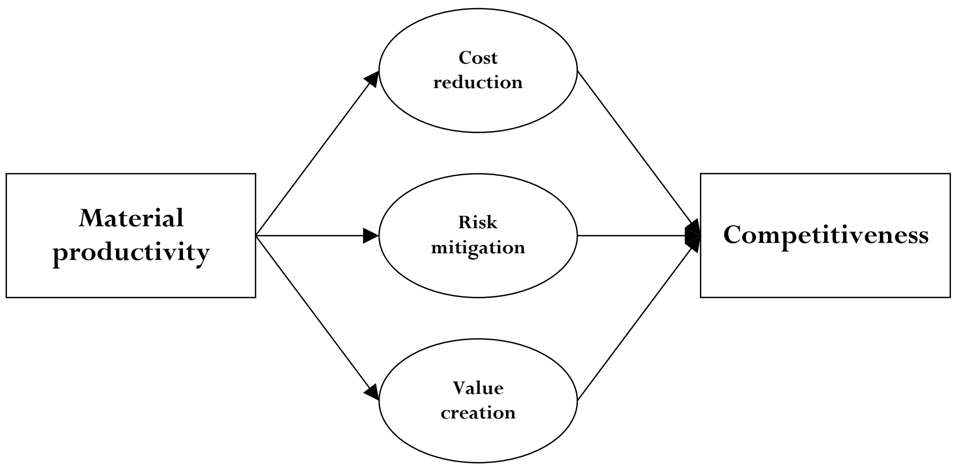
This approach is somewhat in line with the conclusions drawn from the literature; it is a microeconomic concept, closely related to yet different from productivity growth, and determined by a 'favourable' macroeconomic environment (Aiginger 2006). It is however not clear why the EU's competitiveness mainly depends on industry and especially SMEs.

In summary, the EU does not have a commonly agreed definition of competitiveness. Since the three definitions discussed above do not provide a clear picture on what determines competitiveness, or on which level competition takes place, the conclusions drawn from the review of the literature is taken further into the empirical chapters of this dissertation.

3.3.3 Channels linking material productivity and competitiveness

After having considered competitiveness and material productivity separately so far, this section discusses the channels linking them. This discussion reviews why and how the two variables relate from a structural perspective. Whether there is any empirical link visible in the data will be assessed in Chapters 7 and 8.

Figure 9: Channels linking material productivity and competitiveness.



As mentioned in the introduction, the notion that increasing material productivity can lead to an increase in competitiveness is a central theme of the contemporary material, resource efficiency, and circular economy initiatives in the EU and across the world (EC 2011b; EC 2015a). Despite the lack of a common definition of competitiveness in the EU, pursuing material productivity policies are claimed to positively impact on the competitive stance in the EU.

The EU identifies the following channels through which the two variables are linked: reducing material costs, growth and job creation, environmental benefits and resilience to climate change, and macroeconomic stability by reducing import dependencies (EC 2011d). However, there is no elaborate discussion on each channel or their definitions (even though several definitions of, for instance, resilience exist (Lima and Medda 2015)). This section attempts to fill this gap.

Considering the entire evidence base, Figure 9 and Table 10 illustrate and summarise channels through which material productivity and competitiveness are potentially linked. These channels are similar to those identified by the EU. However, this analysis complements the EU approach by taking into account all relevant bodies of literature. Three channels can be identified, inspired by the terminology used in the energy efficiency context (IEA 2014): (i) cost reduction, (ii) risk mitigation, and (iii) value creation.

3.3.3.1 Cost reduction

Reducing input costs: The principal discussion on whether material productivity impacts on competitiveness relates to the material cost channel. In a nutshell, if firms improve their material productivity, they are likely to reduce their material use either absolute terms or relative to output. This will *ceteris paribus* reduce their unit production costs and thus the firms can offer their goods and services at lower prices or increase their profits, thus increasing their (price) competitiveness. There is a considerable amount of studies related to this channel.

Bleischwitz et al. (2009b) find a positive and significant correlation between material productivity and several competitiveness indices, acknowledging the possible problem of endogeneity in their analysis. The authors define competitiveness as increasing the standard of living with lowest possible unemployment. The authors explain their results by referring to the material cost channel since material costs make up a major share of firms' production costs. For instance, in the German manufacturing industry, material costs in terms of their purchasing costs as percentage of gross production value account for 45.3% (KfW 2009; Statistisches Bundesamt 2011). According to a survey of firms in the EU, materials account for more than 50% of total costs for 27% of all companies in the manufacturing sector (EC 2011e). For more than half of the companies in the EU, material costs make up more than 30% of their overall expenses. Additionally, material costs as a share of total costs account for around 30% in the chemical, paper, rubber and plastics, base metal, and wood sectors in the Netherlands (Wilting and Hanemaaijer 2014). However, the recent downturn in material price levels might have changed these percentages.

Table 10: Channels linking material productivity and competitiveness

Channels	Sub-channels	Rationale
Cost reduction	*Firm level* Reducing input costs	– Improving material productivity (MP) means using fewer material inputs per unit of output, thus lowering the unit production costs. – Reducing the unit production costs can increase the (price) competitiveness of firms.
	Firm level Anticipating environmental regulation	– Increasing MP can help firms to comply with (future) regulation (e.g. MP targets, GHG emissions reduction) more cost-effectively. – Environmental regulation can create a first-mover advantage and increase competitiveness.
Risk mitigation	*Firm level* Hedging against material price volatility	– Material price volatility poses risks to firms' operations (i.e. uncertain input prices). – Increasing MP, i.e. using fewer materials per unit of output, can help to reduce firms' exposure to price risks potentially increasing their competitiveness.
	Firm and country level Supply security	– For material importing countries or material purchasing firms, increasing MP can reduce material dependencies, for instance, by using secondary raw materials. – Reducing this dependency can improve competitiveness.
	Global level Climate change mitigation	– Increasing MP can reduce GHG emissions, mitigating climate change and reducing pollution. – Mitigating climate change can improve competiveness.
Value creation	*Firm level* Eco-innovations	– Improving MP can incentivise or be the result of eco-innovations of products, processes, organisational structures, marketing practices, and entire systems. – Such innovations can increase competitiveness (e.g. by making future innovations more likely; spillover effects).
	Country level Economic growth, productivity, and innovation	– Increasing MP can have positive effects on GDP, productivity, employment, innovation activity, the balance of trade, and the fiscal stance of a country. – All such effect can improve a country's competitiveness, i.e. generate welfare.

A EU-report uses the WIOD database on industry level between 1995-2007 for 21 EU member states to analyse the impact of energy efficiency on competitiveness (EC 2014d). The authors use a panel data estimation with fixed-effects to quantify the impact of energy intensity on export competitiveness. The report finds a negative relationship, i.e. increasing energy efficiency leads to higher export competitiveness. The results suggest that the higher the cost share of energy for industries is, the more significant the results become. However, the results lack robustness (significant only at the 10%-level) and controlling for possible endogeneity.

In an analysis for the United Kingdom in 2009, the estimated saving potential for firms becoming resource efficient is £23 billion (£18 billion for waste prevention) with pay-back periods of less than 12 months (Oakdene Hollins 2011; OECD 2011a). It is argued that most of these saving potentials are not associated to lowering direct material purchasing costs, but rather by reducing 'hidden costs', such as disposal, transportation, production, energy use, among others (Schmidt and Schneider 2010).

An empirical study looks at the impacts of resource efficiency investments (namely water, energy, and waste) for the manufacturing industry and six energy-intensive subsectors (Bassi et al. 2012). Its main finding is that incremental resource efficiency investments pay off on average after nine years, reduce the unit production costs in the short term, and increase the firms' economic performances in the medium and long term. The authors use a system dynamics model to compare a business-as-usual with a scenario of investing in resource efficiency. Such cost savings are mainly due to reducing energy consumption and to a lower extent the result of minimising wastes.

A study on the firm level considers tangible benefits from introducing resource efficiency measures in the sectors food and drink manufacturing, fabricated metal products, and hospitality and food services in the EU (AMEC and Bio IS 2013). Resource efficiency in the scope of the study entails a reduction of waste generation, water use, and material use. The average net benefit for firms is estimated to range between 10% and 17% of their annual turnover. This accounts for €27,500 – €424,000 reflecting heterogeneous firm sectors and sizes, whereas SMEs gain relatively more compared to larger firms. The study uses available literature, industry data, and case studies to estimate the saving potentials.

A further report focusing specifically on material efficiency in SMEs in Germany considers the saving potentials, evaluates current programmes attempting to enhance material efficiency, and provides advice for policymakers (Fh-ISI et al. 2005; Schröter et al. 2011). The report suggests payback periods for material efficiency measures of less than six months. Average savings have been estimated in the order of 7–8% of material costs for SMEs in the German manufacturing sector. The report takes case studies from individual firms and material efficiency studies as a basis to extrapolate potential material savings for entire sectors.

An international report analyses the impact of industrial energy efficiency on competitiveness in 35 developed and developing countries (UNIDO 2011). The report summarises macroeconomic and microeconomic components which link energy efficiency to competitiveness: a reduction of energy purchasing costs, an increase in productivity and the balance of trade, and the creation of a domestic market for energy efficiency technologies. The material cost channel is thus also identified in this example of the energy efficiency literature.

These studies provide evidence suggesting that the material cost channel is relevant and substantial. However, there is also one analysis finding the contrary. Material costs typically not only include the cost of raw materials but all upstream labour, transportation, and storage costs. Bruyn et al. (2009) find no statistically significant relationship between energy productivity and competitiveness. The authors suggest that there is no relationship using cross section data models for 109 countries in 2006 controlling for the stage of development of countries. The authors use data on energy productivity (based on total primary energy supply) as a proxy for resource efficiency. The authors argue that the 'actual costs' of raw materials excluding upstream value-added account for approximately 3-6% of total costs. Bruyn et al. (2009) conclude that the cost channel might simply not be relevant. However, the study does not address the issue of endogeneity. Additionally, it seems doubtful that firms are more likely to consider the 'actual costs' of raw materials rather than the immediate price tag they are confronted with. Generally, material costs are (theoretically) always a direct reflection of their production costs since materials themselves have no intrinsic value and they are not available without putting (costly) effort into acquiring them.

Nonetheless, the relevance of the material cost channel appears to be largely supported in the literature, but most studies pay little attention to the potentially problematic issue of endogeneity, or are based on case studies which possibly limits their external validity. The overwhelming majority of the evidence concludes that increasing material productivity leads to cost savings of firms which increases their (price) competitiveness. However, whether there is a causal link between material productivity and competitiveness is yet to be researched, notwithstanding initial attempts (Flachenecker 2015b).

Anticipating environmental regulation: Considering this sub-channel requires to draw two connections. The first one is to establish the link between material productivity and environmental regulation. The second one is to identify ways in which regulation impacts on competitiveness which is discussed thereafter.

1) ***Regulation and competitiveness:*** The role of environmental regulation as a channel for competitiveness is a much debated issue in the literature since the seminal work by Porter and Linde (1995). According to the authors' analysis, regulation might incentivise firms to grasp a first-mover advantage of innovating and thus become more competitive. A more nuanced approach finds that innovative improvements triggered by regulation might produce both 'winners' and 'losers' (Lankoski 2010). Similarly, environmental taxes increase productivity and innovation, but mainly in the upstream industry, while the downstream part might be adversely affected (Franco and Marin 2015).

   Recent empirical evidence suggests that environmental regulation approximated by pollution abatement and control expenditures (PACE) increases patent applications, but not R&D investments or competitiveness (Rubashkina et al. 2015). The authors use a 2SLS dynamic panel data model for 17 European manufacturing sectors between 1997-2009. The authors use the PACE of another sector within each country as an instrument which might have a direct impact on competitiveness (measured by innovation activity) of the manufacturing sector. There is no discussion on this possible endogeneity which could potentially invalidate the instrumentation strategy.

   Larrán Jorge et al. (2015) find that generally improved environmental performance has a positive and direct effect on competitiveness as well as an indirect impact on competitiveness through an improved corporate image and relational marketing. The authors analyse surveys of 481 Spanish SMEs in 2010/2011 using structural equation modelling. The rationale is that competitiveness requires acquiring and managing valuable, scarce and inimitable resources, which leads to cost reduction, improved reputation, strengthened links with the entire supply-chain, product differentiation, all of which increases competitiveness and business performance.

   Galdeano-Gómez (2008) empirically analyses the effect of mostly voluntary environmental practices on the competitiveness of 56 firms in the Spanish horticultural sector between 1997-2002. The author uses a structural equation model to address endogeneity and finds that firms applying such environmental practices as first-movers become more competitive, in particular due to differentiating their products by becoming 'greener'.

Chan et al. (2013) analysis a panel of 5,800 firms in the electric power, cement, and steel industry in 10 EU countries between 2001-2009 to estimate a difference-in-difference fixed-effects estimation. The authors estimate the impact of carbon trading and initial amount of allowances on competitiveness, which is measured as unit material costs, number of employees, and revenue. The authors separate two groups with similar sizes, one participating in emissions trading, the other group not (control group) in order to estimate an average treatment effect. The authors find that only the power sector is affected, as its material costs are increased while the firms' turnovers increased as well. A related theoretical analysis finds that carbon taxes are useful when implemented in several countries simultaneously (Hemous 2016).

2) ***Material productivity and regulation:*** The connection between material productivity and regulation is not straight forward. One way could be that low levels of material productivity incentivise governments to introduce regulation, including material productivity targets.

Another way material productivity and regulation are linked is sequential. Firms anticipating future environmental regulation (e.g. material productivity targets, GHG emission levels), increase their productivity in order to comply with the measures more cost-effectively, for instance, by enjoying a longer transition time.

Furthermore, expected regulation (and social pressures) can incentivise firms to voluntarily go beyond existing rules and standard (Gunningham et al. 2004). This could also be the case for increasing their material productivity. Firm level evidence suggests that resource efficiency investments are partly due to anticipating future changes in environmental regulation: 12% in the EU, 27% in the United Kingdom, 16% in Turkey, and 20% in Russia (EC 2012c). Similarly, 11% of firms in the EU, 13% in Germany, 9% in Russia, and 16% in Turkey voluntarily go beyond current environmental regulation (EC 2013b). If firms can take advantage of being the front-runners in complying with future regulation, they could increase their competitive stance.

Another possible link is that the anticipation of 'societal pressure' can incentivise firms to increase their material productivity, which would in turn increase their corporate image (Ecorys 2011). Generally, 'green' products or production techniques are one form of product differentiation helping firms to improve their corporate image, which in turn may increase their competitiveness (Galdeano-Gómez 2008; Zhang and London 2013).

The environmental regulation channel appears to be strong in affecting competitiveness once regulation is introduced. However, also the anticipation of regulation would explain why firms increase their material productivity to ultimately increase their competitiveness.

3.3.3.2 Risk mitigation

Hedging against material price volatility: As discussed in Chapter 2, the price volatility of most materials has increased over time due to a combination of various factors including market deregulation, technological advances (e.g. digital trading, innovations of financial products), improved access to finance which increased trading volumes (Valiante and Egenhofer 2013), shocks in supply and demand (Zhao et al. 2013), and volatility spillovers from other materials (UNEP IRP 2014; Todorova et al. 2014). Iron ore price volatility is a notable exception which decreased between 2010 and 2012 (Ma 2013).

Increasingly volatile prices, material productivity, and competitiveness are linked (Flachenecker and Rentschler 2015). Fluctuating prices are an important cause of investment uncertainty (Chatham House 2012), a reduction of consumption, a decrease of industrial production and inflation (Zhao et al. 2013; Ebrahim et al. 2014), and a reduction of overall GDP due to lower capital accumulation (Cavalcanti et al. 2015).

Investment uncertainty results in a premium, which firms have to account for in form of higher discount rates and lower expected net present values of investment decisions. Additionally, if price volatility increases and prices for firms are not hedged, production costs become volatile as well. Depending on the stickiness of the firms' prices, this may cause high fluctuations of the cash flow, which in a worst-case scenario can lead to insolvency since companies may have difficulties to pass on all parts of such costs to consumers (AMEC and Bio IS 2013) – their competitive stance is likely to deteriorate. Increasing material productivity leads to a relative or absolute reduction of material use. This reduces the importance of material price fluctuations on the firms' production costs and might increase productivity and output. Thus, it lowers the negative effects of price volatility and could enable firms to become more competitive relative to those firms which have not reduced their exposure to material price volatility.

Supply security: As outlined in Chapter 2, the fear of physical limits of resources has long been an issue in economic and policy debates (Malthus 1798). Even if there is a broad consensus that most materials are physically abundant (Tilton 2001; Tilton 2003), the issue of criticality and supply security seems more urgent than ever, especially in the EU that imports most of its materials (EC 2014a). This dependency on material imports is considered a vulnerability which could become an obstacle to competitiveness, both for countries and firms. If critical materials cannot be accessed and no immediate substitutes or strategic reserves are available, economic activity can decrease (abruptly) leading to a weakening of competitiveness.

Reducing the absolute material use by increasing material productivity through recycling and building up an internal market for secondary raw materials could reduce the magnitude of the problem (EC 2015a). To this end, Malinauskiene et al. (2016) introduces a framework to integrate a criticality dimension into assessing resource efficiency measures. Accordingly, material productivity improvements, in particular those taking criticality into account, can reduce the magnitude of dependency on material imports, therefore increasing competitiveness.

Climate change mitigation: The use of materials is directly or indirectly part of every product or service consumed or produced in modern economies. As mentioned in Chapter 2, materials are associated with environmental pressures all along their life cycles (UNEP IRP 2013). The UNEP IRP outlines such pressures and differentiates between ecological and human health impacts arising from them (UNEP IRP 2010a). The IEA (2010) suggests that 77% of the total direct CO_2 industrial emissions are due to the production of four sets of materials, namely iron and steel, cement, pulp and paper, and aluminium (IEA 2010). Other scholars estimate that material production is responsible for 25% of all anthropogenic CO_2 emissions globally (Worrell et al. 2016).

Hence, the use of materials directly contributes to climate change, pollution, and impacts on human health. Increasing material productivity in the sense of reducing absolute material use can therefore serve as a climate change mitigation strategy (Barrett and Scott 2012; Gilbert et al. 2016). The assumption underlying this measure is that either absolute material use is being reduced or the composition of material use is changed to reduce GHG emissions. Among numerous strategies, this could be achieved by increasing the efficiency with which raw materials are transformed to economic goods and services, the creation of new goods and services requiring fewer materials, discarded materials are being returned to the economic cycle, and the transformation of goods into services (sharing economy).

Climate change is generally argued to have a negative impact on economic activity, and thus on competitiveness, due to the increased costs and risks associated with severe weather events, a reduction of labour productivity and supply, health impacts, and human capital formation

(Böhringer et al. 2009; Toi 2009; Tol 2010; IPCC 2012; OECD 2015b). However, there is also some evidence of positive effects. For instance, agricultural production and productivity can increase due to warmer temperatures and increased precipitation in Norther America and Europe (Adams 1990; Olesen and Bindi 2002) and less sea ice could open up new shipping routes and access to natural resources (Tol 2010).

On the other hand, the agricultural sector of on average warmer countries might experience adverse effects, for instance, China and India (Guiteras 2007; Chen et al. 2016). While most scholars argue that most adverse effects of climate change are likely to be borne by developing countries (Tol 2010), there is little evidence on the direct impacts of climate change on competitiveness (Heal and Park 2016). One study of the United Kingdom finds that addressing climate change has not resulted in a decrease of competitiveness (Bassi and Duffy 2016).

3.3.3.3 Value creation

Eco-innovations: As outlined in Chapter 2, an eco-innovation "is the introduction of a new or significantly improved product (good or service), process, organisational change, or marketing solution that reduces the use of natural resources (including materials, energy, water, and land) and decreases the release of harmful substances across the whole life-cycle." (Eco-Innovation Observatory 2012). Increasing material productivity may be the result of an eco-innovation (Fischer and Brien 2012). At the same time, material productivity improvements can trigger (further) eco-innovations.

An empirical analysis provides evidence for energy and resource efficiency enhancing innovations (i.e. eco-innovations) positively contribute to a firm's economic success (Rennings and Rammer 2009). The analysis uses the German part of the European Commission's Community Innovation Survey. The authors identify supply-side (i.e. R&D budgets, research and innovation infrastructure, and economic proximity to other firms) as well as demand-side factors (i.e. increase productivity and cost reduction) that incentivise eco-innovations. Thus, productivity increases can result in innovative activity, which can increase the market size (EEA 2011b) and incentivises future innovations in a virtuous cycle (Meyer 2011). As most prominently outlined by Porter (1990), continuous upgrading and innovating is an important part of competitiveness.

Therefore, eco-innovations and material productivity are likely to go hand-in-hand, in particular process and product innovations. This goes back to the efficiency with which materials are transformed into economic goods and services which is closely related to processes and products. As outlined previously, this value creation, and thus possibly welfare creation, is at the very heart of outcome competitiveness.

Economic growth, productivity, and innovations: Material productivity can increase economic activity (or be the result thereof), employment, productivity, innovation activity, the balance of trade, and the fiscal stance of a country. This value (and wealth) creating process of converting materials into economic goods and services is a direct measure of the macroeconomic competitiveness.

To this end, there are several empirical studies investigating this process. An EU-wide report uses macro-econometric modelling techniques to estimate impacts of several material productivity scenarios (1–3% yearly productivity increase) using RMC data until 2030 (EC 2014e). The results suggest that a material productivity increase of around 2–2.5% per annum positively affects EU-28 GDP after subtracting the costs of the productivity increase. Beyond this threshold, GDP is (partly) negatively influenced. Moreover, 2 million additional employment opportunities are predicted. All such estimations hold even if the EU-target to achieve a manufacturing share of 20% of EU-GDP by 2020 is complied with.

A related study focusing on Germany models a policy induced increase in resource efficiency until 2030 and groups such policy measures into three categories (Distelkamp et al. 2010; Ecorys 2011; Meyer 2011): (i) economic instruments (i.e. substituting income with resource taxes), (ii) information instruments (i.e. *best practise* campaigns for firms), and (iii) regulatory instruments (i.e. recycling rules). Implementing all three instruments results in doubling material productivity between 2010 and 2030, positive effects on GDP (+14%), employment (+1.9%), public debt (–11%), and a reduction of material use (TMR –20%) until 2030. Such effects are the upper threshold and thus show the maximum potential of resource efficiency gains. The positive effects on employment are in line with other findings (Walz 2011), also on the EU-level (Meyer 2011).

A global macro-econometric modelling study finds that absolute decoupling is possible even up to 3.5–4.5% increase per annum without compromising employment or increases in economic activity (Schandl et al. 2016). Considering various scenarios on the degree of international cooperation, an EU study using environmentally extended global multi regional input-output models find that it is possible to achieve by 2050 a reduction of 80% of CO_2 emissions compared to 1990 and a reduction of material use to 5 tonnes per person (RMC based), among other targets, while increasing GDP by 8.2% and creating 1.5 million jobs compared to a business-as-usual scenario (Meyer et al. 2016).

An extensive study identifies drivers, measures, monitoring practises, barriers, and policy interventions related to resource efficiency and competitiveness in the EU (Ecorys 2011). One of its main findings is that resource efficiency measures can lead to overall productivity improvements in a given sector. The study analyses nine resource-intensive sectors through literature reviews, consultations with stakeholders, qualitative surveys, and to a lesser extent, statistical analyses mainly in terms of actions leading to enhanced resource efficiency. The study acknowledges the limited availability and accessibility of data, especially on financial issues. The impact of increasing material productivity on total factor productivity critically depends on the relationship between the different inputs, for which only limited evidence exists (Baptist and Hepburn 2013).

Aiginger and Vogel (2015) argue that competitiveness is not about economic growth but about sustainability: "Productivity is an important element of competitiveness, but higher labour productivity loses its singular relevance if the growth path becomes more inclusive and sustainable. Higher resource productivity may be more important to welfare if sustainability is among the goals; higher labour productivity is less advantageous if unemployment is high and higher output growth is connected with higher emissions." (Aiginger and Vogel 2015). Zhang and London (2013) draw similar conclusions. The authors argue that sustainability and competitiveness are linked through eco-innovations and material productivity.

Increasing material productivity on a macroeconomic level can thus increase economic growth, employment, productivity, innovation activity, the balance of trade, and the fiscal stance. These variables themselves have been suggested to be used to measure or are likely to increase competitiveness.

3.4 Limitations of the existing literature

While some limitations are specific to single studies or strands of the literature, others are common to a majority of the existing investigations on the topics reviewed above. To this end, this section summarises more general challenges that the literature faces. Parts of this overview serves as the motivation for the subsequent empirical chapters, in particular Chapters 6, 7, and 8, and will be discussed in greater detail in the next section. Addressing the remaining parts of this overview is left for future (and on-going) research.

Most of the challenges the various bodies of literature are confronted with are not new. In fact, Cleveland and Ruth (1998) critically reflect on the early literature focusing on the concepts of dematerialisation and material intensity. The authors conclude that the knowledge about developments in material use and material productivity are largely limited to individual materials or specific industries, while the aggregate economic significance of materials often remains unknown. The authors advise against making "gross generalizations about material use, particularly the 'gut' feeling that technical change, substitution, and a shift to the 'information age' inexorably lead to decreased materials intensity and reduced environmental impact" (Cleveland and Ruth 1998).

Since then, the literature continues to face similar challenges. Expanding on Cleveland and Ruth (1998), the main issues following the literature review can be summarised as follows.

1) ***Aggregation of weight-based material indicators***:

   i. *Economic considerations:* Aggregating material use in terms of weight and comparing it to an indicator of economic activity measured in monetary terms might only have limited economic meaning, as it ignores the quality and value of materials being aggregated (Cleveland and Ruth 1998). Weight is only one of many attributes that economic agents consider when attaching a value to materials, hence it is not clear why it should be the only criterion used during aggregation.

      Despite this potential shortcoming, scholars and international organisations have extensively worked with indicators, such as material productivity, which reflects an on-going effort to combine economic with environmental accounting frameworks (Fischer-Kowalski et al. 2011; United Nations et al. 2014).

      One way to improve material use indicators would be to aggregate materials according to their relative economic usefulness. A price-based aggregation method would allow to consider density, weight, state of technology, the level of other inputs, among other factors. Wernick et al. (1996) point out that measuring the contribution of materials in terms of their mass may understate their economic importance and environmental implications, as materials possess unique properties that provide value, define use, and have environmental consequences.

      While essentially every indicator faces shortcomings, including the most cited and used indicator GDP, the problem with material indicators is that value-based measures are challenging to calculate due to lack of data on material prices traded on local markets, and they are often not sufficiently publically available or coherently measured across time and space to be used in econometric analysis

(Fischer-Kowalski et al. 2011; Ecorys 2012; Wiedmann et al. 2013b). Therefore, the majority of studies, including this dissertation, rely on material indicators aggregated by weight.

ii. *Environmental considerations*: As argued previously, a reduction in the overall quantity of material use does not necessarily reduce environmental pressures – shifts in the composition of material use must also be taken into account. This goes back to heterogeneous environmental pressures arising from individual materials which are not necessarily considered when aggregating materials according to their weight (UNEP IRP 2010a).

Scholars have tried to limit this shortcomings by, for instance, combining life cycle analysis and EW-MFA (Voet et al. 2005a), developing footprint based methodology for resource use (Wiedmann et al. 2006; Wiedmann et al. 2013b), or alternative methods to account for indirect material use (Bringezu and Schütz 2001). Such methods provide a more adequate picture of material use indicators by more comprehensively capturing environmental pressures across materials' supply-chains.

However, what is missing in the existing literature is a comprehensive study on the short and long term effects of material use on environmental pressures, for instance on GHG emissions, taking the heterogeneity across countries, material subgroups, and material indicators into account.

iii. *Availability considerations:* There are two main bottlenecks of applying material indicators (besides DMC) in econometric analyses. First, the publically available data on material use spans over relatively small timeframes or countries (Bleischwitz and Nechifor 2016). As shown in Table 6, Voet et al. (2005a) calculates data for the Netherlands and the year 2000 only, Wiedmann et al. (2013b) global material footprint data ranges between 1980 and 2008 but only data for the year 2008 is publically available, and Bringezu and Schütz (2001) calculate TMR data for the EU-12 for the years 1988-1994 and for the EU-15 aggregate between 1995-1997. Second, in particular for the material footprint (or RMC) data, heterogeneous methods and system boundaries are applied, thus limiting the comparability over time and countries (Eisenmenger et al. 2016).

2) ***Challenges in empirical analyses:***

i. *Omitted factors:* Several econometric analyses do not explicitly take observable into account or control for unobservable factors that could bias the results (Angrist and Pischke 2009). Such 'omitted factors' could comprise energy, labour, technological change, policy measures, changes in preferences, or structural changes in the economy.

   For instance, the analyses on drivers of material use applying an IPAT or a decomposition analysis by definition rely on a limited number of factors to explain developments in material use and productivity. While Hoffren et al. (2001), Hashimoto et al. (2008), Wood et al. (2009), Pothen (2015), and Pothen and Schymura (2015) control for technological and structural changes, these studies do not explicitly take other inputs such as energy, labour, social factors, and policy measures into account.

   However, there is a trade-off between considering all possible factors affecting the relationship between the independent and dependent variable and distorting the effect of individual variables by introducing too many (Wooldridge 2008). As discussed previously, Voet et al. (2005b), Steger and Bleischwitz (2011), and Hirschnitz-Garbers et al. (2015) include a large set of drivers for material use in their analyses, thus limiting the problem of omitted factors, while possibly making it challenging to distinguish between the variables' individual contributions. Finding the 'right' balance is therefore an important challenge to address in empirical analyses on the issue.

ii. *Endogeneity:* The issue of endogeneity from simultaneity has received relatively little attention in the existing empirical literature. Estimating models with endogenous variables can be problematic, as the coefficients could be biased and inconsistent (Angrist and Pischke 2009).

   Endogeneity between economic growth and material use, or material productivity and competitiveness can theoretically arise since the variables are determined simultaneously. For instance, economic growth is argued to drive material use, while materials are an input in the production function generating economic growth (O'Mahony and Timmer 2009; Steger and Bleischwitz 2011). Similarly, more material productive firms are more likely to increase their competitiveness, while more competitive firms tend to improve their material productivity (Flachenecker 2017). This simultaneous relationship constitutes one cause of endogeneity and has mostly not been explicitly addressed in the literature (Angrist and Pischke 2009).

For example, Voet et al. (2005b) estimate the drivers of material intensity by including GDP. Since economic growth features on both sides of the equation, the estimation is very likely to be endogenous. Similar issues apply to Wiedmann et al. (2013b) estimating drivers of material use. Even though Steger and Bleischwitz (2011) exclude GDP in their analysis on material use and intensity, the authors acknowledge that the remaining variables might potentially be endogenous, including the labour productivity in the manufacturing sector and the share of the construction sector of GDP. Additionally, Bleischwitz et al. (2009b) estimate correlations between material productivity and competitiveness based on simple regression analysis. The authors explicitly state that their results could suffer from endogeneity issues.

However, some studies attempt to address the potential problem of endogeneity by using predictive causality, for instance by applying a co-integration test (Steinberger et al. 2013), an instrumental variable approach (Fagerberg 1988; Fagerberg et al. 2007; Rubashkina et al. 2015), or structural equation modelling (Larrán Jorge et al. 2015). Nevertheless, endogeneity issues have received relatively little attention in the literature on drivers of material use and the effects of material productivity on competitiveness.

iii. *Considering the rebound effect*, i.e. the possibility that an efficiency or productivity improvement is partly, fully, or more than counterbalanced by an increase in material use. A rebound effect for materials has not been researched as intensively as in the energy literature (Dimitropoulos 2007; Sorrell and Dimitropoulos 2008; Sorrell et al. 2009; Brockway et al. 2017).

The use of construction minerals and biomass, together accounting for more than two-thirds of global domestic extraction, are considered to be relatively inelastic and thus the risk of a material rebound effect is comparably low (Steinberger et al. 2010; Bahn-Walkowiak et al. 2012). Pfaff and Sartorius (2015) provide evidence that the magnitude of rebound effects for materials is heterogeneous across different materials. For instance, an efficiency improvement in rocks by 100%

‘rebounds’ by 2.5%, meaning that 97.5% of the improvement remains. The ‘rebound figure’ for a 100% improvement in steel amounts to 10.5%, thus 89.5% remain.

Even though the available estimates suggest that the likelihood of a rebound effect for materials is limited, this effect has often not been considered in the existing literature on material productivity improvements (Ecorys 2011; Walz 2011). This is particularly relevant for macroeconomic modelling exercises (EC 2014e). While there are studies explicitly incorporating potential rebound effects (Distelkamp et al. 2010; Meyer et al. 2011), accounting for such effects remains a challenge for the literature.

3) ***Linking material productivity and competitiveness:*** The academic and policy discussions on some of the channels linking material productivity and competitiveness seem to be further advanced than the underlying evidence. While policymakers are convinced that the link exist, empirical studies are sparse and potentially face shortcomings (Flachenecker 2017). This could also be related to the fact that the concept of competitiveness is highly debated among academics and no clear definition exists.

   Most empirical research has focused on the material cost channel and the economic growth, productivity, and innovation channel. Other channels have received much less attention and thus remain under-researched. For instance, the regulation channel might indeed not be a channel at all, but rather an instrument aiming to increase material productivity. Also, it is far from clear that material productivity actually decreases absolute material use or changes the composition of material use so that environmental pressures are decreased, which is often assumed to have the expected effect on competitiveness, for instance for the climate change mitigation channel.

   There are additional and structural problems with linking material productivity and competitiveness. Salvatore (2010) points out that material productivity measures past ‘success’, whereas competitiveness typically reflects the ability to create welfare in the future. Thus, there might be a time lag between them. Moreover, the direction of impact is unclear. Material productivity might simply be the result of competitive firms or country structures, not vice-versa. How to address this simultaneity problem will be discussed in the next section.

Another issue is that construction minerals, predominantly sand and gravel, account for most of the material consumption indicators in essentially all EU economies. Thus, material productivity changes substantially once sand and gravel consumption changes, which might not adequately reflect changes in competitiveness.

Therefore, researching more extensively and applying novel approaches to studying the link between material productivity and competitiveness remains a challenge for future research.

4) ***Heterogeneity across firms, sectors, countries, material subgroups, and material indicators***: In many empirical investigations, materials are only considered as an aggregate, not explicitly researching the results for the four material subgroups. While there are studies explicitly analysing material subgroups (Weisz et al. 2006; Steinberger et al. 2010; West and Schandl 2013; West et al. 2014), this is not done on a systematic basis. Similarly, this holds true for country, sector, or firm heterogeneity since often the literature simply considers the entire world, regions, or countries without explicitly investigating the potential heterogeneity underlying these studies.

   Additionally, few investigations explicitly compare various indicators such as DMC, RMC, and TMR (Moll et al. 2005; Giljum et al. 2014a; Huysman et al. 2015; Eisenmenger et al. 2016). Moreover, the majority of studies on the firm level rely on case studies, thus not taking dynamic effects across firms, sectors, and countries into account and thereby possibly limiting the external validity of their findings (Ecorys 2011; Cooper et al. 2016).

   Hence, considering heterogeneity across firms, sectors, countries, material subgroups, and material indicators could provide important insights of the main drivers behind statistical links. Explicitly taking such factors into account could also help policymakers in designing more targeted interventions.

Most of the shortcomings discussed above are well known. Clearly, not all of them can be addressed at once and require both, methodological advancements in the case of indicators and rigorous application of existing methodologies in the case of empirical assessments.

3.5 Addressing limitations of the existing literature

In line with the limitations brought forward in the previous section, this dissertation attempts to put more emphasis on these issues that have received relatively little attention so far. This section explains how the various investigations in the remaining part of the dissertation addresses some of the limitations in the literature.

In addition to the in-depth review of the concept of competitiveness on the macroeconomic and microeconomic levels, which addresses one limitation outlined in the previous section, the following provides and overview of the upcoming investigations and explains how they address some of the identified limitations in the existing literature.

1) ***A comprehensive cost-benefit analysis of material productivity investments:*** Chapter 4 introduces and applies a novel and comprehensive framework to analyse how material productivity improvements triggered by investments relate to economic and environmental issues. Such considerations embed and contextualise the effects of material use and productivity on competitiveness as well as GHG emissions, but also broadens these links beyond what is explicitly considered in the empirical chapters of this dissertation, including the costs of inaction and secondary effects.

2) ***The effects of material use on GHG emissions:*** Chapter 5 estimates the average effects of material use on GHG emissions. This is particularly important when considering weight-based material indicators such as DMC, as it is not clear how changes in DMC affect GHG emissions. Additionally, Chapter 5 provides initial findings in that regard and fills two minor gaps in the literature. First, short and the long term effects of material use on GHG emissions are estimated separately. Second, heterogeneity across different material subgroups, countries, and material indicators (DMC and RMC) are explicitly considered. Therefore, several limitations in line with the previous section are addressed, namely environmental considerations, omitted factors, endogeneity from simultaneity, and heterogeneity.

3) ***The effects of economic growth on material use:*** While economic activity is found to be an important driver of material use, empirical studies often do not take the endogeneity of GDP into account, i.e. economic growth drives material use, while material use generates economic growth. Thus, Chapter 6 estimates the causal effect of economic growth on DMC in Europe. This chapter aims to improve the current evidence base by applying an instrumental variable approach, hence taking the endogeneity of economic growth into account, while also addressing the lack of omitted factors in empirical analyses. The results are compared to those using RMC data, the contribution of various material subgroups, and country heterogeneity is

explicitly studied. Thus, the issues of omitted factors, endogeneity from simultaneity, and heterogeneity are considered.

4) ***The effects of material productivity on macroeconomic competitiveness and GHG emissions:*** Chapter 7 aims to provide new evidence by introducing an established econometric method to the existing literature on the link between material productivity and competitiveness. More specifically, Chapter 7 takes the endogeneity of material productivity into account, controls for omitted factors, and studies country heterogeneity. To this end, Chapter 7 estimates the causal effects of material productivity on macroeconomic competitiveness and GHG emissions in the EU by applying an instrumental variable approach. The results are further compared to material productivity based on RMC data. Therefore, this chapter attempts to address multiple limitations identified in the relevant literature, specifically omitted factors, endogeneity from simultaneity, linking material productivity and competitiveness, and heterogeneity.

5) ***The effects of material productivity on microeconomic competitiveness and GHG emissions:*** Similar limitations are relevant on firm level. Chapter 8 estimates the causal effects of material productivity on firm level competitiveness and GHG emissions by applying an instrumental variable approach. This chapter thus provides new evidence on the link between material productivity and competiveness by addressing the issue of endogeneity, omitted factors, and country as well as sector heterogeneity. By considering a large international firm level dataset, dynamic effects across firms, sectors, and countries are taken into account. Hence, omitted factors, endogeneity from simultaneity, linking material productivity and competitiveness, and heterogeneity are taken into account.

While several methods exist to assess the effects of material use and productivity on competitiveness and GHG emissions, an instrumental variable approach applied to panel data is best suited to address limitations as outlined above (in particular endogeneity and omitted factors) and capture developments across time and space, thus providing new evidence on the limitations raised in the previous section. Alternative methods either cannot adequately address endogeneity from simultaneity (simple regression analysis) or control for omitted factors such as country or year specific effects and time-variant effects (simple regression analysis, IPAT, decomposition analysis) (Angrist and Pischke 2009).

Econometric methods are generally more flexible to control for any variable that is thought to influence the dependent variable (Wooldridge 2008). While simple regression analyses, which do not take endogeneity from simultaneity and omitted factors into account, can result in biased and inconsistent estimates (Angrist and Pischke 2009), instrumental variable estimations, dynamic panel estimations, and time-series econometrics can make causal inferences under certain conditions. Time-series econometrics allows to tests for co-integration and so-called Granger-causality (Wooldridge 2002). However, this is merely a statistical tool to test for predictive causality (Angrist and Pischke 2009). It has been shown that dynamic panel estimations can violate the exclusion restriction (Kraay 2012; Panizza and Presbitero 2014).

This is why instrumental variable estimation is considered one the most adequate methodology to estimate causal effects for the purposes of this dissertation. A suitable alternative would be to study causal relationships based on structural equation models. While such models are in practice based on several assumptions, their application could complement the approaches taken in this dissertation.

For instrumental variable estimations to be valid, two conditions need to apply. First, the instrument needs to be highly correlated with the endogenous variable. Second, the instrument must not affect the dependent variable other than through the endogenous variable. The latter is called exclusion restriction and cannot be tested empirically, but one needs to build an argument using economic rationale. The former can be tested and argued for using evidence from theoretical and empirical investigations. How specifically the established method of instrumental variable estimations in applied for each analysis, is explained in the subsequent stream of chapters.

Before turning to the empirical parts of this dissertation, the subsequent chapter aims to link the reviews of the relevant bodies of literature with a more structural discussion on the wider implications of moving towards greater material productivity. A cost-benefit framework is introduced and applied to a case study in order to illustrate the costs and benefits of material productivity improvements, and to derive important insights that will feed into the later empirical analyses.

Chapter 4

Investments in Material Productivity: The Introduction and Application of a Comprehensive Cost-Benefit Framework

An abridged version of this chapter is published as

Flachenecker, Florian*;* Bleischwitz, Raimund and Rentschler, Jun Erik (2017). Investments in Material Efficiency: The Introduction and Application of a Comprehensive Cost-Benefit Framework. *Journal of Environmental Economics and Policy* 6:2. 107-120.

4 Investments in material productivity: the introduction and application of a comprehensive cost-benefit framework

After having reviewed the literatures related to material use and material productivity, this chapter introduces and applies a novel and comprehensive cost-benefit framework to analyse the economic and environmental effects of material productivity investments. The taxonomy of this framework aims to structure the existing literature and discussions in this dissertation on the effects of material use and productivity on competitiveness as well as GHG emissions. By linking the literature review with the more detailed empirical analyses in the subsequent chapters, this chapter attempts to illustrate the wider implications of moving towards increased material productivity. By illustrating the mechanisms underlying the framework by applying it to a firm level investment project, it becomes clear that the benefits of material productivity investments typically increase when externalities are internalised, the cost of inaction is considered, and non-monetary dimensions are additionally taken into account.

4.1 Introduction

According to economic theory, economic agents have an incentive to increase their material productivity if the relative prices for materials are higher compared to other inputs, for instance labour and energy. Even though fiscal reform programmes in the past have tended to focus on reducing labour costs and material prices are still relatively high, material productivity has increased at a far lower pace compared to labour or energy productivity (Bleischwitz 2010; Valiante and Egenhofer 2013; IMF 2017a). The lagging behind of material productivity improvements might, however, not come as a surprise. Many environmental implications of material use, for instance GHG emissions, are often not internalised, thus distorting the incentive to increase material productivity.

Nevertheless, increasing material productivity is argued to have positive implications for the economy as well as the environment (Bleischwitz et al. 2009c). To structure and widen the understanding of these implications, this chapter introduces a comprehensive cost-benefit framework that systematically captures the multiple economic and environmental aspects that are relevant for evaluating the viability of material productivity investments. To this end, secondary effects, external effects, and the cost of inaction are explicitly taken into account.

Applying it to a firm level investment project illustrates that the framework can support the identification of aspects relevant to material productivity improvements. As such, the results of the case study reveal that the incentive to invest in material productivity tends to increase when externalities are internalised, secondary effects are considered, the longer firms' investment horizons are, and once the cost of inaction is taken into account.

The remainder of this chapter is structured as follows: Section 4.2 introduces the comprehensive cost-benefit framework. Section 4.3 matches the framework to empirical evidence from the existing literature. Section 4.4 illustrates the framework by applying it to a firm level investment project. Section 4.5 discusses the results, their underlying assumptions, and implications. Section 4.6 concludes.

4.2 Introducing a comprehensive cost-benefit framework

Conventional cost-benefit analyses predominantly consider primary economic (i.e. monetary effects borne by firms) implications of investments. Given the economic and environmental dimensions of materials, the particular nature of material productivity investments requires to not only take economic costs and benefits into account, but also to consider environmental, non-market, and secondary implications – which are often associated with externalities. This allows to derive the social costs and benefits of such investments which are calculated as the sum of economic and environmental effects.

Once a monetary value is attributed to those costs and benefits without market prices, this framework allows to calculate the social net benefits of material productivity investments (OECD 2008b). In order to assess social costs and benefits associated with material productivity, two scenarios are considered:

1) ***Business-as-usual scenario (BAU)***: In the BAU, maintaining the current (positive) rate of investments in material productivity is assumed. This scenario serves as the basis for the costs and benefits associated with 'inaction'.

2) ***Scaling up material productivity investments:*** In the scenario of scaling up material productivity investments, firms and governments drastically increase their investments in productivity improvements compared to current levels.

For both scenarios, primary and secondary effects are considered (Cellini and Kee 2010). Primary effects are closely related to the investments main objectives. Secondary effects include indirect effects (i.e. second round), multiplier, spillovers, and co-benefits/co-costs (i.e. by-products). Going forward, this framework's scenarios, effects, and dimensions are matched to empirical evidence in the existing literature and applied to an investment project to illustrate the framework's usefulness in practice. Moreover, this exercise can support firms and policymakers in identifying relevant issues to incentivise material productivity improvements.

Table 11 illustrates the comprehensive cost-benefit framework as well as summarises costs and benefits, which are found in the literature and summarised in the next section. The framework distinguishes between two scenarios (BAU and scaling up material productivity investments), two dimensions (environmental and economic), and costs as well as benefits – in total eight cells representing various issues raised in the existing literature.

Table 11: Costs and benefits from material productivity investments.

Costs and benefits of investments in material productivity				
	Benefits		**Costs**	
	Environmental	Economic	Environmental	Economic
Business-as-usual		*No initial (and follow-up) investments costs* *Lower compliance costs of environmental regulation*	*Environmental pressures (negative externalities)* *Reduced human & natural capital*	*Micro costs (e.g. exposure to volatility)* *Macro costs (e.g. import dependency)* *Lock-ins* *Supply-chain externalities*
Scaling up MP	*Reduced environmental pressures (negative externalities)* *Reduced negative impacts on human & natural capital*	*Hedging against material price volatility* *Improved micro and macro competitiveness* *Eco-innovations (product, process, systems)* *Reduced env. and social liability (i.e. improved corporate image)*	*Positive relationship between the intensity of exploitation and environmental impacts* *Rebound effect*	*Initial investment and maintenance costs (incl. transaction costs)* *Opportunity costs*

4.3 Matching the framework to the existing literature

This section matches the framework to the evidence provided in the existing literature. Each of the eight cells in Table 11 are considered separately. It should be noted that this section does not review the literature, but rather collects the issues raised by analyses to illustrate the very many aspects related to material productivity improvements. Later empirical analyses will critically reflect and provide new evidence on specific aspects mentioned in this section.

4.3.1 Environmental costs in the BAU scenario

1) ***Environmental pressures:*** Materials are referred to as "important intermediaries of environmental impact" (UNEP IRP 2010a). Impacts associated with material use can be considered a proxy for environmental costs. Such costs arise in each stage of the life cycle, such as emitting particulates (e.g. dust), land use change, biodiversity loss, erosion from mining, and leakages of chemicals used in the separation process into the environment (UNEP IRP 2010a). These costs can occur both at the local and the global level.

   In the EU, the manufacturing industry accounts for 27% of all direct GHG emissions, 27% of all direct emissions of ground-level ozone precursor gases, and 15% of direct emissions of acidifying gases (EEA 2013). According to the IEA, 77% of the total direct CO_2 industrial emissions are due to the production of four materials, namely iron and steel, cement, pulp and paper, and aluminium (IEA 2010). Environmental pressures are often associated with negative externalities arising from any form of waste and pollution. For instance, the GHG methane is emitted from landfills and thus not only negatively impacts the environment locally, but also globally by contributing to climate change (IPCC 2007). These costs need to be considered when calculating the cost of inaction.

2) ***Secondary costs on human and environmental capital:*** Environmental costs of using materials unproductively can also negatively affect economic activity directly and indirectly (UNEP 2014). For instance, low levels of material productivity, or the inefficient use of materials more generally, can negatively affect human health through excess pollution, thus reducing labour productivity (Chang and Neidell 2012; OECD 2015b). Pressures on the environment can ultimately lead to damages to the environmental capital, including biodiversity loss, which in turn is likely to adversely affect productivity activity, for example in the agriculture sector (Adams 1990; Chen et al. 2016). While these indirect costs can be substantial, there are challenging to calculate in practice.

Furthermore, it is crucial to take the concept of irreversibility of environmental functions into account. Once specific environmental functions are harmed beyond a certain threshold, they are unlikely to fully recover which calls for the precautionary principle (i.e. safe minimum standard) (Bishop 1978). Marginal damage curves of some environmental functions are likely to be non-linear (Tol 1996). For instance, they remain relatively flat for an increasing level of pressures until reaching the threshold from which on the damages increase exponentially, i.e. infinitely high costs. In such a scenario, the concept of irreversibility plays an important role in the cost-benefit framework once the 'tipping point' is surpassed.

4.3.2 Environmental benefits in the BAU scenario

There are no apparent environmental benefits in the BAU scenario.

4.3.3 Environmental costs from investments in material productivity

In theory, increasing material productivity could potentially increase environmental pressures, at least relative to output. For instance, cars use relatively more fuel (and thus cause more environmental pressures) per distance travelled when travelling with very high speed compared to lower, more efficient speed levels (Van Mierlo et al. 2004). Therefore, the absolute and relative effects of material productivity increases need to be considered.

Moreover, a potential rebound effect could counterbalance productivity gains. Generally, the literature distinguishes between two possible outcomes: (i) partially offsetting productivity gains by increasing consumption (i.e. reducing benefits) and (ii) outweighing such gains altogether *(backfire* or *Jevons' Paradox)* (Sorrell 2007). It is important to note that only (ii) entails costs from an environmental perspective.

Additionally, there are three categories of rebound effects: a direct, an indirect, and a combined or economy-wide effect (Barker et al. 2007). For example, increasing the fuel efficiency of a car might result in driving more kilometres which is considered a *direct* rebound effect. An example of an *indirect* rebound effect would be using more air transportation due to the savings from the car's increased fuel efficiency. *Economy-wide* effects combine the *direct* and *indirect* rebound effects (Sorrell 2007). Estimates of the rebound effect of energy efficiency improvements vary widely between firm, sectors, and countries, depending on individual characteristics and demand elasticities (Dimitropoulos 2007; Sorrell and Dimitropoulos 2008; Sorrell et al. 2009)

There has been a lack of attention to the rebound effect of materials, because it is thought to be of lower relevance. The use of construction minerals and biomass, together accounting for over two-thirds of global extraction, is considered to be relatively inelastic and thus the risk of a rebound effect is relatively low (Steinberger et al. 2010; Bahn-Walkowiak et al. 2012). A more recent attempt to quantify the country level rebound effects of materials suggests that the effects are mostly within single digit percentages (Pfaff and Sartorius 2015).

4.3.4 Environmental benefits from investments in material productivity

In the absence of a 'backfiring' rebound effect and *ceteris paribus*, *ex post* increasing material productivity can result in a relatively lower use of materials. On average, a lower use of materials implies relatively fewer negative pressures and impacts on the environment, both locally and globally (Barrett and Scott 2012).

Several empirical analyses estimate the effects of material productivity measures on indicators of environmental pressures. For instance, realising numerous material savings opportunities (in terms of environmentally weighted material use) in three sectors of the EU, namely food and drink manufacturing, fabricated metal products, and hospitality and food services, is estimated to reduce total annual EU-wide GHG emissions by 2-4% (AMEC and Bio IS 2013). For the United Kingdom, a variety of productivity improvements could reduce its total annual GHG emissions by up to 13% (Oakdene Hollins 2011). Using a computable general equilibrium model, upscaling material productivity is estimated to reduce global GHG emissions by 15-20% by 2050 compared to 2015 (Hatfield-Dodds et al. 2017). Similar figures are calculated on product level (Gilbert et al. 2016).

Especially through recycling, one strategy to increase material productivity, the environmentally harmful first stages of the materials' life cycles (i.e. extraction, production) can be substituted by using secondary material (Ignatenko et al. 2008; Allwood et al. 2010). This entails lower direct (i.e. less primary production and less waste) and indirect (i.e. lower energy use) negative externalities. For example, secondary production reduces energy use by 55% for lead and 98% for palladium (UNEP IRP 2013). Metals are particularly promising when it comes to recycling, as their recyclability is (theoretically) indefinitely possible (Graedel et al. 2011).

Several chapters in this dissertation attempt to add evidence to this aspect of material productivity improvements. Chapter 7 empirically assesses the effect of material productivity on GHG emissions on the macroeconomic level for European countries. While this empirical analysis suggests that there is no statistically significant link between increases in material productivity and reductions in GHG emissions, Chapter 8 provides empirical results suggesting that the probability of reducing GHG emissions for the average firm increases by around 32% as a result of an increase in material productivity compared to not increasing material productivity. Similarly, the average effect of enhancing material productivity on the probability across all firms of reducing GHG emissions amounts to 30%.

4.3.5 Economic costs in the BAU scenario

1) ***Microeconomic perspective:*** Material price volatility is an important cause of investment uncertainty and can take effect, both *ex ante* and *ex post* of investing (Chatham House 2012; Ebrahim et al. 2014). *Ex ante*, such uncertainty results in a premium, which firms have to account for in form of higher discount rates and hedging costs (e.g. long-term contracts, capacity building to be engaged in financial markets, or direct ownership of suppliers). *Ex post*, price fluctuations can impose costs (or benefits) once the outcome deviates from the expected returns (Pindyck 1991). If volatile prices are not hedged, production costs become volatile as well which in a worst-case scenario can lead to insolvency.

2) ***Macroeconomic perspective:*** If a country is a net material importer, not increasing productivity and thus not reducing material imports (e.g. by substituting material imports with domestically sourced secondary raw materials) implies that the dependency on material imports is not mitigated to the extent possible. Persisting dependency can impose significant costs once negative impacts generated by volatile prices unfold, including investment uncertainty, fluctuating subsidy costs etc. (IMF 2013). Additionally, relying on material imports could result in costs once material trade becomes disrupted as a result of political conflicts and market power (Achzet and Helbig 2013). An insecure access to affordable materials might become an obstacle to economic growth, at least in the short term (Meadows et al. 1972).

3) ***Lock-ins:*** Lock-ins can cause inefficiencies and vice versa. Lock-ins describe a situation in which a technology prevails due to economies of scale, network, and learning effects even if it is sub-optimal or inefficient (Arthur 1989). For instance, if steel producers have previously invested substantially into inefficient technology, they may be unable or unwilling to invest in more efficient technology due to financial constraints or irrational behaviour. This situation is considered a lock-in (Allwood et al. 2011).

   There are also behavioural and organisational lock-ins (Barnes et al. 2004). Such lock-ins can cause economic costs and also barriers for investments in more efficient technologies (EC 2011d; EC 2011f). This is particularly important in the current context of climate finance, as the selection of long-lasting investments such as infrastructure needs to be done with great care in order not to get caught in lock-ins (Peake and Ekins 2016).

4) ***Supply chain externalities:*** Supply chain externalities can arise from the unproductive use of materials if, for instance, the design of a product of one firm influences the recyclability of that material by another firm downstream. For example, multi-layer packaging cannot always be recycled mechanically and producing multi-coloured glass bottles results in increasing recovery costs (Nicolli et al. 2012). The problem is that recycling firms often struggle to provide economic incentives for upstream firms to increase the recyclability of products (Calcott and Walls 2005). Therefore, firm level interactions across supply chains are crucial in improving material productivity (Schliephake et al. 2009), while not cooperating across the supply chain can impose costs on other actors within the same value chain.

4.3.6 Economic benefits in the BAU scenario

By not increasing investments, firms can avoid potentially high up-front costs. However, not all productivity improvements require financial capital, but rather changing practises, behavioural patterns, and organisational structures. Nevertheless, not investing financial capital in material productivity improvements potentially unlocks capital to be invested in possibly more profitable and less uncertain alternatives (Bruyn et al. 2009).

Increasing material productivity is sometimes the result of a costly policy intervention. Such costs of monitoring, reporting, and compliance of material productivity improvements or environmental standards in general could be avoided in a BAU scenario.

4.3.7 Economic costs from investments in material productivity

1) ***Initial investment costs:*** Material productivity investments typically generate annual income streams (i.e. material savings, higher quality products), but the up-front investment costs might be substantial, thus dis-incentivising the investment to take place (AMEC and Bio IS 2013). While up-front costs are mostly known, the returns may be uncertain and distant in time, especially if material prices are volatile (Ebrahim et al. 2014). If firms are risk averse, they are less likely to invest, as they give a relatively lower probability to the expected return or increase the discount rate, i.e. lowering the net present value (Perman et al. 2011). Investing in material productivity also triggers operation, maintenance, and more generally transaction costs. Such costs can take the form of capacity building (e.g. training) and financing the investment (i.e. searching costs, interest rates).

2) ***Opportunity costs:*** Firms only have an incentive to invest in material productivity if no other feasible alternative offers a higher net present value. One alternative could be substituting materials with other inputs, but this might not always be possible (e.g. rare earth metals). Where substitution is possible, increasing labour productivity for instance might be more beneficial (Bruyn et al. 2009). In the past, productivity has increased by 140% for labour and by 90% for materials in the EU-15 between 1970-2007. This could be the result of conventional tax regimes which have mainly taxed labour relative to other inputs, thus making labour more expensive, incentivising investments in labour productivity (Bleischwitz 2012). Bleischwitz (2012) also points to structural changes towards service-oriented economies and shifts in imports as possible explanations of why labour productivity has increased more compared to other inputs.

4.3.8 Economic benefits from investments in material productivity

1) ***Managing uncertainty:*** This is particularly relevant for material importing economies and material purchasing firms, as increasing productivity *ceteris paribus* results in a relatively lower use of materials. Lowering material imports through productivity gains by increasing domestically sourced secondary raw materials can decrease dependencies, increase the bargaining power and improve the balance of trade (Schmidt and Schneider 2010; ECSIP Consortium 2013). Moreover, material price fluctuations would have a relatively lower (negative) effect on the economy and firms – one form of hedging against price volatility (Ebrahim et al. 2014).

2) ***Improving competitiveness:*** According to several studies, increasing material productivity may strengthen competitiveness at the country level by generally stabilising the macroeconomic environment. For instance, Distelkamp et al. (2010) model various effects of doubling material productivity in the German economy by 2030. The authors estimate positive effects for GDP (+14%), employment (+1.9%), a reduction of material use (TMR –20%), and a reduction of the public debt (–11%). Given the approach of the study, such positive effects can be considered the upper threshold and therefore be interpreted as the maximum potential for productivity gains.

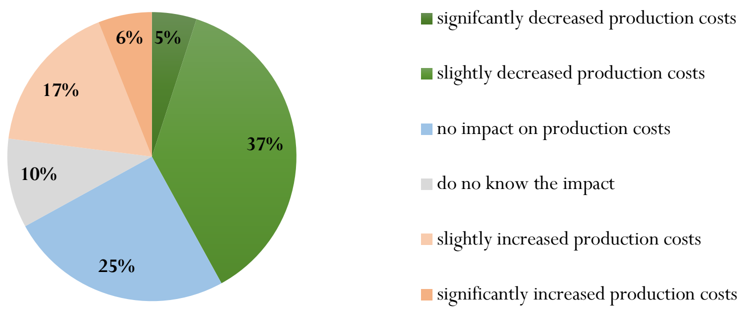
An EU-wide study shows similar positive macroeconomic impacts of resource efficiency improvements until 2030, including as a reduction of resource use by 17-

25% compared to a baseline scenario, an increase in real GDP by 2.0-3.3%, and the increase in real labour income combined with a creation of up to 2.6 million jobs (Meyer 2011). This does not necessarily imply an increase in competitiveness since it also depends on the response from competitors. However, a favourable macroeconomic environment could be considered as a proxy for competitiveness.

At the firm level, surveys of EU-SMEs reveal a generally positive attitude towards productivity improvements. Competitiveness gains for firms could result from lowering negative impacts of material price volatility, lowering production costs, increasing innovative activity, and an increased corporate image (Flachenecker 2015b). A report considers the benefits from productivity measures by EU firms across four sectors (AMEC and Bio IS 2013). The authors suggest that the average net benefit (after subtracting the investments costs) for firms is between 10 and 17% of annual turnover. This accounts for €27,500 – €424,000 reflecting heterogeneous firm sectors and sizes.

Figure 10 illustrates the answers of 10,511 EU-SMEs having taken at least one resource efficiency action to the following question: "What impact have the undertaken resource efficiency actions had on the production costs over the past two years?" The resource efficiency measure decreased production costs for 42% of the SMEs that responded to the question (EC 2013b).

Figure 10: The impact of investments in resource efficiency on production costs. Source: (EC 2013b).



Reducing production costs for firms is particularly important when it comes to materials, because they constitute a relatively high share of total costs. Material purchasing costs as a percentage of gross production value account for 45.3% for the

German manufacturing industry (KfW 2009; Statistisches Bundesamt 2011). For the automobile and machinery sector, materials account for more than 50%. On EU-level, material costs account for similar levels based on surveys (EC 2011e). For more than half of the EU companies, material costs constitute more than 30% of their overall expenses. However, the reported materials costs include the cost of the raw materials as well as upstream labour, transportation, and storage costs (Wilting and Hanemaaijer 2014).

Additional evidence suggests payback periods for material productivity measures of less than six months. Average savings have been estimated in the order 7-8% of material costs for German SMEs in the manufacturing sector (Fh-ISI et al. 2005; Schröter et al. 2011). Most of such cost saving potentials do not pertain to direct material purchasing costs, but rather to *hidden costs* (i.e. disposal, transportation, production, energy, etc.) (Schmidt and Schneider 2010). For the United Kingdom, it was estimated that resource efficiency improvements can enable firms to realise cost savings amounting to £23 billion in 2009 (£18 billion for waste prevention) with pay-back periods of less than 12 months (Oakdene Hollins 2011; OECD 2011a).

The link between material productivity and competitiveness will be empirically assessed in Chapters 7 and 8. While the results in Chapter 7 suggest that there is no statistically significant and causal effect on competitiveness for EU member states, Chapter 8 illustrates that innovative firms, in material-intensive sectors, and mostly Eastern European countries can substantially increase their competitiveness by increasing material productivity. More specifically, the results provide evidence that average-scale material productivity improvements cause microeconomic competitiveness, i.e. market share growth, to increase by around 12%.

3) ***Increased innovation activity:*** Positive macroeconomic effects of material productivity innovations on growth, employment, and competitiveness are particularly pronounced if first-mover advantages can be established (Walz 2011). Early adopters enjoy an additional cost advantage over their competitors until the innovation is being diffused throughout the market. These profits, in combination of the increased capacity to grasp the benefits of innovations, can trigger further (and potentially more sophisticated) innovations, thereby potentially generating additional spillover effects to other firms, initiating a virtuous circle, which has been demonstrated in economic models for the EU and Germany (Meyer 2011).

4) ***Reducing liability:*** As environmental concerns gain increasing importance in the public sphere, it is likely that environmental regulation will become more stringent in the future. Surveys suggest that firms anticipate future changes in environmental regulation (12% in the EU, 27% in the United Kingdom, 16% in Turkey, and 20% in Russia) (EC 2012c). Introducing measures, including increasing material productivity, to lower environmental pressures before it becomes mandatory could constitute a first-mover advantage in the spirit of the Porter hypothesis, thus reducing environmental liability while gaining a competitive advantage (Porter and Linde 1995). A significant number of firms already voluntarily go beyond existing environmental regulation (11% in the EU, 13% in Germany, 9% in Russia, and 16% in Turkey), which could furthermore improve the firms' corporate image and thus market share (EC 2013b).

4.4 Applying the framework to a microeconomic investment project

The cost-benefit framework is now applied to a microeconomic investment project in Turkey financed by the European Bank for Reconstruction and Development (Table 12).[5] The investment project comprises a range of energy efficiency and material productivity measures regarding the production of polyvinyl chloride (PVC) plastics.

It is important to note that this application primarily serves to illustrate the usefulness of the framework as well as to support the identification of relevant issues in improving material productivity. Hence, the specific results of the case study cannot be extrapolated to other investment projects. However, some general issues important to firms and policymakers can be illustrated. The insights of the previous section are relevant to identifying relevant costs and benefits of this material productivity investment project.

However, not all individual components of each of the eight cells of the framework can be matched to the investment project. This is due to the investment's nature as well as lacking information. Furthermore, it should be acknowledged that the environmental implications of the investment are reduced to GHG emissions to facilitate monetarising such effects. Therefore, non-GHG related environmental pressures are not accounted for, in particular local pollution.

A discount rate of zero is assumed to avoid any mismatch between economic and environmental impacts. This assumption requires further explanation. Future costs and benefits are typically

[5] The investment project is presented anonymously to comply with confidentiality agreements.

discounted by using a discount factor δ. For economic costs and benefits, an interest rate in the economy is often taken to represent δ which (in *normal* economic circumstances) is a positive rate ($\delta > 0$). However, the level of the interest rate is highly debated (e.g. Arrow et al. 1996). For environmental costs and benefits, no universally agreed discount factor exists which is due to the high degree of uncertainty involved in estimating future impacts of GHG emissions (Pindyck 2007). Some apply a range of positive discount rates which illustrates this uncertainty (e.g. U.S. Government 2013).

Given the lack of reliable estimates to discount environmental costs and benefits, it is chosen not to apply any discount rate in order to avoid a potential mismatch between economic and environmental impacts. Applying discount rates, the results would only change in terms of their level but not in terms of their trend (unless the economic discount rate exceeds the environmental one in this case study by a factor of 583). This means that the year in which the investment yields a positive accumulated net benefit might change, but the overall conclusions drawn from the results are likely to remain valid.

Moreover, it is assumed that all material productivity measures are fully implemented and yield their expected results in the first year after the investment took place. Wherever possible, methods on how to estimate any remaining information gaps are proposed.

In line with cost-benefit framework, two scenarios (*ex ante* and *ex post* the investment) and two dimensions (environmental and economic) are distinguished. Table 12 illustrates the results of applying the framework to the firm level investment project.

4.4.1 Environmental costs in the BAU scenario

Ex ante of the investment, the firm used approximately 35,000 MWh electricity per year and produced 45,000 tonnes of PVC plastics annually. The GHG emission factors for Turkey is 0.472 tonnes of CO_2 equivalent (tCO_2e) per MWh of electricity and 3.1 tCO_2e per tonne of PVC plastics, covering the GHG emissions of the entire life cycle of PVC plastics (Hammond and Jones 2008).

Thus, the firm's GHG emissions are estimated to be 156,000 tCO_2e per year. It should be noted that the actual GHG emissions are likely to be slightly lower since the embodied GHG emission for PVC plastics already include the electricity consumed during the production process. However, the GHG emission factor for PVC plastics is a 'conservative' figure since it is calculated assuming a best available technology benchmark according to Western European standards. The technological standard in Turkey is likely to be lower, therefore underestimating the environmental costs of PVC production. Additionally, the figure excludes any environmental pressures that occur at the local level (e.g. local air and water pollution) due to the lack of adequate information.

Table 12: Results of applying the framework to a firm level investment project.

Costs and benefits of a material productivity investment project				
	Benefits		**Costs**	
	Environmental	Economic	Environmental	Economic
ex ante		***€9.3 million one-off*** ***€590,000 per year*** *- includes costs of investment, operation, maintenance, and ISO 50001*	***€3.7 million per year*** *- includes GHG emissions from energy and material use* *- excludes local pollution, price of other GHGs besides CO_2, and health impacts*	*- no information on costs of material price volatility, lock-ins or supply-chain externalities*
ex post	***€314,000 per year*** *- includes GHG emissions reduction from material productivity and energy efficiency increases* *- excludes local pollution, price of other GHGs besides CO_2, and health impacts*	***€2.42 million per year*** *- includes energy savings and material recycling* *- excludes eco-innovations, benefits from reduced exposure to material price volatility, reputational benefits, reduced liability*	*€0*	***€9.3 million one-off*** ***€590,000 per year*** *- includes cost of investment, operation, maintenance, and ISO 50001* *- excluding opportunity costs*

Monetising the firm's GHG emissions would require a carbon price for which estimates range between $10-200 per tonne of CO_2 (Pindyck 2013). Following Clements et al. (2013), damages from global warming of $25 (around €24) per tonne of CO_2e emission are assumed, a conservative figure. This results in environmental costs in the BAU scenario of about €3.7 million per year.

There is no information on potential negative impacts on human health, the environmental capital, or labour productivity for this particular case study. However, this does not mean that there are no such impacts, as general environmental and health impacts of PVC production are clearly documented and likely to affect human health, environmental capital, and labour productivity (EC 2004).

4.4.2 Environmental benefits in the BAU scenario

There are no apparent environmental benefits in the BAU scenario.

4.4.3 Environmental costs from investments in material productivity

There is no indication for a more than proportional relationship between the productivity measures and environmental impacts, thus no environmental costs arise from investing in material productivity.

There is also no indication about a potential rebound effect. The productivity improvements would only imply an environmental cost if they 'backfire'. Since material use decreases in absolute terms, a 'backfiring' rebound effect can be excluded. However, there might be an *indirect* rebound effect once the firm decides to expand its production as a result of the productivity gains. There is no information available on any such plans.

4.4.4 Environmental benefits from investments in material productivity

Implementing all productivity measures are estimated to save 13,068 tCO_2e per year. This is achieved by reducing electricity consumption, substituting electricity supplied by the national grid with own as well as more efficient electricity production using natural gas, and recycling 800 tonnes PVC plastics per year replacing primary materials.

Applying a carbon price of €24 per tonne of CO_2 emissions, the environmental benefits are estimated (i.e. reduced emissions compared to the *ex ante* emissions) to be €314,000 per year. Such benefits do not comprise environmental benefits at the local level since this information was not collected for the investment project.

Since there is no information on potential negative impacts on human health, the environmental capital, and labour productivity for this particular case study, no benefits from reducing such impacts can be calculated.

4.4.5 Economic costs in the BAU scenario

Prices for electricity and PVC raw materials are volatile which might impose costs on the firm. With the available information, it is not possible to estimate these costs. However, one method to fill this gap would be to estimate the firm's willingness to pay in order to have price stability (e.g. Epaulard and Pommeret 2003). Using this methodology would reveal a firm specific (and subjective) monetary value (OECD 2008b).

There is no indication that the firm is subject to lock-ins or supply-chain externalities.

4.4.6 Economic benefits in the BAU scenario

The up-front investment costs for the firm's productivity measures amount to a one-off cost of €9 million and continuous (operation and maintenance) costs of €590,000 per year.

The firm has already implemented standards for quality (ISO 90001) as well as environmental management (ISO 14001). As part of the investment project, the firm plans to implement the standard for energy management (ISO 50001) which is estimated to cost €300,000 (excluding benefits) (Therkelsen et al. 2013).

Therefore, the economic benefits amount to €9.3 million and €590,000 per year, assuming the loan would have been granted to the firm regardless of how it plans to invest it.

4.4.7 Economic costs from investments in material productivity

Accordingly, the costs for the firm's material productivity measures sum up to a one-off cost of €9.3 million and yearly costs of €590,000. Once invested, the firm cannot invest in alternative proposals, assuming that the loan would also be granted for alternative investment appraisals. If the firm is a rational actor, there is no alternative investment yielding a higher net present value. Since there is no information on potential alternative investment opportunities, the opportunity costs for this project cannot be calculated.

4.4.8 Economic benefits from investments in material productivity

The economic benefits sum up to €2.42 million per year, comprising €1.8 million per year from energy efficiency measures and €620,000 per year from recycling PVC plastics by reducing the purchasing costs of primary raw materials.

The investment project does not directly incentivise (further) innovations or eco-innovations. However, re-investing the productivity gains combined with the know-how gained from this process could incentive and enable innovation activity. Since the firm reduces its material use, negative effects from prices volatility are reduced. Monetising this benefit cannot be done with the information available, but the method of estimating the firm's willingness to pay described previously could be a starting point for approximating it (e.g. Epaulard and Pommeret 2003).

The firm's corporate image is likely to improve, especially for those customers that value the firm's *green* appearance and compliance with environmental and managerial standards. Monetising the benefits requires customer surveys to estimate the value customers put on such standards. Estimating reduced environmental and social liability would require an estimate of the probability of damages caused by not increasing material productivity. This estimate can then be multiplied with the compensation to be paid in case of becoming liable to damages, which would produce an estimate of the expected benefit of reducing environmental liability by increasing material productivity.

4.5 Results and discussion

In the previous section, the cost-benefit framework was applied to a material productivity investment project on the firm level to illustrate the framework's usefulness. While the results of the case study cannot be extrapolated neither to comparable investment projects or material productivity investments more generally, discussing the results supports the identification of relevant aspects to material productivity improvements.

Table 13 illustrates the results over time. Already monetised (i.e. economic) net benefits are achievable after five years. By attributing a monetary value to costs and benefits without market prices, social (i.e. the sum of economic and environmental) net benefits can be reached one year earlier. Despite positive economic net benefits of 'inaction' (which assume that the investment capital would have been granted to the firm regardless of the investment project), there are social net costs associated with 'inaction' already after two years, mainly driven by the relatively high environmental costs of inaction compared to the economic benefits. Nevertheless, the firm face a trade-off between the (very) short term benefits of not investing in material productivity and the medium to long term benefits from investing.

Table 13: The accumulated economic, environmental, and social net benefits in €1,000.

in €1,000	t_0	t_1	t_2	t_3	t_4	t_5
economic net benefits of inaction	9,890	10,480	11,070	11,660	12,250	12,840
env. net benefits of inaction	-3,700	-7,400	-11,100	-14,800	-18,500	-22,200
social net benefits of inaction	6,190	3,080	-30	-3,140	-6,250	-9,360
economic net benefits of investment	-7,470	-5,640	-3,810	-1,980	-150	1,680
env. net benefits of investment	314	628	942	1,256	1,570	1,884
social net benefits of investment	-7,156	-5,012	-2,868	-724	1,420	3,564

These results demonstrate the particular nature of material productivity investments more generally. It becomes clear that such investments require a more comprehensive approach than simply considering economic benefits. Therefore, investment appraisals should take environmental considerations and the cost of 'inaction' into account. Additionally, externalities would need to be internalised in order to fully reflect all the implications from undertaking material productivity improvements. These measures would increase the incentive for private actors to improve their material productivity.

Nevertheless, there are remaining gaps in applying all components and cases of the cost-benefit framework. This often goes back to a lack of available information or methods to monetise some costs and benefits. In this regard, an increasing number of initiatives have been introduced, linking businesses to natural capital and developing methods to internalise externalities (WBCSD 2010; KPMG 2014; Natural Capital Coalition 2015).

Additionally, the results are based on several assumptions such as the prices of carbon, electricity, PVC plastics, and natural gas, the successful implementation of all productivity measures, the discount rates, exchange rates, and the GHG emission factors (among others). Generally, whether an investment in material productivity provides net benefits depends on the expectations about future price levels and volatility, diffusion of technology, future (environmental) regulation, discount rates, and the response by competitors (AMEC and Bio IS 2013).

Expectations are particularly relevant in the context of material price volatility since volatility both incentivises and dis-incentivises investments. On the one hand, volatile prices can make the expected payoffs of material productivity investments uncertain (Pindyck 1991). On the other hand, increasing material productivity can reduce the exposure to the negative impacts of volatile prices, i.e. one way of hedging against volatile prices (Ebrahim et al. 2014).

A sensitivity analysis based on all these assumptions goes beyond the scope of this chapter. However, as referred to previously, the overall trend behind these results are likely to be independent from the assumptions on discount rates. Additionally, considering local pollution is likely to increase the environmental benefits of investing in material productivity and increase the environmental costs of inaction. However, loosening the assumption on the full implementation of the productivity measures would reduce the social benefits of the investment as well as the cost of inaction.

Given the apparent benefits from material productivity investments for this case study, the question arises why such (net) benefits may not always materialise in practice. Besides general risks, uncertainties, and assumptions, investment barriers and market inefficiencies could prevent material productivity investments or reduce anticipated benefits. Such barriers include information constraints, capacity constraints, financial constraints (i.e. access to finance), uncompetitive market structures, fiscal mismanagement (e.g. subsidies), and general systemic risks and uncertainty (Jordan et al. 2014; Rentschler et al. 2016; Rizos et al. 2016). The allocation of investment risks between private and public actors could be investigated in this context as well (Medda 2007; Medda et al. 2013).

4.6 Conclusions

This chapter aims to structure the existing literature and discussions in this dissertation on the effects of material use and productivity on competitiveness as well as GHG emissions. By introducing and applying a comprehensive cost-benefit framework, this chapter sets the scene for the more detailed empirical analyses in the subsequent chapters. Moreover, this chapter supports the identification of relevant issues related to material productivity improvements.

The comprehensive framework goes beyond conventional cost-benefit analyses by considering primary and secondary effects, two scenarios (business-as-usual and scaling up material productivity investments), and two dimensions (environmental and economic). The framework is matched to the existing evidence base and applied to a material productivity investment project on the firm level.

While the specific results of the case study cannot be generalised, applying the cost-benefit framework illustrates some important issues that are more widely applicable when analysing material productivity improvements:

1) ***Economic and environmental dimension:*** Given the nature of materials, costs and benefits would be misleading when only economic implications of material use and productivity are considered. Thus, it is important to also take environmental effects into account. This is especially relevant when externalities are present to provide adequate incentives to increase material productivity.
2) ***Cost of inaction:*** Material productivity improvements are often associated with costly measures, thus reducing the incentive to undertake them. However, this chapter clearly illustrates that the cost of inaction is important to consider, too.
3) ***Short versus long term:*** The results from the case study reveal that firms might be confronted with the choice between short term benefits of inaction (which increase dramatically when environmental aspects are not considered) and long term gains from investing in material productivity. This constitutes an important trade-off that needs to be addressed by policymaking.

Overall, this chapter calls for a more comprehensive approach when analysing material productivity improvements, going beyond purely commercial consideration by including non-monetary dimensions, externalities, and the cost of inaction. Robust methods are required to adequately monetise costs and benefits without market prices. Ultimately, these considerations could support policy action, aiming to strengthen the incentive for firms to invest in material productivity improvements.

This chapter serves as a link between the literature reviews and the empirical analyses. The subsequent two chapters investigate material use, first, by researching the short and long term effects of material use on GHG emissions, and second, by assessing the effect of economic growth on material use. These insights will then feed into the remaining analyses on the effects of material productivity on competitiveness, both on the macroeconomic and microeconomic levels.

Chapter 5

The Short and Long Term Effects of Material Use on GHG Emissions in the European Union

5 The short and long term effects of material use on GHG emissions in the European Union

5.1 Introduction

Achieving economic growth while limiting environmental pressures associated with economic activity is at the heart of contemporary efforts of sustainable development (e.g. Arrow et al. 1995; Rockström et al. 2009). Since materials are considered to be "the backbone of the economic production and consumption systems" (Bahn-Walkowiak and Steger 2015), their relationship with the environment and economy has received increasing attention by academics, international organisations, and policymakers (Meadows et al. 1972; UNEP IRP 2010a; Allwood et al. 2011; OECD 2016).

Numerous policies have since been formulated to limit the environmental pressures associated with material use, in particular in the context of the EU (EC 2011b; EC 2015a). Such policies have been underpinned by a large body of literature arguing that material use is responsible for a variety of environmental pressures (Meadows et al. 1972; UNEP IRP 2010a; Allwood et al. 2011; Worrell et al. 2016). As discussed in Chapter 2 and shown in Chapter 4, the link between material use and GHG emissions, an environmental pressure, receives particular attention, because material productivity improvements are argued to be one strategy to mitigate climate change (Bleischwitz 2010; Barrett and Scott 2012).

Chapter 3.4 argued that because most material use indicators are aggregated according to the weight of individual materials, the statistical link between such indicators and GHG emissions is unclear. This goes back to heterogeneous environmental pressures arising from individual materials which are not necessarily considered when aggregating materials according to their weight (UNEP IRP 2010a). This results in the paradox that reducing material use could theoretically lead to more GHG emissions, depending on the composition of material use.

The existing literature has tried to mitigate this problem by complementing material with environmental data (Hammond et al. 1995; Voet et al. 2005a), expanding the scope of material use across its life-cycle (Bringezu and Schütz 2001; Wiedmann et al. 2006), and analysing individual materials (Ciacci et al. 2014; Wiedemann et al. 2016; Dong et al. 2017).

However, two shortcomings remain present in the literature which this initial chapter on the topic attempts to highlight. First, the evidence base lacks the separation between short and long term effects. Second, the majority of empirical investigations do not consider the heterogeneity across countries, material subgroups, and material indicators. This investigation attempts to address both limitations by estimating the short and long term effects of DMC on GHG emissions for 15 EU countries between 1995 and 2010.[6] In order to adequately estimate the effects across time, a Koyck transformation is applied (Koyck 1954). The dynamic panel model is estimated using a generalised methods of moments (GMM) estimator following Arellano and Bond (1988).

The results providing evidence for a short and long term effect of DMC on GHG emissions. By disaggregating the various material subgroups, the findings show that the overall effect is mainly driven by fossil fuel use. Limitations of these findings are discussed. Country and material indicator heterogeneity is additionally considered, suggesting that countries and material indicators indeed differ substantially from each other. Using simple predictions, the role of decreasing material use in meeting EU climate change mitigation targets are analysed.

The remainder of the chapter is structured as follows. Section 5.2 briefly reviews the existing literature, also relying on the literature review in Chapter 2. Section 5.3 introduces the model, including the Koyck transformation, Section 5.4 briefly describes the data, and Section 5.5 outlines the results as well as limitations. Section 5.6 discusses the implications of the findings and Section 5.7 concludes.

To complement the investigation in this chapter, Chapters 7 and 8 will investigate whether increased in material productivity on the macroeconomic or microeconomic levels have led to reductions in GHG emissions.

5.2 Literature review

There is a plethora of analyses outlining the extent to which material use is linked to environmental pressures. While the types of environmental pressures resulting from material use go beyond GHG emissions, the focus of this analysis is on country level GHG emissions (Azam and Li 2010; UNEP IRP 2010a). This is due to the importance of GHG emissions to mitigate climate change as well as the availability of high-quality data (UN 2015a). Other environmental pressures predominantly occur locally and are thus often not recorded or challenging to aggregate on the country level (Flachenecker et al. 2017). As discussed in

[6] The 15 EU countries are Belgium, Denmark, Germany, Ireland, Greece, Spain, France, Italy, Luxembourg, Netherlands, Austria, Portugal, Finland, Sweden, and the United Kingdom.

Chapter 2, the consensus in the academic literature is that material use is responsible for GHG emissions (IPCC 2007; IEA 2010; EEA 2013; UNEP IRP 2013).

Since several material indicators aggregate materials based on weight, changes in material use might not necessarily reflect the expected changes in GHG emissions (Voet et al. 2005a; OECD 2008a; UNEP IRP 2016; EC 2017a). This is due to the fact that the composition of material use is important to take into account as well (Cleveland and Ruth 1998). The literature has proposed three interconnected strategies to mitigate this problem. First, scholars have complemented material with environmental data by multiplying various materials with their associated environmental pressures, including GHG emissions (Haan and Keuning 2001; Voet et al. 2005a; United Nations et al. 2014). Second, the scope of material use was expanded beyond considering 'domestic' use to a life-cycle perspective, resulting in indicators such RMC and TMR (Bringezu and Schütz 2001; Wiedmann et al. 2006; Giljum et al. 2013). Third, another strategy restricts its analysis to individual materials, thus avoiding the aggregation problem entirely (Frischknecht et al. 2005; Mongelli et al. 2005; Hammond and Jones 2008; Ciacci et al. 2014; Wiedemann et al. 2016; Dong et al. 2017).

However, what is missing is a comprehensive empirical analysis on the effect of weight-based material indicators on GHG emissions. Additionally, this chapter focuses on two issues that have received relatively little attention in the existing literature.

1) ***Short and long term effects:*** Material use is typically measured as *apparent* and not *final* consumption (EC 2015h). This means that even though materials are stated to be used at a specific point in time, their actual 'consumption' might take place in the future. Thus, material use today is likely to result in GHG emissions today as well as in the future. This issue to consider both short and long term effects of material use on GHG emissions has mostly not been explicitly studied in the relevant body of literature.
2) ***Heterogeneity:*** Since the composition of material use is argued to be important, the literature sometimes distinguishes between material subgroups (UNEP IRP 2010a). However, as already discussed in Chapter 2, there is no empirical evidence on the country level that explicitly takes heterogeneity across countries, material subgroups, and material indicators into account.

Going forward, this chapter aims to shift the attention of the literature to including these issues in future investigations and provides an initial empirical investigation on the relationship between weight-based material indicators and GHG emission in the EU.

5.3 Modelling approach

Materials are considered an input in the production function of economies (O'Mahony and Timmer 2009). Besides useful output, environmental pressures such as GHG emissions are also produced while converting materials and other inputs into output. Since DMC is measured in tonnes and reflects *apparent* and not *final* consumption, it seems reasonable to assume that DMC_t can not only explain GHG_t but also GHG_{t+1}, GHG_{t+2},... Therefore, the relationship between DMC and GHG emissions can be described in the following geometric lag model.

$$GHG_t = \alpha_0 + \beta(DMC_t + \lambda DMC_{t-1} + \lambda^2 DMC_{t-2} + \ldots) + \varepsilon_t \quad (2)$$

where α_0 is the intercept, λ is typically referred to as the retention rate, β is the current or short term effect of DMC on GHG emissions (or sometimes called lag weights), and ε_t is the uncorrelated error term (Franses and van Oest 2007). Accordingly, the carryover or long term effect of DMC on GHG can be calculated by $\frac{\beta}{1-\lambda}$.

Eq (2) assumes that the lag coefficients for DMC have a geometrically decaying effect on GHG emissions, i.e. here the effect declines exponentially. As Eq (2) has an infinite number of variables, it cannot be estimated in its current form. Therefore, a Koyck transformation is applied to transform Eq (2) into a model that can be estimated (Koyck 1954). By subtracting λGHG_{t-1} from both sides of Eq (2), the following first-order autoregressive lag model can be derived.

$$GHG_t = \alpha_0' + \beta DMC_t + \lambda GHG_{t-1} + \varepsilon_t - \lambda\varepsilon_{t-1} \quad (3)$$

where $\alpha_0' = (1-\lambda)\alpha_0$. Eq (3) is essentially an ARMAX model, comprising an autoregressive part λGHG_{t-1}, a moving average part $\lambda\varepsilon_{t-1}$, and an explanatory part βDMC_t. Since $cov(\varepsilon_{t-1}, GHG_{t-1}) \neq 0$, estimating Eq (3) with ordinary least square (OLS) would result in inconsistent estimates (Franses and van Oest 2007). In order to estimate consistent estimates, strict exogeneity needs to be assumed, i.e. $E(\varepsilon_t | \ldots, DMC_{t-1}, DMC_t, DMC_{t+1}, \ldots) = 0$.

Generally, there are three causes of endogeneity: simultaneity, measurement errors, and omitted variables (Angrist and Pischke 2009). Since GHG emissions are the result of a production process in which materials are an input, DMC is unlikely to be endogenous due to simultaneity. However, measurement errors are likely to be of minor concerns since the data is sourced from established statistical authorities. In order to mitigate the potential omitted variable bias, control variables are included in the estimations.

Following Ebert and Welsch (2007), GHG emissions are seen as an output of a production function, whereas past values of GHG emissions also explain current emissions, i.e. path dependency (Morris et al. 2012). As such, not only material inputs have an effect on GHG emissions, but also other inputs such as energy and labour. Thus, these two control variables are included in the estimations.

Eq (3) can be re-written as follows.

$$\mathrm{GHG_t} = \alpha_0' + \beta\mathrm{DMC_t} + \lambda\mathrm{GHG_{t-1}} + \nu_t \tag{4}$$

where $\nu_t = \varepsilon_t - \lambda\varepsilon_{t-1}$. $\mathrm{GHG_{t-1}}$ in Eq (4) needs to be instrumented for since it is likely to be correlated with the error term. Since 15 countries over 15 years are considered, any potential bias is likely to be relatively minor. Nevertheless, following Wooldridge (2008), suitable instruments for $\mathrm{GHG_{t-1}}$ are $\mathrm{DMC_{t-1}}$ and $\mathrm{GHG_{t-2}}$ since, by assumption, they are uncorrelated with ε_t and ε_{t-1}. In order to reduce the likelihood of any complex serial correlation structure, $\mathrm{DMC_{t-2}}$ and $\mathrm{GHG_{t-2}}$ are chosen as instruments for $\mathrm{GHG_{t-1}}$. Additionally, it will be shown in the robustness section that instrumenting $\mathrm{GHG_{t-1}}$ with even deeper lags of DMC and GHG emissions does not systematically alter the results.

Eq (4) is estimated using a GMM approach since having an overidentified first stage makes it more efficient compared to a 2SLS instrumental variable approach. The results of the GMM approach is benchmarked to those using OLS.

5.4 Data

Table 14: Statistics on GHG emissions, DMC, energy price index, and labour costs.

Variables in natural logarithm	N	Mean	Median	Std. deviation	Min	Max
GHG emissions in tonnes per capita	210	2.502	2.535	0.2261	1.999	2.976
DMC in tonnes per capita	210	3.030	2.931	0.3497	2.366	4.093
Energy price index	210	4.316	4.303	0.2036	3.885	4.670
Labour cost per capita (in PPP)	208	9.326	9.402	0.2809	8.272	9.763

5.4.1 GHG emissions

The data are considered for 15 EU economies between 1995 and 2010.

Table 14 indicates that the 15 EU countries are fairly similar in terms of their GHG emissions, DMC, energy prices, and labour costs. Annual data on total GHG emissions in tonnes are retrieved from the EEA and divided by data on the number of inhabitants in each country and year on 1 January from Eurostat, thus generating annual total GHG emissions in tonnes per capita. GHG emissions covers all anthropogenic emissions of the six GHGs (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride) across all sectors (including international aviation and indirect carbon dioxide emissions but excluding emissions or removals from land use, land use change, and forestry) (EEA 2016). The data on GHG emission follows the methodology outlined by the United Nations Framework Convention on Climate Change.

5.4.2 Material use

Data on DMC is taken from the Global Material Flows Database maintained by the Vienna University of Economics and Business (SERI 2013). DMC measures the total amount of materials directly used within an economy. It comprises biomass, metals, minerals, and fossil fuels and is defined as the quantity (in terms of weight) of domestically extracted raw materials, plus direct material imports minus direct material exports (EC 2015h). It is a standard indicator, which is frequently used in academia, and has been taken up by numerous statistical offices around the world (Hinterberger et al. 2003; UNEP IRP 2011; Bahn-Walkowiak and Steger 2015; OECD 2016).

Despite several shortcomings, DMC is the only material indicator for which data using the same methodology across countries and years is publically accessible. Alternative indicators, such as RMC and TMR, are only incompletely available (Bringezu and Schütz 2001; 2013). However, RMC data will be approximated and tested in this chapter. The data is divided by the number of inhabitants in each country and year on 1 January from Eurostat. The reason for choosing this database over the material flow database from Eurostat is that it covers a longer period of time which is essential to reduce the risk of any bias from complex serial correlation structures.

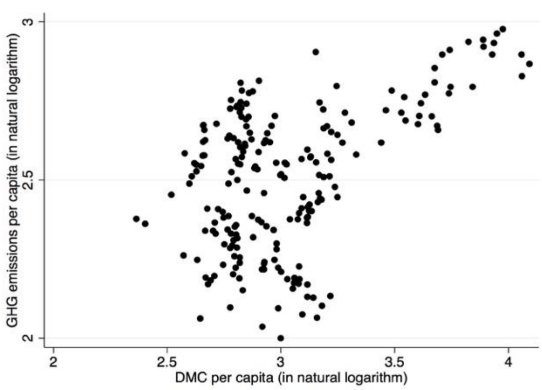
5.4.3 Control variables

The other two variables are controls. Data on a harmonised consumer price index on energy is retrieved from the OECD and measures the average change in electricity, gas, and other fuel prices for consumers. The base year is 2010. The earliest data available is from 1995.

Data on labour cost is taken from Eurostat. The data measures the total compensation for employees in Euros corrected by the country's purchasing power. The data is divided by the number of inhabitants in each country and year on 1 January from Eurostat.

Figure 11 shows a scatter plot for the independent variable, GHG emissions per capita (vertical axis), and the dependent variable, DMC per capita (horizontal axis), for the sample observations. A positive link between the two variables becomes visible, while there is no indication of any outlier in the data.

Figure 11: Scatter of GHG emissions per capita and DMC per capita.



5.5 Results

5.5.1 OLS results

By not addressing the endogeneity of GHG_{t-1}, estimating Eq (4) with an OLS approach could potentially produce biased and inconsistent results. However, to benchmark the results with those from a GMM approach, it provides valuable insights into the existence and magnitude of a potential bias. The results are shown in Table 15.

The results would suggest that increasing DMC per capita by 1% results in a 0.11 – 0.13% increase in GHG emissions per capita in the short term, depending on the specification. The long term effect would suggest that a 1% increase in DMC triggers a 0.27 – 0.33% increase in GHG emissions, also depending on the specification. This is not surprising since the long term effect accumulates short term impacts over time. In line with expectations, higher energy prices reduce GHG emissions. The coefficient for labour costs is statistically insignificant.

Table 15: OLS results.

	(1)	(2)	(3)
$\ln(GHG_{t-1})$	0.6382***	0.6082***	0.6201***
	(0.0714)	(0.0682)	(0.0687)
$\ln(DMC_t)$	0.1104**	0.1060**	0.1264***
	(0.0408)	(0.0383)	(0.0388)
$\ln(energy_t)$		-0.1180**	-0.0981**
		(0.0472)	(0.0385)
$\ln(labour_t)$			-0.0798
			(0.0587)
Country fixed-effects	YES	YES	YES
Time effects	YES	YES	YES
Within R^2	0.80	0.81	0.81
N	210	210	208

Notes. Dependent variable is $\ln(GHG_t)$. Estimated with OLS including country fixed and time effects. SEs are robust against heterogeneity and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.5.2 GMM results

Eq (4) is now estimated using a GMM approach suggested by Arellano and Bond (1988). A first-step dynamic GMM is estimated in first difference, while the instruments are in levels (Roodman 2009). Hence, the country-fixed effects are excluded, as they are time invariant.

As mentioned previously, DMC_{t-2} and GHG_{t-2} are chosen as instruments for GHG_{t-1}. The Arellano-Bond test for no autocorrelation of the first order is – by construction – rejected, while the test for second order autocorrelation is not rejected, indicating that there is no serial correlation in the error terms (Roodman 2009). These tests are argued to perform better in detecting the autocorrelation from lagged variables compared to the Sargan and Hansen tests (Roodman 2009).

Additionally, the table shows the test statistics from estimating Eq (4) with the less efficient 2SLS approach.[7] The Kleibergen-Paap rk LM statistic is a test for underidentification and is clearly rejected. Kleibergen-Paap rk Wald statistic should be above 10, the conventional rule of thumb (Angrist and Pischke 2009). All four tests thus confirm the statistical validity of the instrumentation strategy.

[7] Estimating Eq (4) with a 2SLS approach provides very similar results to those obtained by GMM.

Table 16 provides evidence that increasing DMC by 1% increases GHG emissions by 0.11 – 0.13% in the short term, and by 0.27 – 0.33% in the long term, depending on the specification. Interestingly, these findings are very similar to the OLS results, suggesting that the endogeneity of GHG_{t-1} does not significantly bias the OLS results.

Table 16: GMM results.

	(1)	(2)	(3)
$\ln(GHG_{t-1})$	0.6280***	0.5958***	0.6196***
	(0.0634)	(0.0609)	(0.0643)
$\ln(DMC_t)$	0.1116***	0.1094**	0.1263***
	(0.0362)	(0.0348)	(0.0350)
$\ln(energy_t)$		-0.1164***	-0.0984***
		(0.0438)	(0.0346)
$\ln(labour_t)$			-0.0801
			(0.0551)
Country fixed-effects	NO	NO	NO
Time effects	YES	YES	YES
Arellano-Bond test for AR(1), p-value	0.008	0.005	0.005
Arellano-Bond test for AR(2), p-value	0.434	0.359	0.364
Kleibergen-Paap rk LM statistic, p-value	0.000	0.000	0.000
Kleibergen-Paap rk Wald, F-statistic	97.05	74.26	71.58
R^2	0.81	0.81	0.81
N	210	196	194

Notes. Dependent variable is $\ln(GHG_t)$. Estimated with GMM including time effects. SEs are robust against heterogeneity and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Such estimates can now be compared to findings from the literature. However, most empirical analyses study the effects of changes in material productivity, not material use. For instance, realising numerous material savings opportunities in three sectors of the EU is estimated to reduce total annual EU-wide GHG emissions by 2-4% (AMEC and Bio IS 2013). In order to reach such GHG emissions reductions, material use per capita would need to be reduced by around 10% in the long run as a result of the material productivity increases. This would be equivalent to reducing current EU levels of material use by 1.32 tonnes per capita in the long run.

The results also confirm the estimates by Worrell et al. (2016) that materials account for 25% of the CO_2 emissions globally. Even though this study considers GHG emissions and the EU, reducing DMC by 100% would suggest a decrease in GHG emissions by 27-33% in the long term.

5.5.3 Material subgroups

As mentioned previously, materials comprise biomass, minerals, metals, and fossil fuels. In order to better understand which material group drives these findings, the GMM approach is re-run for the various material subgroups. The data is again sourced from the Global Material Flows Database maintained by the Vienna University of Economics and Business (SERI 2013) and measures the domestic extraction of the four groups of materials.

Table 17 shows the results for the GMM approach. For each estimation, the subgroup of each material is taken both as the independent variable (generic_t) and as the instrument. It becomes apparent that fossil fuels are the main driver behind the positive effect for the DMC aggregate.

The short run effect of increasing fossil fuel use by 1% on GHG emissions is 0.07% and the long run effect 0.27%. Thus, the effects are not significantly different from the ones above, as the mean value is within the 95% confidence intervals of the previous estimations. This finding confirms that fossil fuels are the types of materials most associated with GHG emissions, even when measured in terms of their weight. Interestingly, the other material groups insignificantly affect GHG emissions. The conclusions drawn from these findings remain robust against introducing the same control variables as in the previous section. Additionally, the instrumentation strategy remains statistically valid across the various statistical tests.

Table 17: Material subgroups - GMM results.

	Biomass	**Minerals**	**Metals**	**Fossil fuels**
$\ln(\text{GHG}_{t-1})$	0.7252***	0.6886***	0.7333***	0.7404***
	(0.0367)	(0.0488)	(0.0287)	(0.0343)
$\ln(\text{generic}_t)$	-0.0871	0.0005	0.0012	0.0688*
	(0.1371)	(0.0390)	(0.0525)	(0.0393)
Country fixed-effects	NO	NO	NO	NO
Time effects	YES	YES	YES	YES
Arellano-Bond test for AR(1), p-value	0.006	0.006	0.006	0.010
Arellano-Bond test for AR(2), p-value	0.338	0.340	0.331	0.350
Kleibergen-Paap rk LM statistic, p-value	0.000	0.000	0.000	0.000
Kleibergen-Paap rk Wald, F-statistic	138.37	88.88	116.28	129.08
R^2	0.77	0.76	0.76	0.77
N	225	225	225	225

Notes. Dependent variable is $\ln(\text{GHG}_t)$. Estimated with GMM including time effects. SEs are robust against heterogeneity and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

However, such results are likely to not provide the full picture underlying the relationship between material use and GHG emissions due to the following two reasons.

1) ***Weight-based measures:*** As mentioned previously, DMC and all material subgroups are measured in terms of their weight. Thus, based on these results, it cannot be concluded that most materials (with the exception of fossil fuels) do not affect GHG emissions. This could merely be a composition effect caused by heavy materials which do not trigger significant GHG emissions (such as sand and gravel) (UNEP IRP 2010a). Unfortunately, a more disaggregated estimation is not possible due to the gap between data availability and data requirements for applying the econometric method used in this chapter.
2) ***Uncertainty:*** The margin of error for the long term effect includes the commonly cited figure that 65% of global GHG emissions are due to fossil fuel use, because the results are consistent with a reduction of up to 76% of GHG emissions in the 15 EU countries if they were to stop using fossil fuel entirely (IPCC 2014). This indicates that the uncertainty of the results are non-negligible, despite being statistically significant to the 5 or 10% significance levels.

5.5.4 Country heterogeneity

Table 18 shows the heterogeneity across countries. The 2SLS approach is chosen here to explicitly estimate the country-specific coefficients. Belgium is the reference category. It becomes apparent that country heterogeneity plays an important role, as the vast majority of the 15 EU economies have a significantly lower impact of material use on GHG emissions compared to Belgium. This heterogeneity across countries could be the result of different levels of technology or simply different material compositions (e.g. due to different sectoral structures). A detailed investigation on the reasons behind this heterogeneity goes beyond the scope of this chapter, but one important conclusion can be drawn: even in the EU-15, a one-size-fits-it-all approach is likely to be misguided.

Table 18: Country heterogeneity - 2SLS results.

$\ln(GHG_{t-1})$	0.7193***
	(0.0770)
$\ln(DMC_t)$	0.0819**
	(0.0323)
Belgium	*reference*
Denmark	-0.0448**
Germany	-0.0327***
Ireland	-0.0359
Greece	-0.0533**
Spain	-0.1123***
France	-0.1117***
Italy	-0.0847***
Luxembourg	-
Netherlands	-0.0030
Austria	-0.0915***
Portugal	-0.1520***
Finland	-0.0494
Sweden	-0.1749***
United Kingdom	-0.0327***
Time effects	YES
Kleibergen-Paap rk LM statistic, p-value	0.000
Kleibergen-Paap rk Wald, F-statistic	97.05
R^2	0.98
N	224

Notes. Dependent variable is $\ln(GHG_t)$. Estimated with 2SLS including time effects. SEs are robust against heterogeneity and shown in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.5.5 Raw material consumption

For RMC, data for the EU countries between 2000 and 2012 are being approximated following the methodology in EC (2014c). Unfortunately, choosing another time span is not possible, as no publically available data for the same time period exist. Essentially, raw material equivalents (RME) coefficients for each EU-27 country, each material category, each year as well as for imports and exports are derived. Those coefficients are calculated by dividing the EU-27 average in RME trade data by the DMC trade data. Subsequently, Croatia's DMC trade data is converted into RME trade data and added to the EU-28 average to determine the EU-28 based RME trade coefficients.

Then, each country for each material category for each year is multiplied by the coefficients. To calculate the coefficients for intra-EU imports, the EU-28 average of exports is taken, as there is no intra-EU imports RME data available. The underlying assumption is that intra-EU imports are more similar across the EU than with extra-EU imports since exports are more similar in the EU relative to its imports. Clearly, there are several limitations to such data. The core assumption of this method is that RME trade data is similar to the EU-28 average to justify this method. Given that there is currently no RMC data available for all member states and across time, it is the best option available.

Table 19 illustrates that the instrumentation remains statistically valid. Two aspects are worth mentioning. First, the effect of RMC on GHG emissions is significantly lower compared to the DMC indicator, because the mean value is outside the 95% confidence interval of the estimations using DMC.

Table 19: RMC results.

$\ln(GHG_{t-1})$	0.5682***
	(0.1066)
$\ln(RMC_t)$	0.0403***
	(0.0108)
Country fixed-effects	NO
Time effects	YES
Arellano-Bond test for AR(1), p-value	0.003
Arellano-Bond test for AR(2), p-value	0.335
Kleibergen-Paap rk LM statistic, p-value	0.005
Kleibergen-Paap rk Wald, F-statistic	10.11
R^2	0.80
N	148

Notes. Dependent variable is $\ln(GHG_t)$. Estimated with GMM including time effects. SEs are robust against heterogeneity and shown in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

This is surprising since it was expected to cover more of the initial and GHG emission intensive stages of the material life cycle. However, GHG emissions are measured within a given territory, thus GHG emissions produced outside of that territory are included in the emission statistics of another territory which accounts for the *indirect* material use. Hence, a relatively smaller part of the variation in the RMC indicator triggers domestic GHG emissions compared to the DMC indicator. This could be the result of by Europe being a net importer of materials. Moreover, the long term effect is 0.09% for every 1% RMC increase, hence, more than three times lower compared to the DMC effect.

Nevertheless, the crude approximation of the RMC data, the different time period considered, or the uncertainty of the estimated coefficients mentioned previously could be further reasons explaining these results.

5.5.6 Robustness checks

The robustness of the main results using DMC is tested by excluding individual countries and years. The conclusions drawn remain valid, as no country or year drives the results. Additionally, different sets of standard errors, i.e. homoscedastic, clustered over countries, and those robust to autocorrelation are used to estimate the model. The results are not changed in any significant way. The time effects are jointly highly significant and thus included in the estimations. Excluding the country fixed effects in the 2SLS estimations do not systematically alter the findings.

Throughout all these checks, the instrumentation strategy remains robust. Additionally, the robustness of the instrumentation strategy is tested by simultaneously applying deeper lags to DMC and GHG emissions, thus reducing the possible problem of more complex serial correlation structures. As Table 20 shows, using deeper lags does not change the findings. In line with expectations, deeper lags reduce the Kleinbergen-Paap rk Wald F-statistic.

Table 20: Robustness test using deeper lags of DMC and GHG emissions as instruments - GMM.

	Lagged 3 periods	*Lagged 4 periods*	*Lagged 5 periods*
GHG_{t-1}	0.6310***	0.6223***	0.6175***
	(0.0671)	(0.0715)	(0.0658)
DMC_t	0.1122***	0.1143***	0.1230***
	(0.0394)	(0.0382)	(0.0399)
Country fixed-effects	NO	NO	NO
Time effects	YES	YES	YES
Arellano-Bond test for AR(1), p-value	0.008	0.008	0.009
Arellano-Bond test for AR(2), p-value	0.436	0.435	0.430
Kleibergen-Paap rk LM statistic, p-value	0.000	0.000	0.000
Kleibergen-Paap rk Wald, F-statistic	54.52	41.31	26.19
R^2	0.81	0.81	0.81
N	210	210	210

Notes. Dependent variable is GHG_t. Estimated with GMM including time effects. SEs are robust against heterogeneity and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.6 Discussion

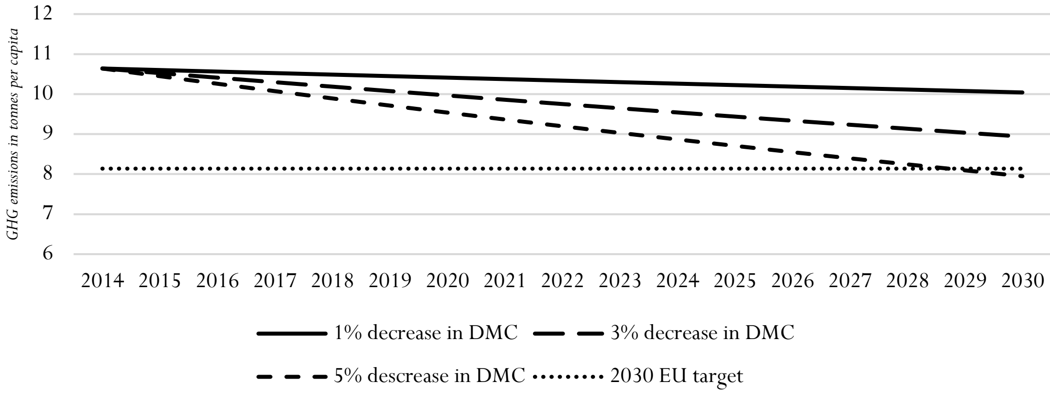
Despite showing the robustness of the results and the instrumentation strategy, complex and very long term serial correlation structures cannot be ruled out entirely. It has been argued by the literature that using lagged endogenous variables or dynamic panel approaches can be problematic in making causal inference (Kraay 2012; Panizza and Presbitero 2014; Reed 2015). Therefore, this analysis does not argue to have identified a causal relationship, but it provides a first steps towards additional efforts to support the empirical basis on the link between material use and GHG emissions, focusing on the short and long term effects as well as heterogeneity across countries, material subgroups, and material indicators.

Despite limitations, this chapter provides evidence that material use not only increases GHG emissions in the short but also in the long term. These findings are mainly driven by fossil fuel use. Crucially, the results indicate that the long term effect of DMC on GHG emissions is more than three times higher compared to the immediate effect. Thus, drastically reducing material use today would not result in a substantial decrease in GHG emissions immediately but in a prolonged decrease over time.

The policy implications of these results are striking. Taking the coefficients for the long term effect from Table 16 Column 3, if one were to assume various magnitudes of decreasing material use on an annual basis, Figure 12 shows the extrapolated linear predictions of decreases in GHG emissions per capita. The population predictions of Eurostat for the year 2030 and the EU's reduction target for domestic GHG emissions of 40% compared to 1990 are considered and applied to the 15 EU member states in terms of GHG emissions per capita (EC 2014f).

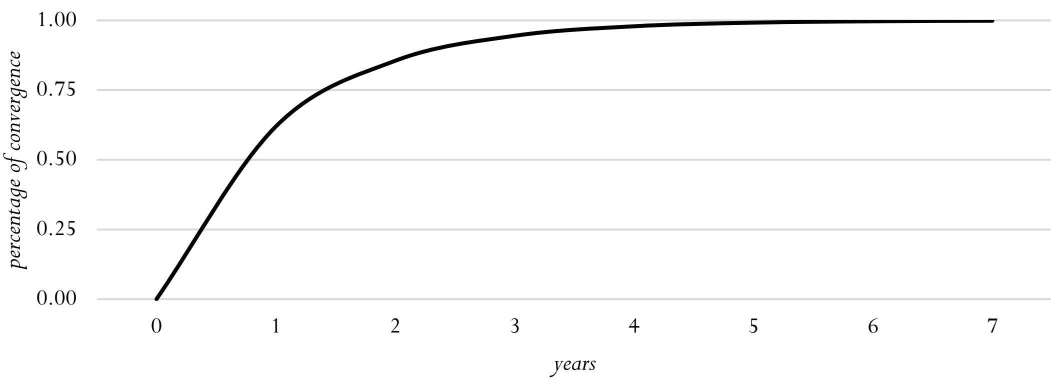
Accordingly, the 15 EU countries emit 10.64 tonnes GHG emissions per capita in 2014 and would need to reach 8.14 tonnes per capita in 2030. The prediction indicates that DMC per capita would need to be reduced by approximately 5% per annum in order to reach the GHG emission reduction target in terms of GHG emissions per capita. However, it should be kept in mind that reducing material use is not the only strategy to reach a reduction in GHG emissions.

Figure 12: Scenarios of GHG emissions per capita for different DMC per capita reductions.



Another policy implication is illustrated in Figure 13. Given the estimations on the short and long term effects, the question arises how long does a short term reduction in material use take to unfold its full effect on GHG emissions? It becomes apparent that after 1 year, the effect of a short term reduction in DMC by 1% has resulted in around 62% of the full GHG emission reduction effect, 86% after 2 years and 94% after 3 years. Thus, it takes around 4-6 years to have (almost) reached the full effect of a DMC reduction today. This statistical exercise reveals that it is important to act sooner rather than later to reduce GHG emissions over time since any reduction in DMC later in time will need to be relatively higher in order to achieve the same reduction as acting today.

Figure 13: Convergence rate of changes in DMC on GHG emissions.



5.7 Conclusions

This analysis provides empirical evidence for the effect of material use on GHG emissions, thus providing important insights in an area that has been identified as an important limitation in Chapter 3.4. While a connection between the use of materials comprising biomass, minerals, metals as well as fossil fuels and GHG emissions appears evident at first sight, the majority of material indicators are weight-based measures, thus changing the composition of material use can affect GHG emissions in either direction (Cleveland and Ruth 1998; Voet et al. 2005a).

The existing literature tried to mitigate this problem by complementing material with environmental data, expanding the scope of material use across its life-cycle, and restricting analyses to individual materials (Bringezu and Schütz 2001; Voet et al. 2005a; Wiedmann et al. 2006; Ciacci et al. 2014). However, the existing literature has put little attention on two issues. First, most studies do not distinguish between the short from the long term effects of material use on GHG emissions. Second, few investigations consider the heterogeneity across countries, material subgroups, and material indicators.

This investigation attempts to shift the attention to both limitations by considering the short and long term effect of DMC on GHG emissions for 15 economies in the EU between 1995 and 2010. After applying a Koyck transformation, the dynamic model is estimated with a GMM approach, providing evidence for a positive effect of DMC on GHG emissions in the short and long term.

Additionally, this investigation suggests that the link between DMC and GHG emissions is mainly driven by fossil fuel use. Two shortcomings of the results are discussed – weight-based aggregation and uncertainty. Moreover, this chapter shows that country heterogeneity is important to consider in empirical investigations on the topic. Furthermore, heterogeneity across the DMC and RMC indicator is relevant as well, given that the effects are significantly different from each other.

A simple linear prediction shows that significantly reducing material use every year (by around 5% per annum) could enable the EU to reach its climate change mitigation target of reducing GHG emissions by 40% by 2030 compared to 1990. It is further shown that reducing material use today requires 4-6 years to unfold its full effect on GHG emissions, thus illustrating a trade-off between reducing material use now by less compared to reducing it later.

In conclusion, material use is found to effect GHG emissions, both in the short and long term. This is an important finding strengthening the arguments brought forward in Chapter 4. Whether material productivity improvements have led to a reduction in GHG emissions on the macroeconomic and microeconomic levels will be subject of analyses in Chapters 7 and 8. The following chapter first analyses the effect of economic growth on material use, as suggested by vast parts of the literature reviewed in Chapter 3.1.

Chapter 6

The Causal Impact of Economic Growth on Material Use in Europe

An abridged version of this chapter is published as

Agnolucci, Paolo; ***Flachenecker, Florian*** and Söderberg, Magnus (2017). The causal impact of economic growth on material use in Europe. *Journal of Environmental Economics and Policy* 6:4. 415-432.

6 The causal impact of economic growth on material use in Europe

6.1 Introduction

The previous chapter showed that material use is associated with GHG emissions, both in the short and long term. But what spurs the ever-increasing material use? As distilled from Chapter 3.1, the current literature identifies economic growth as the dominant driver of material use. In this regard, there have been extensive discussions among scholars and policymakers on how economic growth can be achieved while staying within the planetary boundaries (e.g. Arrow et al. 1995; Rockström et al. 2009). This has triggered three more general strands of the literature.

1) ***GDP-environment:*** Numerous scholars have investigated the effects of economic growth on various types of environmental pressures, in particular GHG emissions (Selden and Song 1994; Schmalensee et al. 1998; Galeotti et al. 2006; Vollebergh et al. 2009; Wagner 2015).
2) ***Material use as environmental indicator:*** Interdisciplinary scholars have argued that GHG emissions and other single indicators of environmental pressures often used in economic studies fail to comprehensively capture (i) the variety of pressures arising at different stages of contemporary supply-chains and (ii) pressures that occur with a delay. These scholars have proposed material flow and footprint indicators as a more comprehensive measure for environmental pressures (Alfsen and Sæbø 1993; Bringezu et al. 2003; Ibenholt 2003; Voet et al. 2005b; UNEP IRP 2010a; Bleischwitz 2010; Hoang and Alauddin 2012; Bouwmeester and Oosterhaven 2013; Wiedmann et al. 2013b; Teixidó-Figueras and Duro 2015).[8] What has become clear from the previous chapter, material use is associated with higher GHG emissions in Europe in the short and long term, a link that is predominantly driven by the use of fossil fuels.
3) ***Decoupling:*** Policymakers in Europe and around the world have made the decoupling of material use from economic growth a central policy objective, with the explicit aim to reduce environmental pressures associated with it (EC 2011b; EC 2015a; G7

[8] Other researchers, however, oppose this view since materials are typically measured in weight and aggregated across material types, leading to a biased and imprecise measure of specific environmental pressures (Cleveland and Ruth 1998; Voet et al. 2005a).

> 2015a; UN 2015b; OECD 2016). Taking into consideration the findings of the previous chapter would suggest that in order to decouple environmental pressures from economic growth, a decoupling of material use from economic growth is necessary.

The different strands of the literature on the relationship between economic growth (GDP) and material use predominantly find a positive correlation between the two variables (e.g. Bringezu et al. 2004; Voet et al. 2005b; Wiedmann et al. 2013; Jaunky 2013), but investigations on the shape of the relationship between GDP and material use produce inconclusive results (Hüttler et al. 1999; Bruyn 2002; Canas et al. 2003; Bringezu et al. 2004). Studies investigating the drivers of material use, however, conclude that GDP is an important, if not the most important, determinant which has been discussed in detail in Chapter 3 (Hoffren et al. 2001; Voet et al. 2005b; Weisz et al. 2006; Steger and Bleischwitz 2011; Weinzettel and Kovanda 2011; Pothen and Schymura 2015).

Crucially, some studies claim that most European countries, in particular Western Europe, have managed to decouple, i.e. broken the link between material use and economic growth, at least in relative terms (Bringezu and Schütz 2001; Moll et al. 2005; Voet et al. 2005b), a belief which is reflected in several policy initiatives in Europe, for instance, the Raw Materials Initiative (EC 2008), the Europe 2020 strategy (EC 2010a), the Roadmap to a Resource Efficient Europe (EC 2011b), and the Circular Economy Package (EC 2015a).

In summary, investigating the effect of economic growth on material use entails (i) a more comprehensive investigation on environmental pressures arising from economic activity, (ii) an analysis on the drivers of material use, and (iii) a verification on the decoupling efforts in Europe.

This chapter identifies and addresses two major shortcomings in the literature. First, the heterogeneity across countries, material subgroups, and material indicators is predominantly not considered. Second, most studies rely on correlation and simple regression analyses, failing to take the endogeneity of GDP into account, which could result in biased and inconsistent estimates (Angrist and Pischke 2009).

In this chapter, the causal relationship between GDP and material use, measured by DMC and RMC, is estimated explicitly acknowledging that GDP and material use are simultaneously determined. On the one hand, income drives consumption, including the consumption of materials (Ando and Modigliani 1963; Hall and Mishkin 1982). On the other hand, materials are an input into economic production functions (Ayres and van den Bergh 2005; O'Mahony and Timmer 2009). This analysis attempts to address endogeneity triggered by simultaneity, along with potential problems caused by omitted factors by using an instrumental variable approach. In addition, the heterogeneity across countries, material subgroups, and material indicators is analysed.

This analysis considers 32 European countries[9], which is a group of industrialised countries that are bound by similar regulation and use a standardised method to measure DMC (and thus indirectly RMC). A 2SLS approach is taken, including country and time effects, and GDP is instrumented by the number of storm occurrences.

This approach allows to make causal inference under two conditions. First, storms need to be correlated with GDP, i.e. the instrument needs to be relevant. Second, storms must not impact DMC other than through GDP, i.e. the instrument needs to comply with the exclusion restriction.

1) ***Relevance condition:*** The literature suggests that severe weather events have an impact on countries' current and future GDP, with the majority of the literature suggesting a negative effect (Cavallo et al. 2010; World Bank and UN 2010; Cavallo et al. 2013; Noy and DuPont 2016).
2) ***Exclusion restriction:*** Two potential links between storms and DMC are discussed in Section 6.2, i.e. changes in trade, a link which is captured by GDP, and changes in material prices as a result of a storm. This chapter presents empirical evidence that some material prices are affected in the short term, but this effect disappears two years after a storm occurs. As a consequence, a temporal instrumentation strategy is used to estimate the causal impact of GDP on DMC with the instrument lagged two years to meet the exclusion restriction.

The results provide new evidence that increasing the GDP growth rate causes an increase in the DMC growth rate for Western Europe, whereas the effect is insignificant for Eastern European economies. A more disaggregated analysis shows that minerals and biomass materials are the main material subgroups affected by increases in the GDP growth rate for Western Europe. Furthermore, this study shows that there is significant heterogeneity across countries and material indicators.

[9] A list of the countries can be found in Table A1 in the Appendix.

These findings question the current wisdom, especially among European policymakers, that the link between GDP and material use in Western Europe has been broken. Why would Western European economies demand more materials when their economies expand? Two possible explanations are discussed that are consistent with these results. Lower energy prices in Western Europe compared to the rest of Europe could increase the demand for materials through its complementarity to energy, and higher labour cost in Western Europe compared to the rest of Europe could have stimulated substitution from labour to materials.

The remainder of the chapter is structured as follows: Section 6.2 introduces the modelling approach, where the instrumentation strategy is described in detail. Section 6.3 describes the data. Section 6.4 outlines the results. Section 6.5 places the results in a wider context and Section 6.6 concludes.

6.2 Modelling approach

6.2.1 The problem of endogeneity

As outlined in Chapter 3, a considerable body of literature investigating drivers of material use and decoupling suggests that GDP affects material use (Voet et al. 2005b; Weisz et al. 2006; Steger and Bleischwitz 2011; Pothen and Schymura 2015). As national income increases, consumption also increases as proposed by the theoretical work on the Modigliani's life cycle hypothesis which essentially argues that consumption is a function of income (Ando and Modigliani 1963). Empirical studies provide evidence for short and long term effects of changes in income on consumption (Hall and Mishkin 1982; Campbell and Mankiw 1989). Although the size of the impact of changes in income on the use of material depends on the material requirements of economic goods and services being consumed, economic activity ultimately leads to an increase in the use of materials as long as economic activity affects the consumption of economic goods.

Two sources of endogeneity are likely to be present in models investigating the impact of GDP on material use in Europe – simultaneity and omitted factors.

1) ***Simultaneity:*** Simultaneity between GDP and material use arises since materials are inputs to a country's production function (Ayres and van den Bergh 2005; O'Mahony and Timmer 2009). This follows from the basic production process where inputs are converted into outputs, and materials have also been included as production inputs in recent growth models (O'Mahony and Timmer 2009).

2) ***Omitted factors:*** Endogeneity due to omitted variables occurs when determinants of the dependent variable which are omitted from the model, e.g. economic structure, energy prices, etc., are partially correlated with GDP.

Both sources of endogeneity would make OLS estimation biased and inconsistent (Angrist and Pischke 2009). Therefore, an instrumental variable estimation is applied.

6.2.2 Choice of instrument

The number of storms occurred in a country is chosen as an instrument for GDP. Natural hazards have previously been used as instruments for economic variables such as trade, aid inflows, productivity, and oil income (Ramsay 2011; Felbermayr and Gröschl 2013; Jackson 2014; Flachenecker 2017). The main rationale for using storm occurrences as an instrument is that such events affect GDP in an exogenous manner.

Kahn (2005) finds that the general level of economic development, institutional quality, and geography affect the implications of natural hazards. However, the economy's sensitiveness to storm disasters is unlikely to change in a relatively short time period (World Bank and UN 2010). In addition, this risk is minimised by using the number of storms rather than monetary variables, e.g. damages caused by storm, as these are more likely to be influenced by the level of economic development. Moreover, country-specific trends are eliminated by taking the first difference which might further reduce the risk of storms being endogenous, as changes in storm occurrences are less likely to correlate with economic development. Additionally, by taking the first difference, any standard complication related to spurious regressions is avoided.

Storms occur relatively frequently, both across countries and time. Since a fixed effects model is estimated in first differences, the instrument needs to vary over time. This has a led to the exclusion of earthquakes, volcanoes, and droughts which either do not occur frequently or not at all in several countries. Using storms is preferred to floods, since storms typically affect larger areas. For instance, storms could affect transportation routes and energy generation as well as supply networks, thus impacting economic activity regardless of its proximity to economic centres. Areas affected by storms are also more likely to vary across time, as areas affected by floods need to be close to rivers or to the sea. Storms have been reported in every European country except Finland and Serbia, whereas eight European countries have not reported any flood during the sample period used in this study. In addition, flood defence mechanisms may reduce the likelihood of re-occurring floods or their impact on GDP, therefore potentially compromising the exogeneity of the instrument.

Data on extreme weather events are publically available in the Emergency Events Database EM-DAT (Guha-Sapir et al. 2014). EM-DAT contains indicators that measures storms in different ways. Such measures include total deaths, number of people affected, damages in dollars and a count variable on the number of storm occurrences. Storm occurrences, rather than any of the alternative measures, has the advantage of being more likely to be a precise, objective, and exogenous measure. However, this comes at the expense of treating all storms equally, regardless of their impact – a classical trade-off arises. Nevertheless, the EM-DAT database only comprises those storms that had a significant impact, i.e. ten or more people reported killed, hundred or more people reported affected, declaration of a state of emergency, or call for international assistance.

It is also important to note that reporting might be heterogeneous across countries, although this is believed to be a minor problem since most European countries are industrialised economies with established monitoring authorities and reporting requirements. Under-reporting is not likely to be an issue, as European countries have an incentive to correctly report disasters since they become eligible to emergency aids to cope with immediate damages as well as long-term investments in prevention from the European Union's Solidarity Fund and the Civil Protection Mechanism. Given that the requirements for receiving aid is linked to monitoring the impacts, over-reporting is also unlikely to be an issue.

6.2.3 Instrumentation strategy

As already mentioned, instruments need to be relevant and valid. Relevant instruments require a strong correlation between the instrument and the endogenous variable. The great majority of investigations embrace the view that disasters are a setback for economic growth due to damages to the capital stock and additional disruptions of economic activity during their immediate aftermath (e.g. electricity cuts, obstructing people to work) as well as their subsequent course (e.g. crowding-out investments, migration, reconstruction delays, welfare transfers) (Hochrainer 2009; Raddatz 2009; Hsiang and Jina 2014; DuPont et al. 2015).[10]

This can be exemplified by the extra-tropical cyclone Xynthia which affected France in February 2010. It had severe negative impacts on economic activity, both immediately and in the aftermath of the disaster. The storm killed 53 people, affected more than 500,000 people nation-wide and caused more than $4.2 billion worth of damages (EM-DAT database).

[10] Some studies find a positive relationship between natural hazards and economic activity which is often linked to reconstruction efforts and the long term (Cavallo et al. 2013; Noy and DuPont 2016).

Approximately half of the damages were insured, the rest had to be borne privately, suggesting a reduction in long term consumption of affected households assuming Modigliani's life-time consumption smoothing hypothesis. Workers were prevented from going to work, electricity supply was cut for over a million homes and the train infrastructure was damaged. The storm triggered a major flood in Charente-Maritime which had a number of impacts: Oyster farms (a major employer in the area) were destroyed, the tourism sector suffered, and productivity of agricultural land (including wine production) was affected by salty sea water (Lumbroso and Vinet 2011; Genovese and Przyluski 2013).

The exclusion restriction requires the instrument to affect the dependent variable (DMC, RMC) only through the endogenous variable which has been instrumented for (GDP). Felbermayr and Gröschl (2013) use natural hazards in neighbouring countries rather than the home country to instrument for the endogenous regressor in the home country to increase the chances of meeting the exclusion restriction. However, this spatial differentiation approach is not suitable for this study since storms tend to affect several neighbouring countries simultaneously. Instead, a temporal instrumentation strategy is adopted that attenuates the potential direct impact of storms on material use.

However, one way storms could impact material use is through trade. If a country is hit by a storm, the national production capacity is temporarily reduced, which could reduce its exports and increase imports. As net exports are part of GDP, changes in trade due to storms would affect material use only through GDP which is not a violation of the exclusion restriction. Another way storms could affect material use is through their impact on material prices. This possibility is explored by assessing the relationship between storms and prices of the material subgroups since there is no comprehensive material price indicator available for Europe.

Metals and fossil fuels are traded on global markets and local storms are unlikely to affect those prices. This is particularly likely in the case of Europe since it is a small producer of metals and fossil fuels. As the markets for biomass and minerals are to some extent local, it is investigated whether storms have an impact on those prices, as a statistical association would cast doubts on the instrument. The following models are estimated.

$$\Delta p_{i,t} = \kappa \, \Delta storms_{i,t-h} + \varphi_t + \theta_i t + \upsilon_{i,t} \quad (5)$$

where φ_t are time effects, $\theta_i t$ are country-specific trends, $\text{storms}_{i,t-h}$ indicates the number of storm occurrences. These are taken from the EM-DAT database unless stated otherwise. The letter h indicates the time lag with $h \in (0,1,2)$. $p_{i,t}$ indicates the price of biomass, material inputs, and minerals as dependent variables in the three different models that are estimated and shown in Table 21.

1) ***Biomass prices:*** To proxy biomass prices, real industrial crop prices in Europe between 2000 and 2014 are retrieved from Eurostat. As shown in Columns 1-3, there is no significant relationship between storms and crop prices.
2) ***Material input prices:*** In the case of material input prices, Columns 4-6, the correlation between the number of storm occurrences and the material input prices is considered for constructing residential building from Eurostat in Europe between 2000-2014. As shown in Table 21, there is no statistically significant association between storms and material input prices across time.
3) ***Mineral prices:*** In the case of mineral prices, Columns 7-9, data from the Nordic Statistic Database on the mineral costs of dwelling construction and the number of storms from the Extreme Wind Storms Catalogue for Finland, Sweden, and Denmark from 2000 to 2013 are considered. The Nordic countries are the only group of countries that collects mineral price data using a standardised approach, both in terms of data collection and variable definition. As shown in Table 21, the relationship between storms and mineral prices in the current period is significant at the 10% level and negative. The impact of a storm in the previous period on mineral prices is positive (possibly due to reconstruction) and just outside the 10% significance level, but when storms are lagged two years, the statistical association disappears completely.

This brief analysis suggests that the relationship between storms and material prices becomes statistically insignificant after two years. In line with the temporal strategy mentioned above, the instrument is lagged twice to ensure that the instrument satisfies the exclusion restriction so that no impact of storms affect material use without going through changes in the level of economic activity.

Table 21: Relationship between the number of storm occurrences and material prices in Europe.

	Biomass prices			Material input prices			Mineral prices		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta storms_{i,t}$	4.167			0.324			-1.568*		
	(3.525)			(0.202)			(0.818)		
$\Delta storms_{i,t-1}$		2.718			0.120			1.142	
		(1.846)			(0.254)			(0.711)	
$\Delta storms_{i,t-2}$			2.147			-0.091			-0.066
			(1.402)			(0.194)			(0.716)
(within) R^2	0.12	0.16	0.24	0.39	0.44	0.42	0.78	0.77	0.76
N	129	120	106	178	167	154	45	42	39

Notes. Columns 1-3: Dependent variable is $\Delta \text{crop price}_{i,t}$. Within fixed effects estimation including country and year fixed effects for Europe between 2000-2014. SEs are clustered over countries and shown in parentheses. Columns 4-6: Dependent variable is $\Delta \text{material input prices}_{i,t}$. Within fixed effects estimation including country and year fixed effects for Europe between 2000-2014. SEs are clustered over countries and shown in parentheses. Columns 7-9: Dependent variable is $\Delta \text{mineral prices}_{i,t}$. OLS with country and year fixed effects for Finland, Sweden, and Denmark between 2000-2013. Robust SEs are shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

6.2.4 Model specification

In the model, material use in the current period is influenced by GDP in the previous period. Increasing material use involves coordination across several stages of the supply-chain, as inventories are not likely to be able to accommodate large demand shifts. Also, the material use of households tend to respond with a delay to changes in income, e.g. cars and houses are not purchased immediately after a raise in income (Shapiro and Slemrod 2009; Jappelli and Pistaferri 2010). Hence, the model is formulated as.

$$\mathrm{DMC}_{i,t} = \pi\, \mathrm{GDP}_{i,t-1} + \gamma_t + \theta_i t + \varepsilon_{i,t} \quad (6)$$

where DMC represents material use in tonnes per capita, GDP is per capita real gross domestic product in PPP, γ_t are time effects to control for any year-specific events, e.g. the financial crisis, $\theta_i t$ are country-specific trends, and $\varepsilon_{i,t}$ is the idiosyncratic error term.

Countries are likely to have a different cultural and historic backgrounds, economic development paths, institutional quality, material policies, and other country-specific trends which might influence the time pattern of material use and GDP (Bahn-Walkowiak and Steger 2015). As discussed above, by taking the first difference of Eq (6) country-specific trends are eliminated therefore reducing the risk of spurious regressions. Thus, the main model is specified as follows.

$$\Delta DMC_{i,t} = \pi' \, \Delta GDP_{i,t-1} + \gamma'_t + \theta'_i + \varepsilon'_{i,t} \qquad (7)$$

where γ'_t are time effects and θ'_i are country fixed effects. The first stage of the model considers the impact of storm occurrences on GDP. As mentioned above, storms are lagged twice in order to comply with the exclusion restriction. The first stage of the model is specified as.

$$\Delta GDP_{i,t-1} = \zeta \, \Delta storms_{i,t-2} + \epsilon_t + \eta_i + \phi_{i,t} \qquad (8)$$

where ϵ_t are time effects, η_i are country fixed effects, $storms_{i,t-2}$ are the number of storm occurrences, and $\phi_{i,t}$ is the idiosyncratic error term. Eqs (7) and (8) are estimated using 2SLS with standard errors clustered over countries. All data are in natural logarithm.[11]

6.3 Data

Materials are usable substances obtained or derived from natural resources and consist of biomass, metals, minerals, and fossil fuels (Eurostat, 2013; OECD, 2007). Data on DMC is considered in tonnes per capita for 32 European countries between 2000 and 2014, extracted from Eurostat. DMC is the only measure of material use with publically available data which is directly comparable across the sample (EC 2015h). For economic activity, real GDP in Euro (in PPP) per capita is extracted from Eurostat. For RMC, data for the EU-28 countries between 2000-2012 are being approximated following the methodology in EC (2014c) and described in detail in Chapter 5.

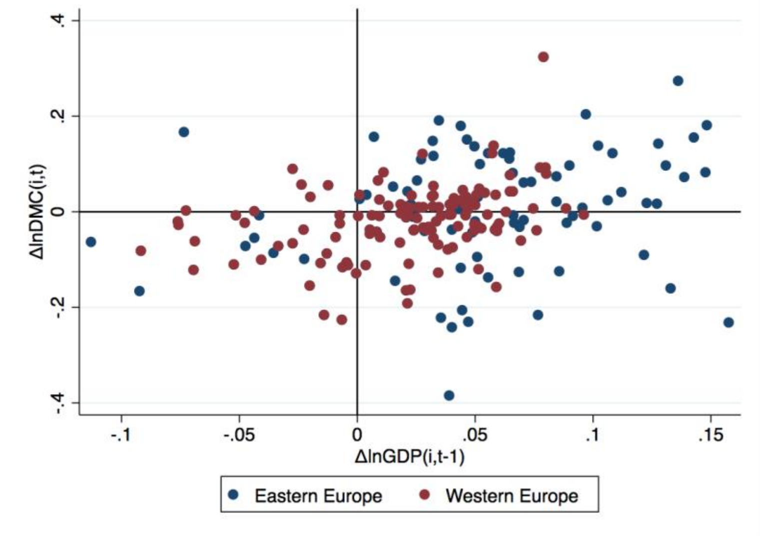
Figure 14 displays the observations used in the main model, Eq (7), of the estimation. Western and Eastern European countries are considered separately because they were exposed to different political and economic systems in the recent past. An overview of the country groupings is shown in Table A1 in the Appendix. There is no universally agreed definition of Western Europe. Western Europe is considered to be those countries that neither have been part of the Soviet Union nor Yugoslavia, as those countries have not been integrated into the free-market economies of the West. Turkey is considered part of East Europe. Finland, Malta,

[11] In the case of the number of storm occurrences, the natural logarithm is taken after adding one to avoid missing values caused by this transformation.

and Cyprus are considered more closely connected to the Western European economies, in particular during the sample period, and it is acknowledged that Malta and Cyprus have strong historic links to the United Kingdom.

As an instrument, the number of storm occurrences is used from the EM-DAT database. This database, which is maintained by the Centre for Research on the Epidemiology of Disasters at the Université Catholique de Louvain in Belgium, contains information on more than 18,000 extreme weather events and accidents. Data is collected from the United Nations, non-governmental organisations, insurance companies, and research institutes. Storms are included in the database if at least one of the following criteria applies: (i) ten or more people reported killed, (ii) hundred or more people reported affected, (iii) declaration of a state of emergency, or (iv) call for international assistance.

Figure 14: Relationship between GDP and DMC for Western and Eastern Europe between 2000-2014.



The existing data is complemented by 'recovering' several observations. If a country in a given year has reported any disasters other than storms, it is assumed that no storms occurred in that year. Table 22 shows the main statistics for the dependent variable (DMC per capita), endogenous variable (GDP per capita), and instrument (number of storm occurrences) for the observations used in this study. It becomes apparent that Western Europe has a much higher GDP per capita, but similar levels of DMC per capita compared to Eastern Europe. The standard deviations for DMC and GDP are clearly higher in Western than Eastern Europe.

Table 22: Statistics on DMC, GDP, and the number of storm occurrences.

Group	Variable	N	Mean	Median	Std. deviation	Min	Max
Europe	DMC per capita	201	16.35	15.01	7.22	7.10	55.59
	GDP per capita	201	22,496	22,450	8,440	6,558	56,612
	Storm occurrences	166	0.63	0	0.85	0	4
Western Europe	DMC per capita	123	16.85	14.90	8.57	7.10	55.59
	GDP per capita	123	27,704	27,527	16,734	16,734	56,612
	Storm occurrences	105	0.74	1	0.90	0	4
Eastern Europe	DMC per capita	78	15.56	15.35	4.24	8.46	31.31
	GDP per capita	78	14,282	13,910	3,970	6,558	22,545
	Storm occurrences	61	0.43	0	0.72	0	3

6.4 Results

6.4.1 First stage results

Starting with the first stage model, Eq (8), the relationship between storms and GDP is estimated. As indicated in Table 23, the results show a negative and statistically significant association between changes in the number of storms and the GDP growth rate for all three groups of countries. Those results support the literature advocating that disasters have a negative impact on economic activity (Hochrainer 2009; Raddatz 2009; Hsiang and Jina 2014; DuPont et al. 2015). The impact of changes in storm occurrences on the GDP growth rate is lower in Western Europe compared to Eastern Europe, suggesting that the Western European economies can cope with storms more efficiently.

Table 23: First stage results for Europe, Western Europe, and Eastern Europe between 2000-2014.

	Europe	Western Europe	Eastern Europe
$\Delta ln(storms_{i,t-2})$	-0.014***	-0.011***	-0.018***
	(0.003)	(0.003)	(0.005)
Kleibergen-Paap rk Wald F statistic (weak id)	27.94	20.04	14.71
Kleibergen-Paap rk LM statistic, p-value (under id)	0.0016	0.0113	0.0424

Notes. Dependent variable is $\Delta\ln(GDP_{i,t-1})$. Estimated with 2SLS. Country fixed and year effects are included. SEs are clustered over countries and shown in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

Using the number of storms to instrument GDP appears to be a robust instrumentation strategy. The Kleibergen-Paap Wald F statistics for all country groups is well above 10 which is a common rule of thumb for considering an instrument to be sufficiently strong (Angrist and Pischke 2009). The Kleibergen-Paap rk LM test, which assesses whether the equation is identified, i.e. that the instrument is relevant, allows to reject the null hypothesis of the equation being underidentified for all groups. All test statistics in the table are robust to heteroscedasticity and arbitrary within-correlation.

6.4.2 OLS results

The main model, Eq (7), is now estimated with OLS. As displayed in Table 24, the impact of the GDP growth rate on the DMC growth rate is positive for all three groups but insignificant for Eastern Europe. This means that no strong claims can be made about how the DMC growth rates changes in Eastern European countries, whereas the GDP growth rate across Europe and Western Europe has a positive and statistically significant impact on the DMC growth rate. The relatively low number of observations compared to the panel considered stems from the fact that using variables in first difference requires data for at least two consecutive years across all variables in the model.

6.4.3 2SLS results

The results obtained when using 2SLS are slightly different. There is no indication for a significant link between the GDP growth rate and the DMC growth rate for Europe as whole and Eastern Europe. However, the results for Western Europe indicate that a 1% increase in the GDP growth rate causes the DMC growth rate to increase by 2.7%, which is three times larger than the OLS coefficient. Thus, it could be argued that OLS is biased downwards, implying that the omitted variable bias might dominate over the reverse causality bias, because one would expect the effect of DMC on GDP to be positive, which would have lead OLS to be upwards biased. However, the median value of the OLS results for Western Europe lies within the 95% confidence interval of the 2SLS result.

Table 24: OLS and second stage results for Europe, Western Europe, and Eastern Europe between 2000-2014.

	Europe		Western Europe		Eastern Europe	
	OLS	2SLS	OLS	2SLS	OLS	2SLS
$\boldsymbol{\Delta ln(GDP_{i,t-1})}$	0.545**	0.986	0.900***	2.662***	0.298	-1.328
	(0.238)	(0.947)	(0.185)	(0.919)	(0.241)	(0.996)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
within R^2	0.37	0.36	0.40	0.10	0.28	0.40
N	201	196	123	119	195	77

Notes. Dependent variable is $\Delta\ln(DMC_{i,t})$. Estimated with OLS and 2SLS. SEs are clustered over countries and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

At first sight, the 2SLS results are in disagreement with previous findings. For instance, investigations conducted by the G7 conclude that "for every 1% increase in GDP, raw material use has risen by 0.4%" (G7 2015b). Bringezu et al. (2004) find that GDP increases material use (measured as DMI) by approximately 0.6 to 0.8 tonnes per $1,000. Wiedmann et al. (2013) find that the elasticity of DMC with respect to GDP is around 0.15. Interestingly, these results are somewhat similar magnitudes for Europe and Western Europe using the OLS model.

However, the models are estimated in first difference whereas previous results are based on models in levels, thus a direct comparison is not possible. Other studies have found that most European countries, in particular Western Europe, supposedly have broken the link between material use and economic activity, at least in relative terms (Bringezu and Schütz 2001; Moll et al. 2005; Voet et al. 2005b). The 2SLS estimations provide new evidence casting doubt on claims that seem to be accepted by policymakers and international organisations (Ecorys 2011; OECD 2011b; BMUB 2016).

6.4.4 Country heterogeneity

So far, the results have been presented by considering the average of 32 European countries or within two groups of countries. It seems appropriate to investigate the heterogeneity across countries in greater detail. Table 25 shows the results for explicitly estimating the country fixed effects for the three groups. Two interesting aspects become visible.

1) ***Country heterogeneity is important:*** Most countries are significantly different compared to the reference countries, i.e. Belgium for Europe and Western Europe, and Turkey for Eastern Europe. This is in line with previous findings of country heterogeneity in the literature (Pothen and Schymura 2015). The effect between the GDP growth rate and the DMC growth rate for most countries is lower compared to the reference countries.

   In particular Luxembourg and Norway appear to have a much lower effect. While a more detailed analysis goes beyond the scope of this chapter, this could suggest that these very high-income countries do not invest their additional income in material-intensive goods but rather in financial or business services, confirming recent trends evaluated by the International Monetary Fund (IMF 2016; IMF 2017b).

Table 25: Country heterogeneity.

	Europe	Western Europe	Eastern Europe
$\Delta ln(GDP_{i,t-1})$	0.986	2.662***	-1.328
	(0.947)	(0.919)	(0.996)
Year FE	Yes	Yes	Yes
Belgium	*reference*	*reference*	
Bulgaria	-0.020		0.006
Czech Republic	-0.028***		-0.090***
Denmark	-0.033***	-0.022	
Germany	-0.011	-0.022***	
Estonia	-0.111***		-0.151***
Ireland	-0.027	-0.064***	
Greece	-0.010	0.011	
Spain	-0.067***	-0.058***	
France	-0.013***	-0.006	
Croatia	-0.043**		-0.076***
Italy	-0.037***	-0.014	
Cyprus	0.007	-0.037	
Latvia	-0.166**		-0.105**
Lithuania	-0.164***		-0.125***
Luxembourg	-0.121***	-0.164***	
Hungary	-0.020		-0.075***
Malta	-0.085***	-0.108***	
Netherlands	-0.004	0.007	
Austria	-0.005	-0.005	
Poland	-0.008		-0.008
Portugal	-0.023***	-0.026***	
Romania	-0.004		0.066**
Slovenia	0.069***		-0.010
Slovakia	-0.035		-0.020**
Finland	-0.006	-0.022	
Sweden	0.021	-0.014	
United Kingdom	-0.021***	-0.013***	
Norway	-0.078	-0.177***	
Switzerland	-0.005	-0.026**	
Serbia	-0.050		-0.003
Turkey	-0.001		*reference*
R^2	0.46	0.25	0.47
N	201	123	78

Notes. Dependent variable is $\Delta ln(DMC_{i,t})$. Estimated with 2SLS. SEs are clustered over countries and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

2) ***Country specifics:*** Some countries are different for Europe and their respective country group such as the Czech Republic, Estonia, Croatia, Latvia, Lithuania, Luxembourg, Malta, Portugal, and the United Kingdom, while other countries are

only statistically different within their subgroups such as Germany, Ireland, Hungary, Romania, Slovakia, Norway, and Switzerland. Most notably, France and Italy are two countries that differ within the European but not within the Western European country group. This suggests that country-specific circumstances are likely to drive such differences.

Most importantly, this brief investigation reveals that the average effect for all three groups is subject to country heterogeneity, thus providing evidence for the importance of country-specific approaches when considering policies to decouple material use from economic growth. To some extent, this is already common practice in Europe since natural resource policies as well as tax policies lies within the competences of the countries themselves (and not on the EU level) and are considered important instruments in the decoupling debate (Bahn-Walkowiak et al. 2012; EU 2017). An overview of the heterogeneity of material policies in Europe on the country level is summarised by Bahn-Walkowiak and Steger (2015). More generally, country or local-specific approaches have gained increasing traction in the last years (OECD 2015c).

6.4.5 Material subgroups

After considering DMC on an aggregated level, Table 26 disaggregates the estimates of changes in the GDP growth rate on the DMC indicator in its four material subgroups. The results for Western Europe indicate that increases in the GDP growth rate mainly lead to an increase in biomass and mineral use. The significant result for Eastern Europe is likely to be misleading since the number of observations is severely reduced.

These results provide evidence that income increases in Western Europe cause biomass and mineral use to increase. The results are in line with previous findings suggesting that mineral use is correlated with income on the global level (Steinberger et al. 2010). The increased mineral use could be an indication that countries that increase their income tend to modernise and further extend their (existing) infrastructure, incentivise real-estate development, and expand their low-carbon mobility possibilities (Esfahani and Ramirez 2003). For instance, the average number of rooms per capita in Western Europe has increased by 8.5% between 2000-2014, and the European Investment Bank, the largest infrastructure financer in Europe, has invested €613 billion in Western Europe between 2000-2014 (Eurostat 2017), both developments are consistent with these results.

The reasons for an increased biomass are not immediately obvious. Changes in energy policies could substitute fossil fuel-based consumption towards biomass-based forms of energy, for instance biofuels (IEA 2010). However, the increase in biomass could also simply be the result of increased food production, as higher incomes allow consumers to purchase more biomass-intensive food products such as meat as well as non-seasonal fruits and vegetables (Schroeder et al. 1996; UNEP IRP 2010a). Furthermore, additional income could be re-distributed to agricultural subsidies which has led to an increase in the total factor productivity of farms in all Western European countries that are part of the EU-15 (except Greece) between 2000-2008 (Rizov et al. 2013).

Table 26: Second stage results for Europe, Western Europe, and Eastern Europe for material subgroups.

	Europe				Western Europe				Eastern Europe			
	Biomass	Minerals	Metals	Fossil	Biomass	Minerals	Metals	Fossil	Biomass	Minerals	Metals	Fossil
$\boldsymbol{\Delta ln(GDP_{i,t-1})}$	1.91	1.27	1.91	-0.16	2.89**	3.51**	11.07	0.85	-1.10	-2.29**	-13.06	-2.05
	(1.28)	(1.78)	(4.56)	(0.94)	(1.25)	(1.63)	(6.72)	(1.02)	(0.99)	(1.04)	(9.03)	(1.53)
N	168	168	164	164	106	106	106	102	62	62	58	62

Notes. Dependent variable is $\Delta\ln(DMC_{i,t})$ for the four material subgroups: biomass, minerals, metals, and fossil fuels. Estimated with 2SLS, including country and year fixed effects. SEs are clustered over countries and shown in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

6.4.6 Raw material consumption

Instead of using DMC per capita, the approximated RMC per capita indicator is now used as the dependent variable, leaving everything else unchanged. Table 27 shows the results. Interestingly, the significant effect of the GDP growth rate on the DMC growth rate becomes insignificant when using the RMC rate. Thus, the results would indicate that an increase in the GDP growth rate does not significantly change the RMC growth rate. Unfortunately, the insignificant coefficients make it impossible to directly compare the DMC with the RMC indicator.

Since no further decomposition of material subgroups in RMC is possible, it is challenging to deepen the understanding of these results. One possibility is that a decrease in the indirect materials use, something domestic consumers have limited influence over, counterbalances the increase in the direct material use. Another explanation could be related to the method of approximating the RMC data. Since averages are used to calculate the RMC data, the variation in the RMC growth rate might simply not be sufficient to be explained by the variation in the GDP growth rate.

Table 27: OLS and second stage results for Europe, Western Europe, and Eastern Europe for RMC data.

	Europe		Western Europe		Eastern Europe	
	OLS	2SLS	OLS	2SLS	OLS	2SLS
$\Delta\ln(GDP_{i,t-1})$	0.430*	0.158	1.262**	4.443	-0.200	-4.993**
	(0.246)	(1.498)	(0.439)	(2.824)	(0.364)	(2.440)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
N	305	160	185	100	120	60

Notes. Dependent variable is $\Delta\ln(RMC_{i,t})$. Estimated with OLS and 2SLS. SEs are clustered over countries and shown in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

The negative and significant coefficient for Eastern Europe is likely to be misleading since the number of observations drops down to 60 which is insufficient to make any meaningful statements. The remaining parts of this investigation will thus focus on the DMC variable, as a significant effect of the GDP growth rate on the DMC growth rate was estimated.

6.4.7 Robustness checks

Table 28 summarises robustness checks for Europe, Western Europe, and Eastern Europe. Throughout all checks, the instrumentation remains robust. The time effects are highly significant and thus included in all estimations. The impact of excluding the country fixed effects is assessed and discovered that dropping them does not change the results significantly.

Table 28: Robustness checks for Europe, Western Europe, and Eastern Europe using 2SLS.

	(1)	(2)	(3)	(4)	(5)	(6)
	Europe	**Western Europe**	**Eastern Europe**	**Europe**	**Western Europe**	**Eastern Europe**
	excl. 2008-2010			excl. MT, LU, CY		
$\Delta ln(GDP_{i,t-1})$	1.322	2.801**	-0.408	0.861	2.368**	-1.328
	(1.062)	(1.468)	(0.994)	(0.972)	(1.090)	(0.967)
Kleibergen-Paap rk Wald	19.42	18.16	9.51	29.26	21.13	14.71
Kleibergen-Paap rk LM	0.003	0.008	0.038	0.002	0.011	0.042
N	132	85	47	190	113	77

Notes. Dependent variable is $\Delta\ln(DMC_{i,t})$. Country and year fixed effects are included. SEs are clustered over countries are shown in parentheses. Columns 1-3 exclude 2008-2010. Columns 4-6 exclude Malta, Luxembourg, and Cyprus. * p < 0.10, ** p < 0.05, *** p < 0.01.

The results' robustness and sensitivity is also tested by excluding individual countries and years. In particular, excluding the years of the financial crisis 2008-2010 (Columns 1-3) somewhat reduces the significance of the coefficient for Western Europe, but the magnitude of the coefficients is very similar. The model is estimated after excluding the smallest European countries which have a population below 1 million, i.e. Malta, Luxembourg, and Cyprus (Columns 4-6). This does not change the results significantly.

It is further investigated whether the financial crisis caused a structural break in the data, but there is no indication for a structural break in 2007 or 2008 based on visual inspection of pre and post crisis trends for each country.

As an additional robustness check, a grid search approach is conducted to test various transformations of GDP and DMC to see whether any transformation (other than natural logarithms) better explains the relationship. Considering the residual sum of squares and the value of the coefficients, results from other transformations of the variables were found to be only marginally different from the natural logarithm. Furthermore, the residuals of the estimations for Europe, Western Europe, and Eastern Europe are studied separately in order to evaluate whether the assumption of a common relationship between GDP and DMC within these three groups is reasonable. Since there are no obvious outliers visible in the residuals of the country groups, the assumption of a common relationship within these groups appears justified.

Table 29: Control variables for Europe, Western Europe, and Eastern Europe.

	Europe			Western Europe			Eastern Europe		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta ln(GDP_{i,t-1})$	1.29	1.35	1.19	2.76***	2.90***	2.88**	-1.90**	-2.00**	-1.68**
	(0.98)	(0.98)	(0.94)	(0.97)	(1.05)	(1.39)	(0.90)	(0.89)	(0.66)
$\Delta ln(labour_{i,t})$	1.54***	1.54***	1.51***	0.43	0.29	0.08	1.84***	1.80***	1.86***
	(0.41)	(0.41)	(0.45)	(0.51)	(0.48)	(0.48)	(0.49)	(0.54)	(0.54)
$\Delta ln(service_{i,t})$		-0.19	-0.19		-0.72	-1.13		0.16	0.11
		(0.22)	(0.25)		(0.95)	(0.83)		(0.34)	(0.32)
$\Delta ln(electricity_{i,t})$			-0.08			-0.16			-0.08
			(0.07)			(0.12)			(0.06)
Kleibergen-Paap rk Wald	23.98	25.88	25.88	14.77	16.26	12.74	11.54	14.11	17.77
Kleibergen-Paap rk LM	0.004	0.003	0.002	0.017	0.016	0.027	0.078	0.064	0.045
R^2	0.44	0.44	0.44	0.08	0.03	0.10	0.52	0.50	0.57
N	185	185	165	119	119	109	66	66	56

Notes. Dependent variable is $\Delta ln(DMC_{i,t})$. Estimated with 2SLS, including country and year fixed effects. SEs are clustered over countries and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

As part of the robustness checks, three variables are controlled for that are considered important drivers of DMC (Schandl and West 2010; Giljum et al. 2012; Steinberger et al. 2013).

1) ***Labour productivity:*** Real per capita labour productivity ($\Delta\ln(\text{labour}_{i,t})$) is controlled for. The data are retrieved from Eurostat. Labour productivity has a positive effect on DMC in Europe and Eastern Europe. The impact of the GDP growth rate on the DMC growth rate becomes negative and significant for Eastern Europe, which seems to be an unreliable and most of all not robust result given the large p-value of the Kleinbergen-Paap rk LM test.

2) ***Service sector:*** The service sector share of GDP ($\Delta\ln(\text{service}_{i,t})$) is controlled for. The data are retrieved from Eurostat. Although the service sector is associated with lower material use, it does not appear to have a significant impact on DMC.

3) ***Electricity prices:*** Industrial electricity prices in Euro per kWh including all taxes and levies ($\Delta\ln(\text{electricity}_{i,t})$) are controlled for, and data are retrieved from Eurostat. There is no significant relationship between electricity prices and DMC. The results are shown in Table 29. It is worth mentioning that the standard errors in Columns 4-6 are fairly similar to the ones in Table 24, confirming the robustness of the estimations.

Different types of standard errors are also evaluated, i.e. those assuming homoscedasticity and those robust to heteroscedasticity, but all give qualitatively the same results. Furthermore, the possibility of serial correlation is considered, using the approach suggested by Newey and West (1987). In Table 30, it is shown that the results are essentially unchanged when using AR(1), AR(3), and AR(5) error structures, particularly the standard errors for Western Europe are fairly similar to the ones in Table 24.

Table 30: Results assuming different autocorrelation structures.

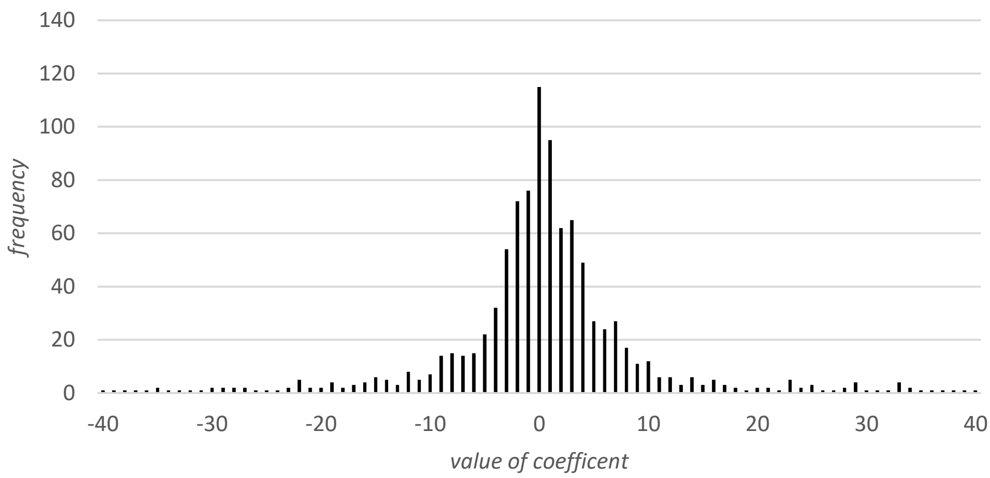
	Europe			Western Europe			Eastern Europe		
	AR(1)	AR(3)	AR(5)	AR(1)	AR(3)	AR(5)	AR(1)	AR(3)	AR(5)
$\boldsymbol{\Delta ln(GDP_{i,t-1})}$	0.986	0.986	0.986	2.662**	2.662**	2.662**	-1.328	-1.328	-1.328
	(0.950)	(0.910)	(0.990)	(1.267)	(1.034)	(1.024)	(1.695)	(1.459)	(1.381)
N	201	201	201	123	123	123	78	78	78

Notes. Dependent variable is $\Delta\ln(\text{DMC}_{i,t})$. 2SLS estimation with country and year fixed effects. Newey-West SEs are shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

So far, weak instruments were tested by showing that the Kleibergen-Paap rk Wald F statistic is sufficiently high for Western Europe. An alternative approach is to generate random variables, i.e. variables with random values, but with the same mean and standard deviation as the instrument and use these variables with the same statistical properties as the instrument to estimate the model by 'placebo' 2SLS regressions. If the results were similar to those displayed in Table 24, the instrument could be questioned (Bound et al. 1995).

Therefore, 1,000 'placebo' 2SLS regressions are run to estimate the model with random variables which have the same statistical properties as the 'real' instruments. The second stage coefficients π_1' are shown in Figure 15 and

Figure 15: 'Pseudo' 1,000 2SLS regressions for Europe.



Notes: To increase readability, the range has been limited to -40 and 40, thereby excluding 29 coefficients.

Table 31: 'Pseudo' regression statistics for Europe.

	π_1' from Eq (7)
Mean	1.09
Std. dev.	112.53
Median	0.34
5th percentile	-19.37
95th percentile	19.39

Notes. Statistics of 1,000 π_1' coefficients of 'pseudo' 2SLS regressions. Model is from Eq (7).

Table 31 for Europe. The results for Western Europe are shown in Figure A1 and Table A2 and for Eastern Europe in Figure A2 and Table A3 in the Appendix. As expected, the median, and to a lesser extend the mean values, are similar to the OLS coefficients in Table 24, but they are imprecisely estimated. In short, the instrument passes the non-robustness test proposed by Bound et al. (1995).

6.5 Discussion

The results suggest that increasing the GDP growth rate causes an increase in the DMC growth rate for Western European countries, while there is no indication for an effect on the DMC growth for Eastern Europe. Therefore, a potential difference between Western and Eastern Europe can be explored further using statistical methods.

This section descriptively explores if substitution and complementarity across input factors is consistent with the potential difference between the two groups. It has sometimes been claimed that energy and materials are complements (Nordic Council of Ministers 2001; Hannon 2013), while labour and materials are substitutes (Bruyn et al. 2009; Allwood et al. 2011; Bleischwitz 2012).

Table 32: Energy prices and labour costs in Western and Eastern Europe.

		2000	2004	2008	2012
Electricity prices	*Western Europe*	63.29	77.47	114.91	131.90
Industry | in MWh	*Eastern Europe*	113.74	135.03	172.07	199.90
Gasoline prices	*Western Europe*	1.12	1.18	1.58	2.01
in litres	*Eastern Europe*	2.00	1.96	2.12	2.85
Natural gas prices	*Western Europe*	17.25	20.73	40.26	46.75
Industry | in MWh	*Eastern Europe*	27.93	35.67	64.84	76.51
Labour costs	*Western Europe*	24.28	21.38	21.03	26.93
per hour	*Eastern Europe*	9.51	8.93	10.39	13.23

Notes. Energy prices and labour costs, PPP-adjusted. Sources. Eurostat, World Bank, IEA.

In Table 32, energy prices and labour costs are shown for Western and Eastern European countries. Energy prices are PPP-adjusted and include taxes and levies; the arithmetic average of 21 European countries[12] for the years 2000, 2004, 2008, and 2012 from the IEA is shown. It

[12] Out of the 21 European countries, 15 are Western European (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom) and 6 are Eastern European countries (Czech Republic, Estonia, Hungary, Poland, Slovak Republic, and Slovenia).

is clear that energy prices are lower in the Western Europe compared to Eastern European countries. Given complementarity between energy and materials, lower energy prices in Western Europe are consistent with, *ceteris paribus*, a higher demand for materials in Western Europe.

Table 32 also compares labour costs in Western and Eastern European countries by using data on total average hourly labour costs in Euros, i.e. including social security contributions, taxes, and subsidies. The data show the arithmetic means of 28 European countries[13] for the years 2000, 2004, 2008, and 2012 (from Eurostat). Labour costs are PPP-adjusted using the price level ratio of PPP conversion factors from the World Bank. Labour costs in Western Europe are more than double the costs in Eastern European countries. Therefore, given substitutability between labour and materials, the demand for materials in the Western Europe is likely to be higher than demand in Eastern Europe, thus being consistent with the significant link between an increase in the GDP growth rate and the DMC growth rate.

6.6 Conclusions

The aim of this analysis is to determine the causal impact of economic growth on material use in Europe. A number of academic studies have advocated for the use of material and footprint indicators, arguing that they better represent environmental pressures compared to single pressure indicators such as GHG emissions (Alfsen and Sæbø 1993; Bringezu et al. 2003; Ibenholt 2003; Voet et al. 2005b; UNEP IRP 2010a; Bleischwitz 2010; Hoang and Alauddin 2012; Bouwmeester and Oosterhaven 2013; Wiedmann et al. 2013b; Teixidó-Figueras and Duro 2015). In addition, a number of recent policy initiatives have adopted material indicators and the associated environmental pressures (EC 2008; EC 2010a; EC 2011b). The previous chapter has shown that material use triggers GHG emissions in Europe.

The empirical literature investigating the link between economic growth and material use has not convincingly dealt with the endogeneity of GDP as well as the heterogeneity across countries, material subgroups, and material indicators – all of which is the focus of this chapter. This chapter provides new evidence for a causal and positive impact of the GDP growth rate on the DMC growth rate for Western European economies, using the number of storm occurrences as an instrument for GDP. OLS, which has been used in the previous literature, is likely to underestimates that relationship. In the case of Eastern Europe and Europe as a whole,

[13] All countries in Table A1 in the Appendix are considered with the exception of Norway, Switzerland, Serbia, and Turkey.

this study does not provide any evidence contrary to the general belief that material use has decoupled from economic growth.

However, in the case of Western Europe, the results contradict previous studies and the current wisdom among policy circles, suggesting that Western European countries have indeed broken the link between material use and economic growth (Bringezu and Schütz 2001; Moll et al. 2005; Voet et al. 2005b). Thus, new evidence is presented that the impact between the two variables is likely to exist and to be higher than previously thought.

A more disaggregated analysis shows that minerals and biomass materials are the main material subgroups affected by increases in the GDP growth rate for Western Europe. While a more detailed analysis is required, this suggests that infrastructure investments and an increase in food production might be the result of the increased income growth. Furthermore, this study shows that there is significant heterogeneity across countries, indicating the need for country-specific policy approaches. Moreover, the effect becomes insignificant when RMC data are used.

Two potential explanations are offered that are consistent with the findings of this chapter. First, energy prices are lower in Western Europe compared to Eastern European countries, suggesting that material demand has increased in Western Europe due to the complementary between energy and materials. Second, the labour costs in Western Europe are higher compared to Eastern European countries. This indicates that labour might have been substituted by materials (e.g. by increasing the service sector).

These results are important from a policy perspective since they imply that more effective policy interventions are necessary to break the link between material use and economic growth, in particular in Western European economies. As such, these findings put in question the effectiveness of current policies to decouple material use from economic growth.

This chapter complemented by the findings from the previous chapter suggest that material use is driven by economic growth (in Western Europe) and increases GHG emissions in the short and long term. This emphasises the importance of alternating the way economic growth is being generated, as the current economic model relies on an ever-increasing use of those materials that are associated with GHG emissions. Thus, the following two chapters investigate whether higher levels of productivity with which materials are converted to economic activity can increase competitiveness and reduce GHG emissions, thus reconciling these two important topics.

Chapter 7

The Causal Impact of Material Productivity on Macroeconomic Competitiveness and GHG Emissions in the European Union

An abridged version of this chapter is published as

Flachenecker, Florian (2018). The causal impact of material productivity on macroeconomic competitiveness in the European Union. *Environmental Economics and Policy Studies* 20:1. 17-46.

7 The causal impact of material productivity on macroeconomic competitiveness and GHG emissions in the European Union

7.1 Introduction

After having investigated the effects of material use in GHG emissions (Chapter 5) and the effects of economic growth on material use (Chapter 6), the next two chapters consider material productivity. In particular, the effects of material productivity on competitiveness and climate change mitigation efforts in the EU will be studied, both on the macroeconomic and microeconomic level. Following the discussions in Chapters 2 and 3, the relationship between material productivity and competitiveness as well as GHG emissions (and other environmental pressures) has been an explicit policy objective for some time: "Reducing the amount of energy and materials used per unit in the production of goods and services can contribute both to the alleviation of environmental stress and to greater economic and industrial productivity and competitiveness." (UN 1992).

Since then, the notion that increasing material productivity improves competitiveness while reducing environmental pressures, is at the centre stage of contemporary resource efficiency, circular economy, and raw materials policies in the EU (EC 2008; 2011; 2015a). In particular, the environmental benefits from reducing material use and improving material productivity are reflected in a broad literature in industrial ecology (Voet et al. 2005a; Kagawa et al. 2014; Wei et al. 2015) and environmental economics (Tietenberg 2000; Nakano and Managi 2012).

Discussions on material productivity also feed into the recent attempt to better understand and ultimately overcome what is often referred to as the 'productivity puzzle', i.e. the fact that productivity growth across the developed world has essentially been stagnant since the Great Recession (Blundell et al. 2014; Patterson et al. 2016; Harris and Moffat 2017). While the exact reasons underlying this puzzling development are still unclear, the research conducted across the following two chapters investigates whether material productivity can contribute to competitiveness increases, thus potentially completing the discussions on labour productivity to material productivity as a source for future productivity growth.

The interdisciplinary literature provides evidence that increasing material productivity improves competitiveness (e.g. Bleischwitz et al. 2007; Bleischwitz and Steger 2009; Schröter et al. 2011; Bassi et al. 2012), relevant macroeconomic indicators (e.g. Distelkamp et al. 2010; Walz 2011; Meyer et al. 2011), and reduces environmental pressures, including GHG emissions (e.g. Barrett and Scott 2012; Meyer et al. 2016; Schandl et al. 2016; UNEP IRP 2017).

However, there are three limitations in the current literature. First, there is mostly no in-depth discussion and clarity about the concept and measurement of competitiveness on the macroeconomic level. Second, the majority of empirical studies do not take the endogeneity of material productivity into account. Third, the majority of investigations do not explicitly focus on heterogeneity across countries or material indicators. Such shortcomings are particularly relevant, as major financial resources as well as policy efforts are dedicated to material productivity improvements and partly motivated by these findings (EC 2014g; OECD 2016; UNEP IRP 2016).

This analysis first briefly reviews the concept of macroeconomic competitiveness (based on the in-depth review in Chapter 3). Following this discussion, six conventional macroeconomic indicators are identified to approximate it, acknowledging that no optimal measure for macroeconomic competitiveness exists. Second, using a panel data set for the EU's 28 member states between 2000 and 2014, the causal impact of material productivity on each of the six indicators is estimated. Material productivity is instrumented with the number of deaths from natural hazards which is shown to be both relevant and valid.

The results suggest that increasing the material productivity growth rate causes (i) the wage growth rate to increase, (ii) with lower confidence, the current account growth rate to improve, while the other competitiveness indicators are insignificantly affected, and (iii) no statistically significant effect on GHG emissions. The causal impact on the wage rate is robust and relevant, raising the question whether higher wages increase or decrease competitiveness. The results are tested against country heterogeneity and the alternative material indicator RMC. Additionally, this chapter discusses policy options to reduce the magnitude of potential rebound effects and thus GHG emissions. Overall, these findings call for more caution when making the claim that increasing material productivity improves macroeconomic competitiveness and reduces GHG emissions in the EU on the country level.

The chapter is structured as follows. Section 7.2 briefly summarises the literature on macroeconomic competitiveness and material productivity based on Chapter 3. Section 7.3 describes the modelling approach and instrumentation strategy in detail. Section 7.4 introduces the data, Section 7.5 outlines the results, Section 7.6 considers the effect of material productivity on GHG emissions, Section 7.7 discusses the findings, and Section 7.8 concludes.

7.2 Macroeconomic competitiveness and material productivity

7.2.1 Macroeconomic competitiveness

There is no commonly agreed definition on macroeconomic competitiveness. Nevertheless, by briefly re-iterating four approaches to competitiveness, the concept is evaluated and six conventional macroeconomic indicators are identified to approximate it.

1) ***Krugman's critique:*** In two seminal papers, Krugman (1994; 1996) questions whether the concept of macroeconomic competitiveness is at all relevant by bringing forward three arguments. First, countries, unlike firms, do not compete with each other on markets because they predominantly produce public goods. Additionally, countries cannot go out of business (only default) and, on average, mutually benefit from exchange. Second, if the aim is to raise the standard of living, competitiveness is essentially achieved by productivity growth. Hence, defining productivity growth as competitiveness is misleading. Third, the author warns against protectionist tendencies since proponents of competitiveness may favour imposing trade restrictions to safeguard their country from competitors.

   However, Krugman (1996) acknowledges that competitiveness has some merit outside standard models: "[…] people who talk about competitiveness must understand the basics [of trade theory] and have in mind some sophisticated departure from standard economic models, involving imperfect competition, external economies, or both." Therefore, proponents of macroeconomic competitiveness typically refer to any types of market failures to justify their understanding of competitiveness (Reinert 1995; Budzinski 2007; Fagerberg et al. 2007). In a nutshell, the concept of macroeconomic competitiveness becomes a relevant concept according to Krugman (1996) once market failures are present.

2) ***Price competitiveness****:* Among economists and policymakers, macroeconomic competitiveness is frequently measured by standard cost and trade indicators, including unit labour costs, the real effective exchange rate, interest rates, and the current account (Siggel 2006). The rationale is that competition plays out on prices, essentially resulting in offshoring production and employment from high-cost to low-cost economies (Acemoglu et al. 2016). In order for high-cost countries to remain competitive, they need to reduce costs (Salvatore 2010).

However, Porter (1990) argues that such measures focusing on costs are insufficient to explain a competitive advantage. For instance, a fall in wages or the exchange rate does not make a country more competitive if competitiveness is defined as raising the standard of living (Snowdon and Stonehouse 2006). Accordingly, 'price competitiveness' is a reasonable measure in perfectly competitive markets and for low-income countries since they are competing along homogeneous goods, but not in imperfect markets and high-income countries, as they typically compete along innovations, qualities as well as environmentally sustainable and socially inclusive growth (Rozmahel et al. 2014).

Consequently, price measures are important in determining competitiveness, but are insufficient and potentially misleading if they are not complemented by non-price indicators, comprising outcome measures (e.g. GDP per capita, employment, wages) and process measures (e.g. institutions, technology) (Aiginger 2006).

3) ***Porter's diamond:*** Porter (1990) argues that competitiveness can only be realised by firms through continuous innovation and upgrading. This approach essentially argues that only firms compete with each other, but the country's environment is an important factor for firm's success. In short, microeconomic and macroeconomic factors combined determine competitiveness (Thompson 2004). Porter (1990) calls these the "diamond of national competitiveness" which comprises interrelated factors that together explain competitiveness on the macroeconomic level. Hence, competitiveness is essentially about setting the business and legal environment in which firms can compete.

4) ***Institutions:*** The consensus in the literature seems to be that institutions directly or indirectly establish constraints to the economic system, thus shaping the 'rules of the game'. According to Caplin and Nalebuff (1997), institutions have an impact on their environment by shaping the formal, informal, internal, and external setting in which firms operate, i.e. institutions are a determinant of competitiveness. As such, institutions are thought to support factor accumulation, innovation, the efficiency of resource allocation, and thus affecting economic growth and development (de Soto 2003; Lee 2010). Furthermore, institutions can incentivise the spread of knowledge by influencing its content, direction, and dynamic (Vanberg and Kerber 1994) which is at the core of Schumpeterian competition (Budzinski 2007). In short, institutions play an important role in the competitiveness debate since they shape the environment in

which firms operate, both internally and externally (Bleischwitz 2003; Bleischwitz 2010).

Considering these four approaches, the following understanding is identified to best approximate macroeconomic competitiveness. First, the existence of market failures is a necessary condition for macroeconomic competitiveness. Second, price measures need to be complemented by non-price factors. Third, country level indicators need to be linked with firm or sector level measures. Fourth, competitiveness is about generating welfare. Fifth, institutions shape the environment in which competitiveness plays out.

Accordingly and following Dechezleprêtre and Sato (2014), six indicators are chosen to approximate the various understandings of macroeconomic competitiveness: (i) GDP per capita, (ii) the unemployment rate, and (iii) wages per capita, because all three reflect the ability of an economy to generate welfare. Furthermore, (iv) R&D investments is identified since it refers to Porter's concept of continuous innovation and upgrading on the microeconomic level. Moreover, (v) the current account is chosen as one indicator representing a conventional price measure, and (vi) the Global Competitiveness Index from the World Economic Forum is identified as emphasising the role of institutions as well as microeconomic factors as determinants of competitiveness.

While these six indicators are argued to approximate macroeconomic competitiveness, it has to be acknowledged that no optimal measure (or set of measures) exists. Thus, this analysis brings forward one possible set of indicators based on reviewing the literature, without claiming to capture all aspects of it. However, it should be noted that the subsequent analysis has also been performed on additional indicators (i.e. exports per capita, exports of high-technology goods and services per capita, CO_2 emissions per capita, a price competitiveness measure from the European Central Bank, patent application per capita, foreign direct investments, and labour productivity) finding no significant effect of material productivity on those indicators.

7.2.2 Material productivity

As mentioned previously, productivity is typically represented as the ratio between the output of a production process and its inputs (OECD 2007). Material productivity can be expressed as follows.

$$MP_{t,i} = \frac{Y_{t,i}}{M_{t,i}} \tag{9}$$

where *Y* represents output, *M* material input or material use ($M_{t,i} > 0$), *t* the time dimension, and *i* the level dimension (country).

7.3 Modelling approach

7.3.1 The problem of endogeneity

There are three sources of endogeneity – omitted variable bias, simultaneity, and measurement errors. The latter can be problematic if there are additive random errors. Since the EU has established monitoring and reporting authorities, any time-invariant and arbitrary measurement errors are unlikely to occur. But even if measurement errors exist in the sample, 2SLS would address this problem provided that the instrument is uncorrelated with the error term (Angrist and Krueger 2001).

The second source of endogeneity is omitted variable bias. Without controlling for all possible factors that influence competitiveness, the coefficients can become biased. 2SLS can be a viable solution to this problem, even if the possible variables causing the bias are unknown. This is because the instrument only considers the part of the variation in the endogenous variable that is uncorrelated with the omitted variables, assuming that the instrument is indeed exogenous (Angrist and Krueger 2001).

The third source of endogeneity is simultaneity, which will be the focus of this analysis. Even though increasing material productivity is argued to improve competitiveness,[14] competitiveness in turn is likely to affect material productivity, as more competitive countries are more likely to be more material productive (Bringezu et al. 2004). This is because they are technologically further advanced and they generate more (eco-)innovations which increase

[14] Bleischwitz and Steger (2009) find a positive and significant correlation between material productivity and several competitiveness indices. An investigation on the savings potential of increasing material efficiency in SMEs in Germany suggests that the average savings are in the order of 7–8% (Fh-ISI et al. 2005; Schröter et al. 2011). This positive link between material productivity and competitiveness is also reflected in related studies on energy efficiency (UNIDO 2011; EC 2014d) and resource efficiency (Oakdene Hollins 2011; OECD 2011a; Bassi et al. 2012; AMEC and Bio IS 2013). Material productivity is argued to improve the macroeconomic environment. Scholars find evidence that material productivity increases GDP (Distelkamp et al. 2010; Meyer et al. 2011; EC 2014e), employment (Distelkamp et al. 2010; Meyer 2011; Walz 2011; Meyer et al. 2011; EC 2014e; Cooper et al. 2016), and total factor productivity (Ecorys 2011), while reducing public debt (Distelkamp et al. 2010; Meyer et al. 2011), and absolute material consumption (Distelkamp et al. 2010; Meyer et al. 2011). Material productivity also leads to more environmentally sustainable economies (Zhang and London 2013; Aiginger and Vogel 2015). A related analysis shows that better energy or environmental performance improves the export activity of industries (Sakamoto and Managi 2017). Whether there is a causal impact of increasing material productivity on competitiveness has not yet been researched, notwithstanding initial attempts (Flachenecker 2015b).

material productivity (Bleischwitz et al. 2007). Additionally, the following outlines the rationale for simultaneity for each competitiveness indicator individually.

1) ***Economic growth:*** Material productivity is argued to have a positive impact on economic growth (Walz 2011; Meyer et al. 2011; Cooper et al. 2016), while growth endogenously determines material productivity.
2) ***(Un)employment:*** Material productivity is found to positively affect employment (Walz 2011; Meyer et al. 2011; Cooper et al. 2016). High employment figures positively affect economic growth through the production function of an economy and material use by increased disposable income for purchasing material-intensive goods.
3) ***Wages:*** Disposable income is closely related to wages, which determine the cost of labour and thus the use of materials, as labour and materials are argued to be substitutes (Bruyn et al. 2009; Allwood et al. 2011; Bleischwitz 2012). Additionally, wages are considered to impact economic growth and trade (Cahuc and Michel 1996; Askenazy 2003). While there is no evidence so far that material productivity has an effect on wages, according to conventional theory, labour productivity determines wages (Millea 2002).
4) ***R&D investments:*** In the case of R&D, some economic models predict increasing material productivity triggers investments in R&D, especially in eco-innovations (Meyer 2011). At the same time, R&D efforts can result in increased material productivity (Eco-Innovation Observatory 2012).
5) ***Current account:*** Material and energy productivity are thought to have a positive impact on trade and thus indirectly on the current account (UNIDO 2011), while trade and the current account endogenously determine material productivity, both through general trade (as part of GDP) and the trade of materials (as part of material use).
6) ***Global Competitiveness Index (GCI):*** Material productivity is correlated with composite competitiveness indicators such as the GCI (Bleischwitz et al. 2009b), however, the direction of a causal effect is unclear. Therefore, this chapter will investigate whether there is a causal effect of material productivity on the GCI.

All such reverse effects could be highly problematic, because the coefficients of correlation and simple regression analyses can become biased and inconsistent (Angrist and Pischke 2009). Thus, 2SLS is used addressing all three sources of endogeneity (Angrist and Krueger 2001). Alternative methods such as testing for causality (e.g. co-integration testing), using lagged endogenous variables, or dynamic panel approaches either identify predictive causality or potentially violate the exclusion restriction (Kraay 2012; Panizza and Presbitero 2014).

7.3.2 Instrumentation strategy

Instruments have to comply with two conditions – they need to be relevant and valid. The former essentially requires a strong correlation between the instrument and the endogenous variable. The impact of natural hazards on material productivity can occur both through changes in output and material use. The great majority of the literature argues that disasters reduce economic activity due to damages to the capital stock and other disruptions in the immediate aftermath of the disaster (e.g. electricity cuts, transportation disruptions, business interruptions) as well as in long term (e.g. crowding-out investments, migration, welfare transfers) (Hochrainer 2009; Raddatz 2009; Hsiang and Jina 2014; DuPont et al. 2015; Thieken et al. 2016). Material use is likely to be positively affected by disasters as a result of reconstruction efforts, which might take place right after the disaster struck or with a delay.

The impact of such disasters on material productivity can be exemplified by the heat wave in Europe in 2003. Many European countries were hit by an unusually severe heat wave in July/August that year, causing a total of more than 70,000 (premature) deaths across 16 countries (Robine et al. 2008). The heat wave had substantial economic consequences relevant for both output and material use, e.g. river transportation was restricted because of low water levels, electricity production was reduced since nuclear power plants had to shut down, public rail transportation was disrupted, construction efforts were paused and later caught up, and total agriculture production decreased by approximately 10% (Ciais et al. 2005). The number of deaths during 2003 was unprecedented and concentrated mainly in Italy, France, Spain, Germany, Belgium, and Portugal. While this is an extreme example, every country in the sample experiences deaths from natural hazards across time from different disasters.

Disasters have previously been used as instruments for economic variables such as trade, aid inflows, economic growth, and oil income (Ramsay 2011; Felbermayr and Gröschl 2013; Jackson 2014; Agnolucci et al. 2017) but not for any productivity measure. 'Natural' disasters occur exogenously, and it is unlikely that an economy's sensitiveness to disasters changes in the short run (World Bank and UN 2010).

However, since panel data is used that spans over 15 years, controls for improvements in the resistance to disasters over time are needed. Kahn (2005) finds that the general level of economic development, institutional quality, and geography affect the consequences of natural hazards. Therefore, country-specific trends are added, and the model is estimated in first-difference, which remove stable transitory developments as well as the impact of time-invariant features, including economic development and institutional quality.

Since a fixed effects model is estimated in first difference, the instrument needs to vary over time. The number of deaths from natural hazards is chosen to instrument for material productivity since the variable varies, both across countries and time. Since this variable covers a variety of disasters (floods, storms, droughts etc.), they are likely to occur in various parts of each country, thus reducing the possibility that re-occurring events systematically alter the effect on material productivity (e.g. local adaptation measures).

Additionally, the number of deaths allows not only to consider the event itself but also its magnitude, unlike the instrument used in Chapter 6. This comes at the expense of a possible imprecision of reporting the exact number of deaths caused by a disaster – again, a trade-off. However, this problem is limited in the sample since all EU countries are industrialised economies with established monitoring authorities and reporting requirements. Additionally, EU countries have an incentive to report disasters since they become eligible to emergency and prevention funding from the EU's Solidarity Fund and the Civil Protection Mechanism. At the same time, over-reporting is unlikely to be an issue given reporting control mechanisms and public scrutiny when it comes to deaths.

An instrument also needs to be valid. Labour productivity (real labour productivity per capita sourced from Eurostat), capital investments (gross capital formation as percentage of GDP from the World Bank), patents (patent applications to the European Patent Office per million inhabitants from Eurostat), and the labour force (the share of the active to total population between 15 and 64 years from Eurostat) are identified as relevant factors that could invalidate the exclusion restriction for the six macroeconomic variables. In order to test whether these factors invalidate the instrumentation strategy, the following models are estimated:

$$\Delta z_{i,t} = \kappa_1 \text{deaths}_{i,t-h} + \varphi_t + \theta_i + \upsilon_{i,t} \tag{10}$$

where φ_t are time effects, θ_i are country fixed effects, and $h \in (0,1,2)$ are time lags. $\Delta z_{i,t}$ is generic since all identified factors mentioned above are used as dependent variables. The results are shown in Table 31.

The following argues that the instrument complies with the exogeneity restriction for all six indicators individually.

1) ***GDP per capita***: Since output endogenously determines material productivity, a temporal strategy is pursued, i.e. lagging material productivity by one period compared to GDP per capita. This temporal strategy attempts to prevent any simultaneous effect of the instrument on the dependent variable and the endogenous variable. However, this requires natural hazards to lose their effect on GDP after two years, which is investigated by estimating the effect of disasters on labour productivity, capital investments, patents, and the labour force. The statistical associations shown in Table 33 indicate that the effect of disasters on these variables lose their effect after one year. Thus, a two-year time lag between the instrument and GDP is considered sufficiently large to comply with the exclusion restriction.

2) ***Unemployment*****:** The deaths resulting from disasters are likely to affect the (un)employment rate since firms go out of business, workers pass away, or colleagues and family members of victims (temporarily) step out of the workforce. The impact of the instrument on the workforce and labour productivity is considered to test whether there is any statistical association. As Table 33 shows, the impact statistically disappears after one year.

3) ***Wages per capita*****:** Wages could be affected by changes in labour productivity as well as the workforce following a disaster. In order to justify that the number of deaths do no impact wages other than through material productivity, the effect of disasters on labour productivity and the size of the workforce is tested as both are important factors in determining wages in an economy. As the results in Table 33 indicate, the instrument appears to comply with the exclusion restriction.

4) ***R&D per capita*****:** Natural hazards could impact R&D investments other than through material productivity by affecting patent applications and alternative investments, including capital investments. Patents are typically the result of R&D activity, but it could also capture a shift in priorities of firms once disasters occur, including investing in reconstruction resulting in reduced applications of patents. Table 33 shows that patents and capital investments are statistically insignificantly affected by natural hazards.

5) ***Current account*:** Similar to GDP, the current account (and with it the trade balance) is an integral part of material productivity, as trade endogenously determines GDP and material use indicators (e.g. DMC, RMC). This means that a temporal strategy is required which lags material productivity by one period compared to the current account. Table 33 indicates that the effect of disasters loses their significance on important macroeconomic variables determining the current account (labour productivity and to a lesser extent patents) already after one year. Therefore, the instrument is lagged twice compared to the current account.

6) ***Global Competitiveness Index*:** The GCI comprises numerous factors that represent competitiveness which can be influenced by natural hazards (e.g. productivity, investments, innovation, labour supply). However, considering the statistical relationships shown in Table 33, the exclusion restriction is likely to hold, in particular because the effect of disasters on labour productivity, patents, and capital investments statistically disappears after one year.

All such considerations support the instrumentation strategy chosen in this chapter.

Table 33: Link between the number of deaths (in 1,000) and labour productivity, capital investments, patents, and the labour force.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	$\Delta labour\ productivity_{i,t}$			$\Delta capital_{i,t}$			$\Delta patents_{i,t}$			$\Delta labour\ force_{i,t}$		
$deaths_{i,t}$	-0.07**			0.0004			0.08			0.03*		
	(0.03)			(0.04)			(0.2)			(0.01)		
$deaths_{i,t-1}$		-0.06			-0.01			-0.02			0.008	
		(0.05)			(0.02)			(0.2)			(0.02)	
$deaths_{i,t-2}$			-0.07*			0.001			0.30			-0.007
			(0.04)			(0.04)			(0.20)			(0.02)
N	265	268	249	246	267	249	249	249	229	262	265	247

Notes. Within fixed effects estimation including country and time fixed effects for the EU-28 between 2000-2014. SEs are clustered over countries and shown in parentheses. Column 1-3: Dependent variable is Δlabour productivity$_{i,t}$. Column 4-6: Dependent variable is Δcapital$_{i,t}$. Column 7-9: Dependent variable is Δpatents$_{i,t}$. Column 10-12: Dependent variable is Δlabour force$_{i,t}$. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

7.3.3 Model specification

In the main model, it is assumed that any generic competitiveness variable $y_{i,t}$ in the current period is influenced by material productivity in the same period (as discussed previously, in t-1 for the variables GDP per capita and the current account). This is because productivity changes are likely to have a short term effect on competitiveness. For instance, wages are negotiated taking current or last year's productivity into account, and R&D investment decisions are likely to be taken in line with changes in productivity (Millea 2002). Thus, the model is formulated as follows:

$$y_{i,t} = \pi_1 \frac{GDP_{i,t}}{DMC_{i,t}} + \gamma_t + \theta_i t + \varepsilon_{i,t} \tag{11}$$

where $\frac{GDP_{i,t}}{DMC_{i,t}}$ is denoted in Euros (PPP) per kilogramme of material use, $y_{i,t}$ is a generic variable for the six indicators approximating competitiveness, γ_t are time effects to control for any year-specific events, e.g. the crises that hit the EU economies in specific years (e.g. financial, sovereign debt), and $\theta_i t$ are country-specific trends. Countries are likely to have a different cultural and historic backgrounds, past investment strategies, and other country-specific factors (e.g. economic development, institutional quality).

The first stage of the model considers the impact of the number of deaths from natural hazards on material productivity. As argued previously, deaths are lagged once (twice for the variables GDP per capita and the current account) in order to comply with the exogeneity condition. The model is specified as follows:

$$\frac{GDP_{i,t}}{DMC_{i,t}} = \gamma_1 \text{deaths}_{i,t-1} + \epsilon_t + \eta_i t + \sigma_{i,t} \tag{12}$$

where ϵ_t are time effects and $\eta_i t$ are country-specific trends.

The first difference is taken in order to eliminate trends and other persistent movements in the competitiveness variables and material productivity, thus reducing the risk of spurious regressions. The main model is therefore specified as follows:

$$\Delta y_{i,t} = \pi_1' \Delta \frac{GDP_{i,t}}{DMC_{i,t}} + \gamma_t' + \theta_i' + \varepsilon_{i,t}' \tag{13}$$

where, γ_t' are time effects and θ_i' are country fixed effects. The first stage of the model, i.e. Eq (12), is specified as:

$$\Delta \frac{GDP_{i,t}}{DMC_{i,t}} = \gamma_1' \text{deaths}_{i,t-1} + \epsilon_t' + \eta_i' + \sigma_{i,t}' \tag{14}$$

where the instrument is the number of deaths from disasters, ϵ_t' the time, and η_i' the country fixed effects. Eqs (13) and (14) are estimated using 2SLS with standard errors clustered over countries.

7.4 Data

7.4.1 Competitiveness

Table 34 describes the six macroeconomic indicators approximating competitiveness.

Table 34: Description of the indicators approximating competitiveness.

Indicators	*Description and data sources*
GDP per capita	Real GDP in Euro (in PPP) per capita; Eurostat
Unemployment	Annual average unemployment rate in % of the labour force; Eurostat
Wages per capita	Compensation of employees (wages and salaries plus employer's social contributions) in PPP per capita; Eurostat
R&D per capita	Total R&D expenditure in PPP per capita at constant 2005 prices; Eurostat
Current account	Net current account balance with the Rest of the World in 1 billion Euro; Eurostat
GCI	Global Competitiveness Index; World Economic Forum

Table 35: Descriptive statistics of the macroeconomic indicators.

Indicators	*Observations*	*Mean*	*Median*	*Std. deviation*	*Min*	*Max*
GDP per capita (t-1)	242	22,674	22,191	8,523	6,026	69,463
Unemployment	261	9.08	8.00	4.46	3.10	27.50
Wages per capita	261	10,107	9,460	4,607	2,081	34,168
R&D per capita	256	328	262	259	23.80	1,050.60
Current account (t-1)	222	-0.37	-3.30	40.98	-105.30	206.00
GCI	261	4.67	4.51	0.49	3.77	5.65

Table 35 displays descriptive statistics of the six indicators. Generally, there is great heterogeneity across the sample, in particular GDP per capita, the unemployment rate, wages per capita, R&D per capita, and the current account. Since the GCI compares countries globally, the EU member states appear to be relatively homogeneous.

Two variables require further elaboration.

1) ***Wages per capita:*** Wages per capita are chosen, i.e. wages and salaries plus employers' social contribution. This is equivalent to GDP per capita minus gross operating surplus (excess amount of money of firms after paying for labour input costs), mixed income from capital and labour (self-employed and family-employed income), and taxes less subsidies on production and imports (EC 2016i). Thus, wages per capita are an approximation of the disposable income of each individual for which only incomplete data is available.
2) ***Global Competitiveness Index:*** The GCI is the arguably the most prominent composite index of competitiveness (Sala-i-Martin and Blanke 2007).[15] The GCI comprises twelve pillars ranging from institutions and innovations to market efficiency, combining over 110 microeconomic and macroeconomic factors. Despite criticism, it remains a frequently used indicator.[16] Since the GCI has a methodology break in 2005, the 2006-2014 trend is extrapolated backwards to the years 2000-2005 to have sufficient observations for the estimations.

7.4.2 Material productivity

One common measure of material productivity is the ratio between GDP and DMC. Data on material productivity in Euro (in PPP) per kilogram of material is sourced from Eurostat. In addition to DMC, RMC data is approximated following the method used in EC (2014c) and described in detail in Chapter 5.

[15] Other composite indices are the World Competitiveness Yearbook (IMD WCY 2015), the currently developed Competitiveness Indicator Platform (OECD 2015d), and the harmonised price competitiveness indicators (ECB 2016).

[16] Thompson (2003) criticises competitiveness indices (and thus also the GCI) on four grounds: (i) content validity (methodologies and underlying indicators changes over time), (ii) convergent validity (correlation across different indicators is high suggesting that they all measure similar aspects but not necessarily competitiveness), (iii) weighting and nature of variables (weights of indicators are arbitrary), and (iv) methodology (the data is not transparently described). Lee (2010) argues that the problem is the lack of theoretical and empirical foundation for using individual sub-indicators. Pérez-Moreno et al. (2015) points to the problem of total substitutability across and within the GCI's twelves pillars, as the index is aggregated using the arithmetic mean.

Figure 16: Trends in GDP per capita, DMC per capita, and material productivity.

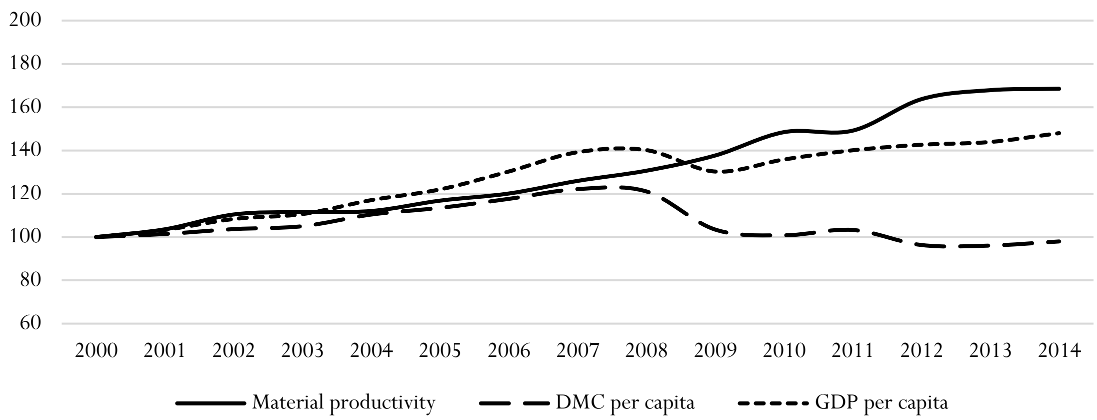


Figure 16 displays the trends in GDP per capita, DMC per capita, and material productivity of the average values of the EU member states across time. Material productivity shows a positive trend, which is temporarily interrupted during 2010-2011 and has levelled out since. GDP per capita increased, except during the financial crisis that has reduced the pre-crisis trend. DMC per capita increased until 2008, followed by a sharp decline in 2009 and has since remained fairly constant. Interestingly, during the financial crisis, material productivity increased because DMC per capita decreased more than GDP per capita.

7.4.3 Instrument

As discussed previously, the number of deaths from natural hazards is chosen as an instrument. The data is retrieved from the EM-DAT database, which is maintained by the Centre for Research on the Epidemiology of Disasters at the Université Catholique de Louvain in Belgium. It contains information on more than 18,000 extreme weather events and accidents. Data is collected from UN agencies, non-governmental organisations, insurance companies and research institutes. Disasters are included in the database if at least one of the following criteria applies: (i) ten or more people reported killed, (ii) hundred or more people reported affected, (iii) declaration of a state of emergency, or (iv) call for international assistance. All deaths from all types of disasters available in the database are taken, namely droughts, earthquakes, epidemics, extreme temperatures, floods, industrial accidents, landslides, storms, transport accidents, volcanic activity, and wildfires.

7.5 Results

7.5.1 First stage results

Starting with Eq (14), Table 36 shows the first stages for all samples of the six indicators. Throughout all samples, the impact of the number of deaths from disasters (in 10,000) have a negative and highly significant impact on material productivity, even though its magnitude is small, i.e. material productivity decreases by around €0.06 per kilogramme for each 10,000 deaths. This finding is in line with the literature that suggests a negative impact of disasters on the productive system of an economy (Hochrainer 2009; Raddatz 2009; Hsiang and Jina 2014; DuPont et al. 2015).

Additionally, Table 36 shows that the instrumentation is valid from a statistical perspective. The Kleinbergen-Paap F statistics measures the instruments' strength. The rule of thumb is that this F statistic should be above 10 (Angrist and Pischke 2009) which is the case across all samples. The Kleinbergen-Paap LM statistic is a test for underidentification which essentially measures the instrument's relevance. For almost all samples, the null hypothesis that the instrument is underidentified is rejected at the 10% significance level. All test statistics in the table are robust to heteroscedasticity and arbitrary within-correlation (Baum et al. 2007).

Table 36: First stage results.

	(1)	(2)	(3)	(4)	(5)	(6)
<u>sample</u>	*GDP*	*Unemployment*	*Wages*	*R&D*	*Current account*	*GCI*
$\boldsymbol{deaths_{i,t-1}}$		-0.06***	-0.06***	-0.06***		-0.06***
		(0.02)	(0.02)	(0.02)		(0.02)
$\boldsymbol{deaths_{i,t-2}}$	-0.06***				-0.06***	
	(0.02)				(0.02)	
Kleibergen-Paap rk Wald F statistic	12.83	14.29	14.29	11.59	10.90	14.29
Kleibergen-Paap rk LM statistic, p-value	0.098	0.094	0.094	0.105	0.108	0.094

Notes. Dependent variable is $\Delta \text{material productivity}_{i,t}$ for Columns (2), (3), (4) and (6). Dependent variable is $\Delta \text{material productivity}_{i,t-1}$ for Columns (1) and (5). Estimated with 2SLS. Country fixed and time effects are included. SEs are clustered over countries and shown in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

7.5.2 Second stage results

The OLS and second stage results are shown in Table 37. Two findings become apparent. First, the material productivity growth rate has neither a positive nor a negative causal impact on most competitiveness indicators, except a positive effect on the wage growth rate, with less confidence, on the current account growth rate. Second, for no competitiveness indicator, OLS and 2SLS are simultaneously significantly different from zero, which makes it virtually impossible to identify the root of the endogeneity problem. Importantly, considering OLS, one would conclude that the material productivity growth rate has a negative impact on the GDP growth rate and a positive effect on the unemployment growth rate, i.e. increasing unemployment. The statistical significance of these effects disappears applying the 2SLS approach, suggesting that either omitted variables, measurement errors, or simultaneity (or any combination thereof) has biased these results.

Increasing the material productivity growth rate by €1 per kilogramme causes the wage growth rate per capita to increase by €1,905. This is equivalent to a 0.60 standard deviation increase in wages resulting from a one standard deviation increase in material productivity. The wage increase can be due to the fact that firms pass on parts of their ‘material savings’ from increased productivity to employees which is referred to as the *cost channel* in Chapter 3. An alternative and complementary explanation would be that unions demand higher wages because of general productivity improvements, thus going beyond labour productivity improvements in their wage bargaining suggested by standard economic theory.

Table 37: OLS and second stage results (MP stands for material productivity).

	GDP		*Unemployment*		*Wages*		*R&D*		*Current account*		*GCI*	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	OLS	2SLS	OLS	2SLS	OLS	2SLS	OLS	2SLS	OLS	2SLS	OLS	2SLS
$\Delta MP_{i,t}$			1.51*	4.98	-158.5	1905.1**	-6.11	10.66			0.02	-0.04
			(0.83)	(4.03)	(220.8)	(822.2)	(9.85)	(45.93)			(0.05)	(0.06)
$\Delta MP_{i,t-1}$	-1118.9**	-2356.3							12.84	136.6*		
	(509.5)	(1862.5)							(10.14)	(75.1)		
Time FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Country FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	242	242	261	261	261	261	256	256	222	222	261	261

Notes. Dependent variables are $\Delta GDP_{i,t}$ for Columns (1-2), $\Delta unemployment_{i,t}$ for Columns (2-3), $\Delta wages_{i,t}$ for Columns (5-6), $\Delta R\&D_{i,t}$ for Columns (7-8), $\Delta current\ account_{i,t}$ for Columns (9-10), and $\Delta GCI_{i,t}$ for Columns (11-12). Estimated with OLS and 2SLS. SEs are clustered over countries and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Increasing the material productivity growth rate by €1 per kilogramme causes the current account growth rate to increase by €137 billion which is equivalent to a 1.37 standard deviation increase in the current account caused by increasing material productivity by one standard deviation. However, the effect is only significant at the 10%-level.

The direction of the effect is in line with previous findings for the trade balance of metals (Dussaux and Glachant 2015). The authors find that increasing material productivity through domestic recycling substitutes the import of primary metals, hence *ceteris paribus* increasing the current account. Similar claims are brought forward in the field of energy efficiency (UNIDO 2011). Nevertheless, the result should merely be seen as an indication of a positive impact of the material productivity growth rate on the current account growth rate.

Since the only statistically significant effects are on the wage growth rate and the current account growth rate, the following analyses will be limited to these variables.

7.5.3 Country heterogeneity

To better understand the results, it is helpful to explicitly estimate the country fixed effects. This information provides insights into which countries drive the results and whether the overall effect underlies country heterogeneity. Table 38 shows the results for the individual countries.

For wages, heterogeneity is clearly visible. The reference country is Belgium. One the one hand, most southern European countries, including Greece, Spain, Italy, Malta, and Portugal, tend to have lower increases in the wage growth rate due to increases in the material productivity growth rate. On the other hand, most northern European countries, including Denmark, Germany, Ireland, Luxembourg, and Finland, as well as the Baltic states tend to have higher wage growth rate improvements triggered by increases in the material productivity growth rate compared to Belgium. This would suggest that higher-income countries benefit more from material productivity improvements in terms of higher wages compared to lower-income economies. Perhaps most surprisingly, the United Kingdom has a lower effect compared to Belgium. However, this could also suggest that the United Kingdom with its relatively important service sector in terms of share of GDP constitutes an outlier.

For the current account, there is less heterogeneity across countries. Additionally, there is no clear grouping among countries possible. Germany, already having a large current account surplus, would benefit relatively more compared to Belgium from an increase in the material productivity growth rate. This could hint towards the fact that exporting economies profit most. However, this claim is not verified by considering the coefficients for Luxembourg or the Netherlands.

It remains outside the scope of this chapter to analyse the results in more depth. Nevertheless, the results of this subsection indicate that taking country heterogeneity into account in future empirical analyses or policymaking is important.

Table 38: Country heterogeneity.

	(1)	(2)
sample	*Wages*	*Current account*
$\Delta MP_{i,t}$	1905.1**	
	(822.2)	
$\Delta MP_{i,t-1}$		136.56*
		(75.11)
Belgium	*reference*	*reference*
Bulgaria	4.04	3.84***
Czech Republic	-26.26	0.53
Denmark	131.46***	8.35*
Germany	87.03***	16.94***
Estonia	615.89***	17.44*
Ireland	221.36***	-0.27
Greece	-145.14***	5.17***
Spain	-261.74***	-8.23
France	-31.75***	-3.72***
Croatia	-2.82	1.56
Italy	-269.31***	-8.37
Cyprus	101.90***	3.73**
Latvia	170.19***	2.08
Lithuania	384.24***	9.20**
Luxembourg	699.40***	-11.04
Hungary	-26.8	-3.45
Malta	-121.38***	-11.52
Netherlands	-65.93	-2.48
Austria	-33.69	-0.19
Poland	17.24	3.97**
Portugal	-131.80***	2.25**
Romania	-23.93	6.36***
Slovenia	-124.25***	-3.11
Slovakia	-50.83*	1.33
Finland	122.80**	8.18***
Sweden	-13.20	-7.51
United Kingdom	-247.27***	-15.16***

Notes. Dependent variable is $\Delta wages_{i,t}$ for Column (1), and $\Delta current\ account_{i,t}$ for Column (2). Estimated with 2SLS. Time fixed effects are included. SEs are clustered over countries and shown in parentheses. The reference country is Belgium. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

7.5.4 Raw material consumption

For RMC, data for the EU countries between 2000-2012 are being approximated following the methodology in EC (2014c). The details of this method are described in Chapter 5.

Unfortunately, using the RMC data to calculate material productivity fails all the tests for valid and relevant instruments. The Kleibergen-Paap rk LM p-value for underidentifaction is only significant at the 25% level and the Kleibergen-Paap rk Wald F statistic for weak identification is 1.7, thus well below the rule of thumb of 10. Therefore, no results are presented here since they cannot be trusted based on the test statistics.

Since the economic rationale behind natural hazards affecting material productivity remain largely valid, this is a surprising result. However, two explanations could hint towards the reasons for why RMC-based material productivity fails to pass the statistical tests in comparison to the DMC-based measure.

1) ***Indicator constructions:*** From a conceptual perspective, it is not clear why natural hazards in one country should impact on the indirect material use in another country (since the RME coefficients are applied to the imports and exports of material use). This is particularly relevant in the EU countries since most indirect material use takes place outside Europe.
2) ***Approximation method:*** The method used to approximate RMC data relies on averages. This could explain why the variation in RMC-based material productivity might not be sufficient to be explained by changes in the number of deaths from severe weather events. Therefore, this analysis on heterogeneity across material indicators would require more sophisticated RMC data to re-run the estimations.

7.5.5 Robustness checks

Since the only statistically significant effects are on the wage growth rate and the current account growth rate, the robustness checks will also be limited to those variables. Excluding individual countries does not change the conclusions drawn from Table 37. Excluding the country fixed effects does not substantially change the results. Excluding any potential outliers does not change the results significantly. The time effects are statistically different from zero and thus included in the estimations. The results are tested regarding different standard errors (i.e. robust to heterogeneity and homogeneity), concluding that the results remain unchanged.

Table 39 shows the results for the wage rate and the current account rate when excluding the years of the financial crisis (2008-2010) and dividing the samples into the EU-15 and non-EU-15 countries. In essence, the results are unchanged, with the exception that the effect on the current account is just outside the 10% significance level when the years of the financial crisis are excluded. This could be the result of the instrument reducing its strength.

Table 39: Robustness checks by excluding the financial crisis and the new member states.

	Wages	**Current account**	**Wages**	**Current account**
	excl. 2008-2010		*EU-15*	
	(1)	**(2)**	**(3)**	**(4)**
$\Delta material\ productivity_{i,t}$	1761.47**		2301.57**	
	(836.03)		(1039.31)	
$\Delta material\ productivity_{i,t-1}$		128.77		104.98*
		(83.14)		(55.83)
Kleibergen-Paap rk Wald F statistic	11.32	7.68	17.21	14.85
Kleibergen-Paap rk LM statistic, p-value	0.101	0.125	0.072	0.077
N	209	170	147	126

Notes. Columns (1) and (3): Dependent variable is $\Delta wages_{i,t}$. Columns (2) and (4): Dependent variable is $\Delta current\ account_{i,t}$ Estimated with 2SLS, including country fixed and time effects. SEs clustered over countries are shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Moreover, several variables are controlled for that potentially have an impact on wages. According to standard economic theory, labour productivity is an essential determinant of wages (e.g. Millea 2002). Data on real labour productivity per capita is sourced from Eurostat. R&D expenditures can impact wages negatively by reducing available funds as well as positively through possible rents from R&D (e.g. Lokshin and Mohnen 2013). Data on R&D expenditures in PPP per capita at constant 2005 prices are taken from Eurostat. The labour force is one factor in determining the supply of labour and thus wages (e.g. Heckman 1974). Eurostat data is considered which defines the labour force as the share of the active to total population between 15 and 64 years. Also, capital investments are argued to impact on wages, not at least due to the substitutability between capital and labour (e.g. Holm et al. 1994; Rowthorn 1999). Data on gross capital formation as percentage of GDP is taken from the World Bank.

As shown in Table 40, the results are unchanged and fairly robust to these control variables.

Table 40: Checking the robustness of the results for wages by including control variables.

	Wages			
	(1)	(2)	(3)	(4)
$\Delta material\ productivity_{i,t}$	1706.15**	1723.78**	2064.18**	1791.25**
	(807.01)	(801.33)	(835.83)	(789.25)
$\Delta labour\ productivity_{i,t}$	17.73			
	(22.04)			
$\Delta R\&D_{i,t}$		6.14***		
		(1.95)		
$\Delta labour\ force_{i,t}$			68.85*	
			(40.04)	
$\Delta capital_{i,t}$				52.23**
				(22.49)
Kleibergen-Paap rk Wald F statistic	11.15	11.78	13.04	14.50
Kleibergen-Paap rk LM statistic, p-value	0.103	0.103	0.096	0.091
N	261	256	260	260

Notes. Dependent variable is $\Delta wages_{i,t}$. Estimated with 2SLS, including country fixed and time effects. SEs are clustered over countries are shown in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

Table 41: Checking the robustness of the results for the current account by including control variables.

	Current account			
	(1)	(2)	(3)	(4)
$\Delta material\ productivity_{i,t-1}$	149.12*	111.55*	136.70*	147.37*
	(85.46)	(62.01)	(75.31)	(84.77)
$\Delta FDI_{i,t}$	-4.36^{-11}			
	(2.76^{-11})			
$\Delta R\&D_{i,t}$		0.1501**		
		(0.0726)		
$\Delta GCI_{i,t}$			11.85	
			(27.64)	
$\Delta patents_{i,t}$				0.2389
				(0.1619)
Kleibergen-Paap rk Wald F statistic	9.18	14.59	10.73	9.26
Kleibergen-Paap rk LM statistic, p-value	0.117	0.087	0.108	0.120
N	221	220	222	222

Notes. Dependent variable is $\Delta current\ account_{i,t}$. Estimated with 2SLS, including country fixed and time effects. SEs are clustered over countries are shown in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

Control variables are also included for the current account model. The literature argues that FDIs can increase the current account by increasing national savings (e.g. Fry 1996). Data on net inflows of FDI in current USD are taken from the World Bank. The literature further finds that investments, including in R&D, can improve the current account (e.g. Glick and Rogoff

1995). R&D expenditure data in PPP per capita at constant 2005 prices are retrieved from Eurostat. Similarly, the general competitiveness of a country and patents have an effect on the current and are thus controlled for (e.g. Crosby 2000). Data on the GCI is taken from the World Economic Forum and patent applications to the European Patent Office per million inhabitants is taken from Eurostat. As shown in Table 41, the results remain robust.

Besides experimenting with different standard errors as mentioned above, it is important to also control for serial correlation using the approach suggested by Newey and West (1987). Eq (13) is thus estimated controlling for various autocorrelation structures. Table 42 shows that the results are essentially unchanged when using AR(1), AR(2), and AR(3) error structures.

Table 42: Controlling for autocorrelation error structures.

	Wages			Current account		
	AR(1)	AR(2)	AR(3)	AR(1)	AR(2)	AR(3)
$\boldsymbol{\Delta MP_{i,t}}$	1905.05* (1061.77)	1905.05* (1063.55)	1905.05* (1046.80)			
$\boldsymbol{\Delta MP_{i,t-1}}$				136.56* (81.25)	136.56* (79.74)	136.56* (82.33)
N	261	261	261	222	222	222

Notes. Dependent variable are $\Delta wages_{i,t}$ and $\Delta current\ account_{i,t}$. 2SLS estimation with country fixed and time effects. Newey-West SEs are shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Individual years are also excluded, which does not change the results, except for the year 2003. This may not come as a surprise since the heatwave in 2003 caused a substantial amount of deaths. For this analysis, this means that the effect of the 2003 heatwave constitutes an important event in explaining the variation in material productivity. However, the effects of this heatwave would have been likely to be similar in other countries, across time, and under different severities (counterfactual). Despite previous heatwaves and other disasters, EU countries still seem unprepared for the substantial impacts and magnitude of such events on human lives and economic activity (García-Herrera et al. 2010). The effect's similarity across economies is particularly likely since the EU is a relatively homogenous group of industrialised countries. Shutting down nuclear power plants is one example which is required every time when extreme temperatures or low river levels occur, independently from when or where such events take place (de Bono 2004). Thus, the economic rationale behind the results are likely to remain valid.

7.6 The effect of material productivity on GHG emissions

As outlined in the Chapter 2, material productivity can also contribute to reduce environmental pressures arising from material use, at least in relative terms. To test whether this claim is justified on a macroeconomic level for the EU, Table 43 shows the results of the causal effect of material productivity on GHG emissions. The data is retrieved from the EEA.

The results do not support the notion that changes in the material productivity growth rate significantly affect the GHG emissions growth rate. At first sight, this finding would not support the claims that material productivity indeed is a valid strategy to reduce environmental pressures on the macroeconomic level, exemplified by GHG emissions (Barrett and Scott 2012; Hatfield-Dodds et al. 2017).

However, one explanation could be that some EU countries have continued to increase their material use in absolute terms during most of the time span considered. According to Eurostat, this is the case for Bulgaria, Estonia, Croatia, Latvia, Lithuania, Luxembourg, Hungary, Malta, Austria, Poland, Romania, Slovakia, and Sweden. In line with the findings in Chapter 5, increasing material use in absolute terms is associated with an increase in GHG emissions. This would hint to the existence of a rebound effect. That productivity increases not necessarily lead to a decrease in absolute material use has also been confirmed by Dahmus (2014) from a historic perspective. Another reason could be that changes in material productivity do not lead to a less (or more) GHG-intensive material composition.

Table 43: Effect of material productivity on GHG emissions.

	GHG emissions	
	OLS	2SLS
$\Delta MP_{i,t}$	-0.194	0.701
	(0.215)	(2.042)
Time FE	YES	YES
Country FE	YES	YES
N	242	242

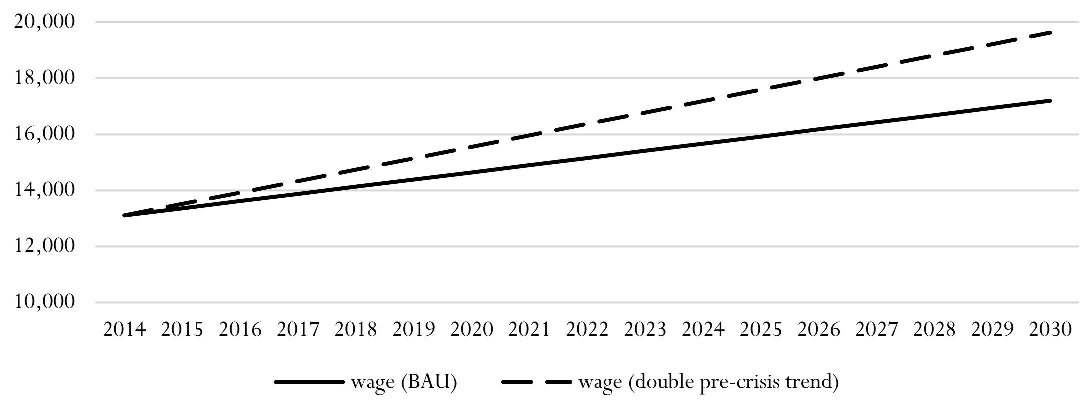
Notes. Dependent variable is $\Delta GHG_{i,t}$. Estimated with OLS and 2SLS. SEs are clustered over countries and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

7.7 Discussion

The results provide evidence that increasing the material productivity rate leaves four out of six macroeconomic indicators approximating competitiveness (i.e. GDP per capita, unemployment, R&D investments, and the Global Competitiveness Index) statistically unchanged. From a policy perspective, this means that the notion that increasing material productivity improves macroeconomic competitiveness and reduces GHG emissions in the EU is not supported. However, there is no evidence that competitiveness is harmed as a result of material productivity improvements. Thus, these results can be interpreted as a statement of caution.

It has to be noted that the analysis critically depends on the indicators considered to approximate macroeconomic competitiveness. The measures chosen in this analysis are the result of reviewing the literature, thus going beyond the current empirical literature that often does not clarify the concept. Nevertheless, as mentioned previously, the set of indicators used in this analysis has been tested against different sets of indicators.[17]

Figure 17: Extrapolated future wage per capita developments of the business-as-usual (BAU) trend compared to doubling the pre-crisis material productivity trend.



The results provide evidence for a statistically significant and causal impact of increasing the material productivity growth rate on the wages growth rate per capita across the EU member states. The meaningfulness of the result's magnitude can be exemplified by extrapolating it into the future. If the EU were to double its material productivity growth rate compared to its pre-crisis trend (i.e. 2000-2007) until 2030, as suggested by the European Resource Efficiency Platform (2014), the wage increase beyond its normal trend would amount to €2,431 for every EU-citizen by 2030. This is equivalent to approximately €1.2 trillion gross gain from doubling

[17] The analysis has also been tested using the following indicators as dependent variables: exports per capita, exports of high-technology goods and services per capita, carbon dioxide emissions per capita, a price competitiveness measure from the European Central Bank, patent application per capita, foreign direct investments, and labour productivity. The results confirm the conclusions drawn from this analysis.

the pre-crisis trend in material productivity. Figure 17 illustrates the change in wages per capita by doubling the pre-crisis trend.

Generally, the findings of this analysis have four implications.

1) ***Competitiveness considerations:*** Those scholars arguing that relatively high wages are detrimental for the competitiveness of countries would interpret this finding as being a setback to competitiveness (e.g. Siggel 2006; Acemoglu et al. 2016). However, those scholars arguing that competitiveness is about increase the welfare could see this result as improving competitiveness (e.g. Aiginger 2006; Snowdon and Stonehouse 2006; Salvatore 2010). Thus, there is no consensus whether wage increases are positive or negative for macroeconomic competitive.
2) ***Rebound effect:*** Wage increases are likely to increase the rebound effect and thus environmental pressures. This consideration is in line with findings from the previous section that material productivity improvements do not necessarily lead to a reduction in GHG emissions. This also has repercussions on the calculation of the rebound effect itself, in particular for macroeconomic models which assume that gains from material productivity, i.e. 'material savings', are re-invested into innovation activity which reduces the magnitude of the rebound effect. This finding suggests that at least part of the gains is passed on to employees.
3) ***Wage bargaining:*** Employees are benefiting from increases in material productivity in addition to increases in labour productivity which is explicitly controlled for in Table 40. It seems that employees benefit generally from productivity improvements rather than the pure increase in labour productivity.
4) ***Productivity puzzle:*** The results moreover suggest that current discussions on the productivity puzzle focus on labour productivity, whereas material productivity could also be considered as a complementary source for productivity growth. While the macroeconomic effects of material productivity increases appear to be limited, the subsequent chapter will investigate this further on the microeconomic level.

The results also indicate that increasing the material productivity growth rate increases the current account growth rate. Two mechanisms are consistent with this result. First, increased productivity leads to an increase in exports because more productive firms self-select themselves into international markets (Kunst and Marin 1989; Wagner 2007). Second, given that the EU imports approximately three times more materials than it exports, imports are likely to increase less (or decrease more) compared to exports once material productivity increases. In both scenarios, the current account *ceteris paribus* increases.

Policymaking could focus on how the gains from material productivity are being channelled. If the gains are passed on to employees, they are likely to increase the rebound effect triggered by higher consumption, undermining efforts to reduce absolute material use (Shao and Rodriguez-Labajos 2016). At the same time, material productivity policies could be justified as a social policy rather than one improving competitiveness.

However, channelling the gains into eco-innovations through incentives (e.g. tax breaks, financial support, risk coverage) could further improve firms' productivity and create spill-over effects while reducing the rebound effect and associated environmental pressures (Ghisetti et al. 2016). Channelling gains from productivity measures into eco-innovation is acknowledged as one strategy to reduce the rebound effect (Font Vivanco et al. 2016). Even though eco-innovations themselves are associated with additional rebound effects (Font Vivanco et al. 2015), the effect is likely to be lower each time gains are re-invested.

Lastly, the results do not confirm the notion that GHG emissions are reduced by material productivity improvements on the macroeconomic level. This provides important insights for the body of the literature that argues material productivity can reduce GHG emissions. One explanation could be that material productivity improvements do not necessarily result in an absolute decrease of material use (or to a less GHG-intensive material composition) which leaves GHG emissions unchanged. This has been shown empirically over time (Dahmus 2014).

7.8 Conclusions

This analysis investigates the causal impact of material productivity on competitiveness in the EU. The current literature, dominated by interdisciplinary scholars and policy circles, argues that increasing material productivity improves macroeconomic competitiveness and reduces environmental pressures, including GHG emissions (Bleischwitz and Steger 2009; Bassi et al. 2012; Barrett and Scott 2012). However, three limitations of the literature can be identified. First, most studies do not discuss and clarify the concept of competitiveness on the macroeconomic level. Second, most empirical studies do not explicitly take the endogeneity of material productivity into account. Third, investigations often do not consider heterogeneity across countries and material indicators.

This investigation attempts to address the three shortcomings by (i) reviewing the concept of macroeconomic competitiveness and identifying six conventional macroeconomic indicators to approximate competitiveness, and (ii) using a panel data set for the EU's 28 member states between 2000 and 2014 to estimate the causal impact of material productivity on each of the six indicators, explicitly taking country and material indicator heterogeneity into account. The number of deaths from natural hazards are taken as an instrument which is shown to be both relevant and valid.

The results suggest that increasing the material productivity growth rate does not have a statistically significant impact on most indicators, with the exceptions of positive and causal impacts on the wage growth rate per capita and, with lower confidence, on the current account growth rate. There is significant country heterogeneity which should be taken into account in future studies. Unfortunately, the estimations using RMC data fail the relevant statistical tests. Additionally, there is no statistically significant effect between the material productivity growth rate and the GHG emissions growth rate.

While it is debateable whether higher wage growth rates improve or harm competitiveness, overall, there is no evidence that increasing the material productivity growth rate is a setback to EU competitiveness. However, it should be acknowledged that there is no optimal set of indicators approximating competitiveness on the country level.

Channelling the gains from material productivity could be the focus of policymaking since increased wages are likely to result in a more pronounced rebound effect and thus environmental pressures. Thus, through incentives, including tax breaks, financial support, and risk coverage, policymakers could redirect gains into eco-innovations which help to further improve productivity and potentially reduce environmental pressures. Whether these results differ when investigating firm-level data will be subject of the subsequent chapter.

Chapter 8

The Causal Impact of Material Productivity on Microeconomic Competitiveness and GHG emissions in the European Union

An abridged version of this chapter is under review and has been presented at the 2017 Annual Conference of the European Association of Environmental and Resource Economists in Athens, Greece.

Flachenecker, Florian and Kornejew, Martin (under review). The causal impact of material productivity on competitiveness and environmental performance in the European Union – firm level evidence. 23rd Annual Conference of the European Association of Environmental and Resource Economists. 28 June – 01 July 2017, Athens, Greece.

8 The causal impact of material productivity on microeconomic competitiveness and GHG emissions in the European Union

8.1 Introduction

The results in the previous chapter suggest that material productivity increases have only limited effects on competitiveness and no statistically significant link to GHG emissions in the EU on a macroeconomic level, this chapter attempts to replicate the analysis on the microeconomic level.

Achieving economic prosperity while staying within the planetary boundaries is one of the main challenges of our time, thus being at the centre stage of contemporary discussions among academics, policymakers, international organisations, and the private sector (e.g. Arrow et al. 1995; Rockström et al. 2009). One side of the spectrum argues that taking environmental aspects into account will come at the expense of economic activity; the opposing side stating that considering environmental issues will unlock additional growth potential (e.g. Porter and Linde 1995; Jaffe et al. 1996). As part of this debate, materials have received increasing attention, because of their vital role in generating economic value as well as their association with environmental pressures (UNEP IRP 2011; Bahn-Walkowiak and Steger 2015).

As such, materials feature prominently in policy making, especially in the context of the EU. One stream of material policies in the EU focus on their strategic role as inputs to the production function (EC 2008; EC 2010b). Another stream relates materials to environmental pressures (EC 2011b; EC 2015a). Irrespectively of different foci, material policies in the EU are motivated by combining both economic and environmental objectives. Specifically, material policies aim to increase the material productivity of firms which is argued to improve firms' competitiveness and reduce associated environmental pressures, in particular GHG emissions.

This assertion has led substantial capital being directed into investment projects on the firm level intending to improve material productivity. For instance, investments in resource efficiency (and related areas) of €14.9 billion between 2005-2014 and €18.3 billion between 2006-2015 have been made by the European Investment Bank (EIB 2015) and the European Bank for Reconstruction and Development (EBRD 2015a), respectively.

The existing literature on the impact of material productivity on microeconomic competitiveness (and associated measures) as well as reductions in environmental pressures finds a positive correlation between these variables (Fh-ISI et al. 2005; Bleischwitz et al. 2009b; Schmidt and Schneider 2010; Ecorys 2011; Schröter et al. 2011; Bassi et al. 2012; AMEC and Bio IS 2013; Cooper et al. 2016; Gilbert et al. 2016).

However, such investigations have two main shortcomings. First, most of the studies do not explicitly account for heterogeneity across firms, sectors, or countries, as findings are largely based on case studies, thus limiting the results' external validity. Second, the majority of empirical studies do not adequately address the potential endogeneity of material productivity, which could arise because material productivity is argued to increase firms' competitiveness, while more competitive firms are also more likely to have higher levels of material productivity (Videras and Alberini 2000; Calantone et al. 2002; Aghion et al. 2005). More generally, investigating the productivity–competitiveness link on the firm level has merit in itself, following the conclusions drawn from the review on competitiveness in Chapter 3.

In this chapter, the first shortcoming is attempted to be addressed by considering the Community Innovation Survey (CIS) of the European Commission for the years 2006 to 2008 which comprises over 52,000 firms across all 13 sectors of the so-called business economy and 12 EU member states.[18] Furthermore, country and sector heterogeneity is explicitly studied. The second shortcoming is argued to be accounted for by applying an instrumental variable approach using the availability of public financial support for eco-innovations as an instrument for material productivity improvements.

Interpreting the results in the spirit of the Local Average Treatment Effect (LATE) Theorem, the findings provide evidence for a positive and causal impact of increases in material productivity on microeconomic competitiveness for those firms that had an eco-innovation stimulated by public funding. These results are particularly strong in Eastern European countries and material-intensive sectors such as manufacturing, construction, retail trade, food production, and transport. It is further shown that such material productivity improvements also reduce the firms' CO_2 footprint, a proxy for GHG emissions.

Thus, material productivity improvements can achieve both economic and environmental objectives. Accordingly, empirically robust evidence is provided supporting eco-innovations, in

[18] A list of all sectors and countries can be found in Tables B1 and B2 in the Appendix.

particular those leading to material productivity improvements since they are likely to be beneficial for firms' competitiveness as well as for reducing GHG emissions.

The chapter is structured as follows. Section 8.2 summarises the literature and channels linking material productivity and microeconomic competitiveness, relying on the more detailed review in Chapter 3. Section 8.3 describes the modelling approach and instrumentation strategy. Section 8.4 introduces the data and Section 8.5 outlines the results, including robustness checks. Section 8.6 provides evidence for the link between material productivity and GHG emissions, Section 8.7 discusses the findings, and Section 8.8 concludes.

8.2 Microeconomic competitiveness and material productivity

8.2.1 Microeconomic competitiveness

As discussed in detail in Chapter 3, competitiveness on the firm level is typically defined as "the ability to compete in markets for goods or services." (Black et al. 2013). Accordingly, a firm is *ceteris paribus* competitive in perfectly competitive markets if it sells goods or services at a price that is equal to its marginal costs. The precondition for this type of competition are the assumptions underlying the first fundamental theorem of welfare economics which is often violated in practice, thus changing the type of competition (Aiginger 2006).

For a theoretical depiction of competitiveness to be practically relevant, a wider range of factors needs to be considered. The literature identifies quality (Ekins and Speck 2010) and information networks as well as continuous learning (Maskell and Malmberg 1999) as determinants of competitiveness. Accordingly, additional factors other than cost structures influence the ability to compete and hence to maintain market shares.

Depending on market conditions, a combination of market failures can occur making it difficult to select a single factor determining competitiveness. To define an empirically estimable indicator, the literature frequently refers to *outcome factors* capturing the characteristics or 'symptoms' of competitive firms. There is no consensus in the literature on which factors best represent the outcome of competitiveness. Factors proposed by the literature include the ability to stay in business (Krugman 1994), generating high revenues and profits (Lehner et al. 1999; Siggel 2006; Ekins and Speck 2010), the expansion of firms' activities (Reinert 1995), improving productivity (Aiginger and Vogel 2015), increasing employment (Chan et al. 2013), positive returns on invested capital (Snowdon and Stonehouse 2006), and exporting activity (Siggel 2006; Dosi et al. 2015; EC 2015e).

Even though such *outcome factors* are measureable and available for empirical analyses, they lack one important aspect of competitiveness – its relative nature, i.e. a firm is more or less competitive compared to another firm (Krugman 1994; Siggel 2006). As such, competitiveness is best described by a relative measure of a firm's market share or any relative performance that benchmarks the firm's performance to its competitors (Siggel 2006).

8.2.2 Material productivity

Analogous to the concept of labour productivity, material productivity describes the ratio between the output of a production process and the material inputs into this process (OECD 2007). Material productivity (MP) can be expressed as

$$MP_{t,i} = \frac{Y_{t,i}}{M_{t,i}} \tag{15}$$

where Y represents output, M material input ($M_{t,i} > 0$), t the time dimension, and i denotes the firm.

8.2.3 Linking material productivity and microeconomic competitiveness

By re-iterating the literature based on Chapter 3, three channels can be identified linking material productivity and microeconomic competitiveness: (i) cost reduction, (ii) risk mitigation, and (iii) value creation. Table 44 summaries them.

1) ***Cost reduction***

   i. <u>*Reducing input costs*</u>: In a nutshell, if firms improve their material productivity, they are likely to reduce their absolute or relative material use. Since material costs account for 45% of the purchasing costs in the case of German manufacturing firms (KfW 2009; Statistisches Bundesamt 2011), for more than 50% of total costs for 27% of all EU firms in the manufacturing sector (EC 2011e), and for around 30% in the chemical, paper, rubber and plastics, base metal, and wood sectors in the Netherlands (Wilting and Hanemaaijer 2014), reducing material costs is argued to enable firms to offer their goods and services at lower prices which essentially increases their competitiveness.[19]

Empirical evidence on the costs channel is limited to case studies for firms (Fh-ISI et al. 2005; Schröter et al. 2011), sectors (Bassi et al. 2012; AMEC and Bio IS 2013), or countries (Oakdene Hollins 2011). Only few studies take a more holistic approach, thus accounting for dynamic effects between firms, sectors, and countries. For instance, Bleischwitz et al. (2009) find a positive and significant correlation between material productivity and several competitiveness indices across the EU. The authors justify their findings by referring to the material cost channel. However, the authors acknowledge the possible problem of endogeneity in their analysis.

ii. *Anticipating regulation*: Regulation might incentivise firms to grasp a first-mover advantage of innovating and thus becoming more competitive (Porter and Linde 1995). A more nuanced approach finds that innovations triggered by regulation might produce both 'winners' and 'losers' (Lankoski 2010). Recent empirical evidence suggests that environmental regulation increases patent applications (Rubashkina et al. 2015). Larrán Jorge et al. (2015) find that generally environmental performance has a positive and direct effect on competitiveness as well as an indirect impact on competitiveness through improved corporate image and marketing efforts.

Linking material productivity and environmental regulation (and thus indirectly competitiveness) is not immediate obvious. The link might be sequential; firms anticipating future environmental regulation, e.g. material productivity targets, GHG emission levels, increase their productivity in anticipation to comply with future regulation more cost-effectively, giving them a first-mover advantage (Gunningham et al. 2004).

[19] However, one study casts doubt on the meaningfulness of these figures, arguing that material costs typically do not only include the cost of raw materials, but all upstream labour, transportation, and storage costs. Bruyn et al. (2009) estimates the 'actual costs' of raw materials (excluding upstream value-added) to be approximately 3-6% of total costs.

Table 44: Channels linking material productivity and competitiveness

CHANNELS	MECHANISM	RATIONALE
Cost reduction	Reducing input costs	– Improving material productivity (MP), i.e. using fewer material inputs per unit of output, can lower the unit production costs – Reducing the unit production costs can increase the (price) competitiveness of firms
	Anticipating environmental regulation	– Increasing MP can help firms to comply with (future) regulation (e.g. MP targets, GHG emissions reduction) more cost-effectively – By anticipating environmental regulation, firms can gain a first-mover advantage over competitors
Risk mitigation	Hedging against material price volatility	– Highly volatile material prices pose risks to firms' operations (i.e. uncertain input prices) – Increasing MP can help to reduce firms' exposure to such risks, thus increasing their competitiveness
	Supply security	– For material purchasing firms, increasing MP can reduce material dependencies by substituting primary with domestically recycled (secondary) raw materials – Reducing dependencies can improve competitiveness
Value creation	Eco-innovations	– Improving MP can incentivise eco-innovations (or be the result of them) which can increase competitiveness through spillover effects, knowledge building, improved economic performance etc.
	Economic performance	– Increasing MP can have positive effects on the macroeconomic and microeconomic environment in which firms operate (e.g. economic performance of market segments, networks and clusters) – Such effects can improve a firm's competitiveness

2) Risk mitigation

i. Hedging price volatility: Material price volatility leads to investment uncertainty (Pindyck 2007), a reduction of material use, and a decrease of industrial production (Zhao et al. 2013; Ebrahim et al. 2014). If price volatility is not hedged, firms' production cost may become volatile. Depending on the stickiness of the firms' prices, this could cause severe fluctuations of the cash flow, which in a worst-case scenario can lead to insolvency (AMEC and Bio IS 2013). By definition, increasing material productivity leads to a relative or absolute reduction of material use. This reduces the exposure of material price fluctuations on the firms' production costs, therefore enabling firms to become more competitive and resistant to material price volatility.

ii. Supply security: Even if there is a broad consensus that most materials are physically abundant (Tilton 2001; Tilton 2003), the issue of criticality and supply security continues to be discussed from a strategic point of view (EC 2014a). If critical materials cannot be accessed and no immediate substitute or strategic reserves are available, production could be disrupted leading to a weakening of competitiveness of affected firms. Reducing the absolute material use by increasing material productivity could reduce the magnitude of the problem (Dussaux and Glachant 2015).

3) ***Value creation***

i. *Eco-innovations*: Eco-innovations can be the result of any type of innovation, including process, product, and system innovations (Kemp et al. 2013). Crucially, by improving the way materials are transformed into economic goods and services (while reducing their environmental repercussions), economic value is created. Increasing material productivity may be the result of an eco-innovation (Fischer and Brien 2012). At the same time, material productivity improvements can trigger additional (eco-)innovations, which are shown to positively contribute to a firm's economic success (Rennings and Rammer 2009).

   Thus, productivity increases can result in innovative activity, which can increase the market share (EEA 2011b), export activity (Lachenmaier and Wößmann 2006; Czarnitzki and Wastyn 2010), labour productivity (Hashi and Stojčić 2013), and incentivises future innovations in a virtuous cycle (Meyer 2011), all of which is positively associated with competitiveness (Porter 1990).

ii. *Economic performance*: Material productivity can increase economic activity (or be the result thereof), employment, productivity, and innovation activity in firms, networks and clusters (Distelkamp et al. 2010; Ecorys 2011; Meyer 2011; Walz 2011; EC 2014e). On a sectoral level, Ecorys (2011) find that resource and thus material efficiency can lead to improvements in overall productivity. Moreover, Cooper et al. (2016) find (minor) employment effects of material efficiency strategies for the United Kingdom.

8.2.4 Gaps in the literature

The relevance of most channels, in particular the material cost channel, generally finds agreement in the literature. For most channels, there is only general and indirect evidence available, only for the material cost channel there are comprehensive studies. The overwhelming majority of these studies conclude that increasing material productivity leads to improvements in competitiveness (Fh-ISI et al. 2005; Bleischwitz et al. 2009b; Ecorys 2011; Schröter et al. 2011; AMEC and Bio IS 2013).

However, the results are mostly based on simple statistical or correlation analyses on case studies for specific firms, sectors, or countries, not taking heterogeneity into account. For instance, AMEC and Bio IS (2013) bases their results on a literature review, industry data, and case studies to estimate the saving potentials for sectors. Others take results from individual case studies to extrapolate the potential material savings to the entire sector (Fh-ISI et al. 2005; Schröter et al. 2011). Ecorys (2011) rely on nine resource-intensive sectors using literature reviews, consultations with stakeholders, qualitative surveys, and simple statistical analyses.

Thus, the current literature faces two main shortcomings which this chapter aims to highlight. First, most studies do not take dynamic effects and heterogeneity across firms, sectors, or countries into account. Second, most empirical studies do not explicitly consider the potential problem of the endogeneity of material productivity.

8.3 Modelling approach

8.3.1 The problem of endogeneity

There are three potential sources of endogeneity – omitted variables, measurement errors, and simultaneity.

1) ***Omitted factors:*** Omitted variables are likely to be an issue in this analysis, as the factors determining competitiveness are numerous, as outlined previously in Chapter 3. Given that this chapter is based on survey data, the information available is limited to the survey questions. The reason for not being able to match the survey data with other data sources is that the individual firm identification numbers were not obtained, thus limiting the information to the 2006-2008 wave. This restriction makes the analysis prone to omitted variables.
2) ***Measurement errors:*** Measurement errors occur frequently in surveys (Bertrand and Mullainathan 2001). Despite comprising mostly binary questions, leaving relatively little room for systematic biases, they might still be present. Both omitted variable biases and measurement errors may bias OLS results in any direction.
3) ***Simultaneity:*** As outlined in detail in previous sections, the majority of the evidence suggests that increasing material productivity has a positive effect on microeconomic competitiveness. However, a potential reverse causal effect can work in either direction (Galdeano-Gómez 2008; Sakamoto and Managi 2017).
   - On the one hand, highly competitive firms may be more likely to engage in voluntary environmental programmes, such as those increasing material

productivity (Videras and Alberini 2000). Moreover, competitive firms possess capabilities, knowledge, and willingness to learn that makes them more likely to engage in material productivity improvements (Calantone et al. 2002). Additionally, competitive and economically successful firms are prepared to investment more in environmental productivity (Galdeano-Gómez 2008). This raises the concern that OLS estimates may *overstate* the true effect.

- On the other hand, firms in highly competitive markets where market shares are under constant pressure, are likely to be incentivised to innovate more frequently and achieve innovations of higher quality compared to markets with low levels of competition (Aghion et al. 2005). Hence, the prevalence of eco-innovations might correlate with the market's momentum and degree of competition. This will inflict a *downward* bias on the OLS estimate as firms that increase material productivity more often operate in markets where market shares – thus competitiveness – are particularly difficult to maintain.

Which of these two effects will dominate, remains an empirical question which will be investigated during the course of this chapter. In order to address all three sources of endogeneity, a 2SLS instrumental variable approach is chosen (Angrist and Krueger 2001). As argued in previous chapters, it is the most adequate approach in addressing all three sources of endogeneity.

8.3.2 Instrumentation strategy

Instruments must comply with two conditions – they need to be relevant and exogenous. To satisfy the first condition, a variable in the survey needs to be identified that substantially correlates with material productivity. Conveniently, the survey contains questions on the motives for introducing an eco-innovation, some of which led to changes in material productivity. There are five possible answers, all of which correlate with material productivity since they are directly linked to the introduction of an eco-innovation:

- *current or expected market demand for eco-innovations*
- *voluntary agreements within the sector*
- *existing environmental regulation*
- *expected environmental regulation*
- *availability of public funds*

Regarding the second condition, the instrument has to be exogenous, i.e. it must not correlate with any variable absorbed in the structural error, in short, any variable that influences competitiveness but cannot be observed. There are several such variables that cannot be controlled for since there is no information provided in the survey.

For instance, the survey does not measure firm's ability and willingness to embrace change. However, firms that have (successfully) managed changes in demand and regulation in the past – thus increasing their competitive stance – have acquired knowledge and capabilities to cope with future changes as well (Malerba 1992; Caloghirou et al. 2004). Crucially, the prevalence of this so-called 'absorptive capacity' correlates with the firm's competitiveness but simultaneously increases its probability of addressing current or future challenges by taking them as opportunities (Cohen and Levinthal 1990). In fact, those challenges include *current or expected market demand, voluntary agreements, and existing* as well as *expected environmental regulation*. Thus, the first four variables are likely to select a particularly competitive pool of firms – i.e. those with high absorptive capacity – and thus are endogenous themselves, violating the exclusion restriction. This limits the potential instrument to the *availability of public funds*.

The *availability of public funds*, i.e. government grants, subsidies, or other financial incentives, is the most suitable instrument available in the survey for the following four reasons.

1) ***Legal considerations:*** By law, firms have equally access to public funding irrespectively of individual characteristics such as their past experiences of dealing with change, degree of competition in respective markets and their competitive stance. However, sometimes specific groups of firms (especially SMEs) are given preferred access (Busom 2000; Blanes and Busom 2004). It is therefore shown in the robustness section that restricting the sample to SMEs does not alter the findings.

   Additionally, the principle of non-discrimination applies regardless of the funds being EU-wide, national, or local (EU 2012). Public funds cannot discriminate against any firm within the EU, regardless of which jurisdiction it is located in.

2) ***Equal opportunity:*** Any self-selection bias is expected to be of minor concern since there are numerous initiatives to equip firms with the necessary information and support to ensure equal opportunity for all firms to receive public funding. For example, the EU's small business portal support such efforts, together with initiatives of national chambers of commerce and development banks. This is also confirmed by the results shown in Table B3 in the Appendix.

3) ***Funding considerations:*** Public funds for eco-innovations do not directly increase the competitiveness of firms, but only cover (or refund) those costs that are directly associated with the eco-innovation. Therefore, any change in competitiveness followed by the use of public funds is likely to be directly due to the associated eco-innovation.
4) ***Previous application:*** This instrument has been used previously by Czarnitzki and Wastyn (2010) to estimate the impact of R&D on export activity. The authors argue that export activity was unrelated to the selection of the R&D subsidies. Thus, the *availability of public funds* is chosen as the instrument.

8.3.3 Model specification

In the model, the impact of material productivity on competitiveness is estimated by exploiting dynamic effects on the firm level. The model is formulated as follows.

$$\ln(COMP_{t,i}) = \gamma MP_{t,i} + \delta_i + \zeta_s t + \pi_c t + \boldsymbol{X_{t,i}\beta} + e_i \quad (16)$$

where $\ln(COMP_{t,i})$ represents the competitiveness of firms expressed in natural logarithm and $MP_{t,i}$ their material productivity. δ_i are time-invariant firm level fixed effects, $\pi_c t$ and $\zeta_s t$ country and sector specific trends, and $X_{t,i}$ is the control variables matrix.

Country and sector specific time trends ($\pi_c t$ and $\zeta_s t$) are included to control for confounding effects associated with differential national policy developments and changing market structures, most notably the degree of competition. In a later stage of the analysis, different sets of firm level control variables $X_{t,i}$ are introduced.

Given the multi-year time frame of the data, all time-invariant fixed effects can be removed by considering the change between 2008 and 2006, a common approach in the literature (Acemoglu and Johnson 2007; Dinkelman 2011). Therefore, this model controls for time-invariant firm level fixed-effects which comprise most of the components in corporate knowledge (e.g. human capital, business contracts, innovations management), absorptive capacity (e.g. firms' internal structure, information management, retail structure), and the willingness to embrace change (e.g. know-how of past changes, branding, market power).

By taking the first difference of Eq (16) to also reduce the risk of spurious regressions, the main model can be described as follows.

$$\Delta\ln(COMP_{t,i}) = \gamma'\Delta MP_{t,i} + \zeta_s' + \pi_c' + \Delta\boldsymbol{X}_{t,i}'\boldsymbol{\beta} + \varepsilon_i \tag{17}$$

where $\Delta\ln(\mathrm{COMP}_{t,i})$ represents the change in competitiveness of firms expressed in natural logarithm and $\Delta\mathrm{MP}_{i,t}$ their change in material productivity. π_c' and ζ_s' country and sector specific effects, $\Delta\boldsymbol{X}_{t,i}'$ are changes in firm level control variables matrix.

Following the 2SLS approach, the first stage of the model considers the impact of public financial support on material productivity improvements.

$$\Delta MP_{t,i} = \alpha_0 + \alpha_1 PFS_{t-1,i} + \mu_s + \nu_c + \epsilon_i \tag{18}$$

where $\mathrm{PFS}_{t-1,i}$ represents the availability of public financial support, $\Delta\mathrm{MP}_{t,i}$ are changes in material productivity, and μ_s and ν_c are sector and country specific effects. Eqs (17) and (18) are estimated using 2SLS with errors robust against heteroscedasticity.

8.4 Data

The Community Innovation Survey from the European Commission for the years 2006-2008 is used. The Community Innovation Survey is a harmonized and representative survey conducted in different countries across Europe to investigate the innovation activity in enterprises. It has been used extensively in academic research (Lööf and Johansson 2009; Czarnitzki and Wastyn 2010; Harris and Moffat 2011; Hashi and Stojčić 2013; Horbach and Rennings 2013; Horbach 2014).

This sample comprises over 52,000 firms across all 13 sectors that the European Commission defines as the business economy and 12 EU countries (EC 2013c).[20] All firms with zero turnover in 2006 or 2008 (5,166 observations) as well as those outliers that increased their turnover within this period more than 15-fold (1,113 observations) are excluded. Including those firms with zero turnovers reduces the impact of material efficiency but leaves the overall outcome unchanged. Including firms with extraordinary turnover growth somewhat increases the coefficients magnitude, however, not changing the conclusions drawn from this chapter.

[20] The harmonised survey questionnaire of the Community Innovation Survey can be accessed via (last accessed on 15 June 2017) http://ec.europa.eu/eurostat/documents/203647/203701/CIS_Survey_form_2008.pdf

Descriptive statistics on the main variables considered in this analysis are shown in Table 45.

Table 45: Statistics on competitiveness, material productivity, and the availability of public financial support.

Variable	N	Mean	Median	Std. deviation	Min	Max
Market share 2006 ($COMP_{2006}$)	52,731	0.0002	7.88×10^{-6}	0.0019	3.37×10^{-10}	0.183
Market share 2008 ($COMP_{2008}$)	52,731	0.0002	8.18×10^{-6}	0.0018	9.71×10^{-12}	0.176
Market share growth ($\Delta\ln(COMP_{t,i})$)	52,731	-0.004	-0.031	0.50	-12.43	2.53
Material productivity increase ($\Delta MP_{t,i}$)	52,731	0.17	0	0.37	0	1
Public financial support (PFS)	52,731	0.07	0	0.26	0	1
Market share 2006 ($COMP_{2006}$)	52,731	0.0002	7.88×10^{-6}	0.0019	3.37×10^{-10}	0.183

8.4.1 Competitiveness

The Community Innovation Survey does not include any question that directly informs about the competitiveness of each firm. However, there is a question on the firm's total turnover for 2006 and 2008, i.e. market sales of goods and services including all taxes except VAT. Turnovers provide a general indication of the competitiveness of a firm (Lehner et al. 1999; Siggel 2006; Ekins and Speck 2010). Nevertheless, the absolute value undermines the relative nature of the concept of competitiveness (Krugman 1994; Siggel 2006).

Thus, competitiveness is approximated by the firm's market share. For this purpose, the size of a firm's market is estimated by its relative turnover compared to the remaining firms in the same sector the firm operates in.

$$COMP_{t,i} = \frac{turnover_{t,i}}{\sum_{\forall j \in s} turnover_{t,j}} \tag{19}$$

where the subscripts t stands for time (i.e. 2008 or 2006), i for an individual firm, and j for the remaining firms in sector s. In line with the main model in Eq (17), using natural logarithms and taking the first difference of Eq (19) yields.

$$\begin{aligned}\Delta \ln(COMP_{i,t}) &= \ln\left(\frac{turnover_{2008,i}}{\sum_{\forall j \in s} turnover_{2008,j}}\right) - \ln\left(\frac{turnover_{2006,i}}{\sum_{\forall j \in s} turnover_{2006,j}}\right) \\ &= \ln\left(\frac{market\ share_{2008,i}}{market\ share_{2006,i}}\right) \\ &\approx \frac{market\ share_{2008,i}}{market\ share_{2006,i}} - 1 \\ &= \frac{market\ share_{2008,i} - market\ share_{2006,i}}{market\ share_{2006,i}}\end{aligned} \tag{20}$$

Hence, a firm's competitiveness is approximated by its market share growth rate between 2008 and 2006. Accordingly, a firm improves its competitiveness when its market share growth rate is positive, as this is equivalent to outperforming competitors. Similarly, a firm loses competitiveness if its market share growth rate is negative.

8.4.2 Material productivity

Data on material productivity is directly available in the Community Innovation Survey. The 2006-2008 wave is the only one of the Community Innovation Survey that contains an explicit question on material productivity. The question is framed within the context of the environmental benefits resulting from an eco-innovation that firms had between 2006 and 2008. Note, that the survey provides no information about the actual levels of material productivity in neither year. Instead, the binary choice question asks firms whether or not they reduced their material use per unit of output, i.e. increased their material productivity, as a result of an eco-innovation during this period.

Also, the survey does not provide any information on which specific type of eco-innovation resulted in an increase in material productivity. The question refers to the types of innovations asked in previous parts of the survey, namely a product, process, organisational, or marketing innovation. Thus, 16 firms are excluded which have not had any of such innovations but still answered to the questions on eco-innovations. As Table 45 shows, 17% of all firms in the sample have had an eco-innovation that led to a material productivity increase.

8.4.3 Public financial support

As with material productivity, data on public financial support is available only as a binary variable. It turns to 1 whenever public funds were available to a firm that had an eco-innovation between 2006 and 2008. Due to the survey structure, this variable is observed only once per firm and thus assume that funds were available in 2006, i.e. before the material productivity improvement took place.

As reported in Table 45, such firms make up for 7% of our sample. However, they are well distributed across countries and sectors and mirror total sample properties regarding firm sizes and market orientation. Table B3 in the Appendix presents estimates from regressing *public financial support* (PFS) on the full set of country and sector fixed effects, and central firm characteristics such as size, market activity, and export orientation. Provided with such a large number of observations, it is possible to detect significant distributional disproportions. Importantly though, even this rich set of controls explains a mere 3% of the instrument's total variation (unadjusted). This leads to the conclusion that the instrument covers a broad and diverse cross-section of firms.

8.4.4 Local average treatment effect (LATE)

The causal relationship identified by an instrumental variable approach relies on the variation triggered by the instrument. Since the endogenous variable is binary and treatment effects are likely to be heterogeneous across firms, the results need to be interpreted in the spirit of the LATE theorem (Imbens and Angrist 1994; Angrist et al. 1996). The LATE theorem has been used previously in an instrumental variable setting in which the instrument is binary (Lachenmaier and Wößmann 2006). In this case, the estimate γ' in Eq (17) relies on the variation in competitiveness caused by material productivity increases that were triggered by the availability of public funds and would not have been implemented without such funds.

Chesher and Rosen (2013) caution to respect the LATE theorem since making any causal inference beyond the subsample that complies with the instrumental treatment is likely to be unfounded. This restricts the explanatory power of the results to those firms having increased their material productivity by an eco-innovation that was motivated by the availability of public financial support. Thus, essentially, it is evaluated whether those funds have been used successfully.

According to Imbens and Angrist (1994) and Angrist et al. (1996), one additional condition to those described in the previous section need to be met in order to make causal inference in this setting – monotonicity. The direction of the effect of public financial support on the likelihood of changing material productivity should be the same across all firms. This seems reasonable in this case because public funding is only granted to firms if they use the resources to generate an eco-innovation, while the funds should not *prevent* firms from increasing their material productivity.

8.5 Results

8.5.1 First stage results

The first stage model from Eq (18) is presented first. Table 46 indicates that firms motivating the realisation of their eco-innovation by the availability of public funding have a 27% higher likelihood to improve their material productivity as a result of an eco-innovation than those firms motivating their eco-innovation differently or not eco-innovating at all. The effect is statistically highly significant.

Table 46: First stage results.

PFS_i [public financial support]	0.2653***
	(0.0078)
Kleibergen-Paap rk Wald F statistic (weak id)	1,162.49
Kleibergen-Paap rk LM statistic, p-value (under id)	0.0000

Notes. Dependent variable is MP_i. Estimated with 2SLS. Country and sector dummies are included. SEs are robust against heterogeneity and shown in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

Moreover, using public financial support appears to be a robust instrumentations strategy. The Kleibergen-Paap Wald F statistics is well above 10 which is typically used to indicate the strength of instruments (Angrist and Pischke 2009). High F statistics are often found in large samples (e.g. Khandker et al. 2014). The Kleibergen-Paap rk LM test assesses whether the instrument is 'relevant'. The null hypothesis of the equation being underidentified is comfortably rejected. All test statistics in the table are robust to heteroscedasticity.

8.5.2 OLS results

The second stage model from Eq (17) is now considered and estimated using simple OLS. Table 47 shows that the impact of material productivity improvements on changes in competitiveness is positive and highly significant. The magnitude of the effect is modest, however. Having increased material productivity, a firm's market share growth rate – which is the measure for competitiveness in this analysis – will increase by 3%, on average. This corresponds to a 0.02 standard deviation increase as a result of a one standard deviation increase of material productivity.

8.5.3 2SLS results

The results obtained when using 2SLS are different. The results provide evidence that average-scale material productivity improvements cause microeconomic competitiveness, i.e. market share growth rate, to increase by around 12%. This corresponds to a 0.09 standard deviation increase as a result of a one standard deviation increase of material productivity.

These results are highly significant, and the magnitude is more than four times larger compared to OLS. This illustrates that endogeneity biases the OLS estimate downwards, implying that firms that face the highest pressure on their market shares are most likely to increase their material productivity. Hence, the dominant source of endogeneity appears to arise from the omitted variable bias from a market's dynamism and innovativeness, as typically spurred by competition, putting market shares under constant pressure which is correlated with (eco-)innovations.

The low R^2 in both estimations does not undermine the validity of the estimates, especially as the regressors' variability is very limited due to their binary nature (e.g. Dell et al. 2012). The robustness checks will show that introducing control variables increases R^2 while leaving the coefficients practically unchanged, thus confirming the robustness of the results.

These results are in line with evidence brought forward in the literature in terms of finding a positive relationship between material productivity and competitiveness (Fh-ISI et al. 2005; Bleischwitz et al. 2009b; Schmidt and Schneider 2010; Ecorys 2011; Schröter et al. 2011; Bassi et al. 2012; AMEC and Bio IS 2013). However, this analysis considers the dynamic effects between firms, sectors, and countries as well as addresses the endogeneity of material productivity. Therefore, the results show that taking these shortcomings into account significantly alter the estimations.

Table 47: Second stage results.

	OLS	**2SLS**
ΔMP_i	0.0266***	0.1176***
	(0.0054)	(0.0267)
Country dummies	YES	YES
Sector dummies	YES	YES
R^2	0.04	0.04
N	52,731	52,731

Notes. Dependent variable is $\ln(COMP_i)$. Estimated with OLS and 2SLS. Country and sector dummies are included. SEs are robust against heterogeneity and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

8.5.4 Country and sector heterogeneity

To better understand which particular countries or sectors drive the results or whether there is any country or sector heterogeneity, country and sector specific effects are explicitly estimated and shown in Table 48.

Table 48: Country and sector heterogeneity.

	2SLS
ΔMP_i	0.1228***
	(0.0268)
Bulgaria	*reference*
Cyprus	-0.0954***
Czech Republic	-0.0813***
Germany	-0.2432***
Estonia	-0.1445***
Hungary	-0.1961***
Italy	-0.2505***
Lithuania	-0.0569***
Latvia	-0.1342***
Portugal	-0.2338***
Romania	-0.0707***
Slovakia	0.0124
mining and quarrying	*reference*
manufacturing	0.1438***
electricity, gas, steam and air conditioning supply	0.0935***
water supply, sewerage, waste management and remediation activities	0.1275***
construction	0.2178***
wholesale and retail trade; repair of motor vehicles and motorcycles	0.1880***
transporting and storage	0.1652***
accommodation and food service activities	0.1608***
information and communication	0.0792***
financial and insurance activities	0.0014
real estate activities	0.1416***
professional, scientific and technical activities	-0.0142
administrative and support service activities	0.1909***

Notes. Dependent variable is $\ln(\text{COMP}_i)$. Estimated with 2SLS. Country and sector dummies are included. SEs are robust against heterogeneity and shown in parentheses. Reference country is Bulgaria. Reference sector is mining and quarrying. * p < 0.10, ** p < 0.05, *** p < 0.01.

1) ***Country heterogeneity:*** There is great heterogeneity across countries. The reference country is Bulgaria. All other countries thus have a lower impact of material productivity on their competitiveness compared to Bulgaria. This is particularly visible for the Western European economies, including Germany, Italy, and Portugal,

whereas Eastern European countries such as Slovakia, Romania, Lithuania, and the Czech Republic have a relatively higher impact. This might be due to the already high levels of material productivity in Western European countries, i.e. there might be decreasing marginal benefits of material productivity increases.

2) ***Sector heterogeneity:*** With regards to the sectors, the reference category is mining and quarrying. There is also substantial heterogeneity. Manufacturing, construction, retail trade, food production, and transport are among the sectors with the highest positive effect of material productivity on competitiveness compared to mining and quarrying. This could be due to the high material intensity of such sectors; thus, substantial benefits can be grasped within material-intensive sectors outside the mining sector.

8.5.5 Robustness checks

Throughout all robustness checks, the instrumentation strategy remains robust. The country specific effects are jointly significant and thus included in all estimations. The same holds true for the sector specific effects. Individual countries and sectors are excluded to identify specific subsamples that may drive results, but those results are not substantially different to the ones in Table 47. Furthermore, the assumptions on the standard errors are alternated to homoscedastic, clustered over countries, sectors, and a combination of them. The estimations are robust to all such changes.

So far, the 'raw effect' has been presented, i.e. not controlling for variables in additional to sector and country effects and trends. Table 49 gradually introduces further control variables that the literature identifies as being determinants of competitiveness. In terms of the underlying structural model of Eq (16), controls comprise both additional time trends and level variables. The table shows that the 'raw effect' is robust against introducing further control variables.

1) ***Column 1*** introduces a separate time trend for a firm's initial size as measured by the number of employees in 2006. Due to data protection clauses, the Community Innovation Survey 2006-2008 does not report the actual number of employees but rather three categories. The first one is between 10-49 employees (55.9% of all sample firms), the second between 50-249 (34.5% of all sample firms), and the third are firms above 250 employees (9.6% of all sample firms). The results suggest that larger

enterprises tend to be less competitive compared to smaller ones. This could be due to larger being less dynamic and having built up complacency.

2) ***Column 2*** investigates, whether the level of employment affects the competitive stance (Hall 1987; Yasuda 2005). Thus, for the first-difference setting, a change in employment is introduced. Due to the categorical type of data, there is no information on the magnitude of increase in employment. However, the variable captures information as to whether there was a change in category of a firm in 2008 compared to 2006. There is a large and positive effect of increasing the size of the firm and competitiveness. While large firms seem to be less competitive, growing firms tend to increase their competitive stance.

Table 49: Control variables.

	(1)	(2)	(3)	(4)
$\Delta MP_{i,2008}$	0.1751***	0.1446***	0.1097**	0.1183**
	(0.0275)	(0.0271)	(0.0480)	(0.0483)
$size_{i,2006}$	-0.0793**	-0.0353***	-0.0372***	-0.0403***
	(0.0043)	(0.0043)	(0.0040)	(0.0041)
$\Delta size_{i,2008}$		0.4029***	0.4006***	0.3989***
		(0.0117)	(0.0116)	(0.0117)
$\Delta product_{i,2008}$			0.0126*	0.0109
			(0.0068)	(0.0068)
$\Delta process_{i,2008}$			0.0157**	0.0143*
			(0.0075)	(0.0076)
$\Delta organisational_{i,2008}$			0.0139*	0.0122
			(0.0077)	(0.0077)
$\Delta marketing_{i,2008}$			-0.0076	-0.0086
			(0.0071)	(0.0071)
$local/regional_i$				*reference*
$national_i$				0.0134***
				(0.0050)
$europe_i$				0.0238***
				(0.0082)
RoW_i				0.0200
				(0.0143)
Country dummies	YES	YES	YES	YES
Sector dummies	YES	YES	YES	YES
R^2	0.04	0.09	0.09	0.10
N	52,637	52,637	52,637	52,517

Notes. Dependent variable is $\ln(COMP_i)$. Estimated with 2SLS. Country and sector dummies are included. SEs are robust against heterogeneity and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

3) ***Column 3*** controls for specific eco-innovation, i.e. product, process, organisational, or marketing, which are introduced in order to isolate the effect of material productivity on competitiveness. One can think about (i) the current product line-up, (ii) the level of process structures and efficiency, (iii) management structures and efficiency, and (iv) marketing capacities to determine a firm's contemporary level of competitiveness. In turn, an innovation is defined in the Community Innovation Survey as the market introduction of a new or significantly improvement in one of the four innovation categories. Since innovation by definition entails change, the variables can be included in the main model in Eq (17). Interestingly, product, process, and organisational innovations are positively associated with competitiveness, while marketing innovations are statistically insignificant.

4) ***Column 4*** additionally controls for time trends in market shares depending on the regional scope of sales. This tests the notion that firms supplying foreign markets tend to be more competitive compared to those supplying local markets (Baldwin and Robert-Nicoud 2008). For example, given that local markets expand, nationally operating firms might benefit more in terms of absolute sales than their local competitors. If so, this would increase their relative market share (reflecting and materialising their competitiveness).

   The same reasoning holds for the relation of domestic firms, European multinationals and global players, respectively. The survey asks in which market the firm generated most turnovers, local/regional (39.6% of the sample firms), national (45.6% of the sample firms), Europe (12.2% of the sample firms), or the rest of the world (2.7% of the sample firms). The local/regional market is the reference category. The results corroborate the narrative provided above, in particular for the European market, except for firms that generate most of their revenue in the rest of the world which could be due to the initiating adverse effects of the financial crisis at that time.

Table 50 displays further robustness checks by restricting the sample of firms considered. First, going back to the section covering the instrumentation strategy, the sample is restricted to SMEs, thus reducing the sample size by 11%. According to the definition of the EU, firms are considered to fall into this category if they have below 250 employees and an annual turnover of below or equal to €50 million (EC 2015i). The results remain qualitatively unchanged, confirming the robustness of the instrumentation strategy.

Additionally, the sample is restricted to the so-called non-financial business economy, defined as the NACE sectors B to J and L to N (EC 2013c). Again, the results are similar to the entire sample considered previously. Lastly, the manufacturing sector is considered individually (NACE code 3) finding that the conclusions drawn are the same, but the magnitude of the effect has dropped.

Table 50: Restricted samples.

	SMEs only	excl. financial sectors	manufacturing only
ΔMP_i	0.1466***	0.1047***	0.0697**
	(0.0323)	(0.0268)	(0.0296)
Country dummies	YES	YES	YES
Sector dummies	YES	YES	YES
R^2	0.03	0.04	0.03
N	46,881	50,688	24,659

Notes. Dependent variable is $\ln(COMP_i)$. Estimated with 2SLS. Country and sector dummies are included. SEs are robust against heterogeneity and shown in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

Lastly, a placebo strategy is implemented to test the instrument's strength as proposed by Bound et al. (1995). Specifically, 500 binomial random variables are generated that have a success probability equal to the mean of the binary instrument. This creates independent vectors that by construction exhibit the same statistical properties as the instrument. As the 2SLS procedure is repeated with every generated instrument, one would expect the precision of placebo results to be lower compared to those estimations presented previously. Otherwise, suspicion of finite sample bias would undermine confidence in the results.

As expected, the placebo results' standard errors lay far apart from those presented in Table 47. Table 51 presents the distribution of the placebo standard errors. Evidently, the precision the previous estimates (0.0267) exceeds even the most precise placebo results by an order of magnitude. This suggests that the instrument passes the non-robustness test proposed by Bound et al. (1995).

Table 51: Distribution of the standard errors for the coefficient of interest from 500 placebo 2SLS regressions.

	min	1%	5%	25%	50%	75%	95%	99%	max
$se(\gamma)_{placebo}$	0.469	0.577	0.785	1.478	3.111	11.98	324.73	4,010	3,462,073

8.6 The effect of material productivity on GHG emissions

Given that eco-innovations (i.e. innovations with environmental benefits), including those leading to material productivity improvements, are thought to address both economic and environmental concerns (Machiba 2010; Kemp et al. 2013), the analysis is complemented by estimating the relationship between material productivity improvements and the GHG emissions of firms.

The Community Innovation Survey 2006-2008 includes binary information on whether or not firms have reduced their CO_2 footprint. The two main differences between firm level GHG emissions and the CO_2 footprint are that GHG comprise additional emissions than CO_2, and the footprint also takes CO_2 emissions across the supply-chain into account. Nevertheless, for the purposes of this chapter, the GHG emissions are approximated by the CO_2 footprint.

A positive relationship would indicate that improving material productivity reduces the GHG emissions. Since material productivity can be interpreted as an input-output relationship and GHG emissions as a result of this relationship, it is reasonable to assume that material productivity is exogenous in this model and time frame. The following model is estimated.

$$\begin{aligned} \Delta GHG_{t,i} = \alpha_0 + \alpha_1 \Delta MP_{t,i} + \alpha_2 \Delta MP_{t,i} * product_i + \alpha_3 \Delta MP_{t,i} \\ * process_i + \alpha_4 \Delta MP_{t,i} * organisational_i + \alpha_5 \Delta MP_{t,i} * marketing_i \\ + \alpha_6 product_i + \alpha_7 process_i + \alpha_8 organisational_i + \alpha_9 marketing_i \\ + \Delta \mathbf{X}_{t,i} \boldsymbol{\beta} + \mu_s + \lambda_c + \varepsilon_i \end{aligned} \tag{22}$$

where ΔGHG_i are GHG emissions (approximated by the CO_2 footprint), $\Delta MP_{t,i}$ is material productivity, $product_i$, $process_i$, $organisational_i$, and $marketing_i$ are dummies to account for different innovation types, $X_{t,i}$ denotes a matrix with a set of control variables (size, Δsize, turnover growth, environmental programme (binary) and export activity as measured by national, europe, RoW), μ_s are sector specific effects, and λ_c represents country specific effects.

Material productivity is interacted with all types of innovations in order to better isolate the 'pure effect' of material productivity on GHG emissions, disentangling the effects of the different types of innovations (i.e. non-material productivity innovations) on GHG emissions.

The model is estimated applying a probit approach. The results of the probit estimations can be found in Table B4 in the Appendix.

Table 52 shows the marginal effect at the mean and the average marginal effect of material productivity improvements on changes in GHG emissions, using the results from Column 4 in Table B4 in the Appendix, i.e. including all control variables. The probability of reducing GHG emissions for the average firm increases by around 32% as a result of an increase in material productivity compared to not increasing material productivity. Similarly, the average effect of enhancing material productivity on the probability across all firms of reducing GHG emissions amounts to 30%. Both are highly significant and relevant effects. Thus, this provides evidence that material productivity improvements also lead to a reduction of GHG emissions of firms.

Table 52: The effect of material productivity on GHG emissions.

	Marginal effect at the mean	**Average marginal effect**
$\Delta \boldsymbol{MP_i}$	0.3163***	0.2961***
	(0.0091)	(0.0082)
Full set of controls	YES	YES
Country dummies	YES	YES
Sector dummies	YES	YES
Pseudo-R^2	0.29	0.29
N	54,234	54,234

Notes. Dependent variable is GHG_i. Estimated with probit. Country and sector dummies are included. SEs are robust against heterogeneity and shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

8.7 Discussion

The results provide evidence for a positive and causal impact of material productivity improvements on microeconomic competitiveness. By considering firms across 13 sectors and 12 EU countries, dynamic effects and heterogeneity across firms, sectors, and countries are taken into account. Furthermore, this is the first study that investigates this effect based on such wide-ranging data. Previous studies have not focused on addressing the potential problem of endogeneity and heterogeneity which are shown to be a relevant.

The study also suggests that Eastern European countries and material-intensive sectors tend to experience a larger increase in competitiveness as a result of material productivity improvements. Furthermore, this analysis provides evidence that material productivity also reduces the firms' GHG emissions. It is thus shown that increasing material productivity results in a boost in competitiveness and is in line with climate change mitigation efforts.

Nevertheless, this analysis faces some limitations.

1) ***Channels:*** By reviewing the literature, potential links between material productivity and competitiveness are grouped into channels. Given the limited information available in the Community Innovation Survey 2006-2008, it is not possible to identify which of such channels drives the results. Additional information is required to distinguish between the various channels.
2) ***Binary variables:*** The endogenous variable is binary, i.e. it cannot provide any information on the magnitude of material productivity improvements that cause firm's increases in competitiveness. Thus, it remains unclear if the material productivity improvements need to be substantial or incremental.
3) ***Short timespan:*** While the Community Innovation Survey considers the time between 2006 and 2008, this time has been marked by an unprecedented rise and fall of material prices (Figure 4). Thus, in times of low material prices, the incentive to increase material productivity might be reduced since gains are likely to be lower compared to times of high material prices. This could somewhat limit the external validity of the results during times of low material prices.

These limitations are due to the way the Community Innovation Survey is constructed. Given the very limited data sources academics and policymakers can rely on for investigating the effects of material productivity, the Community Innovation Survey 2006-2008 is arguably the most comprehensive dataset available. However, any future study would greatly benefit if the Community Innovation Survey would (i) consistently survey firms in all EU countries and sectors about their material productivity in every wave, (ii) collect information in the form of continuous variables, and (iii) introduce questions that can be used as instruments (e.g. any natural experiment type of information).

The results contain one crucial policy insight – enable eco-innovations that result in material productivity improvements through public financial support. As it is shown that eco-innovations triggered by public financial support leading to improvements in material productivity increases the competitive stance of firms as well as reduce their GHG emissions across firms, sectors, and EU countries, the EU and its member states are encouraged to support the development and diffusion of those eco-innovations that increase the material productivity of firms. This can be achieved by providing sufficient finance to firms through, for instance, targeted investment programmes and further comprises reducing investment barriers

(Jordan et al. 2014; Flachenecker and Rentschler 2015; EC 2015b; Rentschler et al. 2016; Rizos et al. 2016).

Mainstreaming such efforts across current investment programmes, in particular the European Fund for Strategic Investments (EC 2014g) and the Circular Economy Package (EC 2015a) would be consistent with these findings. Furthermore, the benefits of policy-guided change have been discussed in depth in the literature (Porter 1990). Hence, enabling eco-innovations does not only trigger direct benefits, but is also likely to result in secondary benefits, such as reducing potential rebound effects (Font Vivanco et al. 2016), creating new business models (Machiba 2010), and enabling systematic change towards more sustainable economies (Bleischwitz et al. 2009a; Kemp et al. 2013), among others.

With regards to the discussions on the 'productivity puzzle' (Blundell et al. 2014; Patterson et al. 2016; Harris and Moffat 2017), the results suggest that material productivity can increase competitiveness of those firms that are in material-intensive sectors and located in Eastern European countries. If those two factors correlate with firms that a further away from the technological frontier relative to the best performing firms that are often found in Western European economies, then incentivising eco-innovations that lead to material productivity increases could help to increase productivity in those countries. While this does not address the 'productivity puzzle' among the richest countries, it certainly would for those economies in Eastern Europe.

However, there is evidence suggesting that environmental innovations can crowed-out more profitable 'conventional' innovations (Marin 2014). This and other *deadweight effects* are an important concern for public measures that try to incentivise innovations through financial support. To approximate this risk, the sample proportions of so-called *always-takers*, *compliers*, and *never-takers* is estimated following standard practice used in the LATE literature (Angrist and Pischke 2009). *Compliers* are firms that innovate because of the availability of public support. *Never-takers* will not innovate regardless of the availability of public funds. *Always-takers* are firms that receive public financial support but would have realised an eco-innovation anyway, thus generating *deadweight effects*. In this sample, 15% of firms are *always-takers*, pointing at a considerable but limited risk of *deadweight effects*. This provides evidence that the principle of additionality in public funding needs to be respected in order to keep such adverse effects to a minimum.

8.8 Conclusions

The aim of this analysis is to investigate the effects of material productivity on microeconomic competitiveness and GHG emissions. Most of the existing literature does not focus on the dynamic effects and heterogeneity across firms, sectors, and countries as well as the endogeneity of material productivity. After reviewing the literature on the channels linking material productivity and competitiveness on the firm level, such gaps are addressed by analysing data from the Community Innovation Survey 2006-2008 comprising over 52,000 firms across 13 sectors and 12 EU member states.

Using a 2SLS instrumental variable approach, this analysis provides evidence for a positive and causal impact of material productivity improvements on microeconomic competitiveness, particularly for Eastern European countries and material-intensive sectors. This suggests country and sector specific approaches towards material productivity improvements.

The availability of public financial support is used to instrument material productivity. Interpreting the results in the spirit of the LATE theorem, these findings provide evidence only for those firms that received public financial support and had an eco-innovation. Furthermore, it is shown that material productivity improvements also reduce GHG emissions of firms. Thus, this shows that firms across the EU can improve their competitiveness and decrease their GHG emissions simultaneously – competitiveness and climate change mitigation objectives can be consolidated.

Material productivity improvements in the sample depend on realising an eco-innovation through public financial support. Thus, these results provide the important insight for policymakers in the EU that they should focus their efforts on enabling eco-innovation through providing sufficient and adequate finance as well as reducing barriers for and within firms. Streamlining eco-innovations that result in material productivity improvements are strongly recommended. Future research on the issue would need to benefit from more precise information on the magnitudes of material productivity improvements that are required in order to achieve both economic and environmental objectives. Additionally, longer timespans comprising times of lower material prices would enhance the external validity of these results.

This analysis suggests that material productivity can align competitiveness and climate change mitigation objectives in Europe. This raises the obvious question. Why is material productivity 'successful' on the microeconomic (Chapter 8) but not on the macroeconomic level (Chapter 7)? There are several possible reasons.

1) ***Sector specifics:*** As Table B2 in the Appendix shows, the sample is dominated by material-intensive sectors, in particular the manufacturing sector. To this end, the results suggest that material productivity is mainly beneficial for material-intensive sectors, while other sectors might not realise such gains or even loose out. Hence, this could lead to the disappearance of the effect on the macroeconomic level.
2) ***Firm specifics:*** The evidence on the microeconomic level is based on those firms that had an eco-innovation motivated by the availability of public financial support. Those firms might not be representative for all firms. Thus, only a particular subgroup of firms might be able and willing to grasp the benefits of material productivity improvements.
3) ***Country specifics:*** While the analysis on the country level comprises 28 EU economies, the Community Innovation Survey 2006-2008 only covers 12 EU countries. Since there is great country heterogeneity shown in both the country and firm level studies, the composition of countries could partly explain the different findings.
4) ***Data specifics:*** Survey data always needs to be taken with a pinch of salt, in particular when binary variables are provided. This means that it is not clear whether the material productivity improvements were substantial or simply of minor magnitude that led to the improvements in competitiveness and reductions in GHG emissions.
5) ***Year specifics:*** While the panel data on the macroeconomic level comprises several years, the CIS data covers the years between 2006 and 2008. It is possible that the effect only occurs in particular years, in which material prices change substantially.

Overall, the analyses in Chapters 7 and 8 draw nuanced conclusions on the effectiveness of material productivity to align competitiveness and climate change mitigation objectives. The overall conclusions from this dissertation are discussed in the next chapter.

Chapter 9

Conclusions

9 Conclusions

This dissertation contributes to the discussions on how material use and material productivity affects competitiveness and climate change mitigation efforts in Europe. To this end, the empirical analyses provide new evidence for the effects of material use and material productivity on competitiveness and GHG emissions, thus complementing research conducted by academics as well as international organisations (Bleischwitz and Steger 2009; Allwood et al. 2011; Steinberger and Krausmann 2011; Steger and Bleischwitz 2011; Barrett and Scott 2012; OECD 2016; UNEP IRP 2017).

The great majority of the existing literature as well as vast parts of the debate among policymakers, especially in Europe, argue that material productivity positively impacts on competitiveness while reducing GHG emissions. However, the existing evidence base on this particular issue as well as other topics investigated in this thesis face two main shortcomings, which it attempts to shift the focus to. First, numerous investigations rely on case studies, lacking to consider dynamic effects and heterogeneity across firm, sectors, countries, material subgroups, and material indicators. Second, most empirical studies fail to take the potential problem of endogeneity into account.

This dissertation attempts to highlight the relevance on these and other limitations of the existing literature, while fully acknowledging that it faces its own shortcomings. By taking endogeneity into account and considering the heterogeneity across firms, sectors, countries, material subgroups, and material indicators in Europe, this dissertation advances the current methods used, provides new findings generating new knowledge, potentially initiates a partial revision of existing views, and could foster advances in the application of empirical methods.

The remainder of this chapter briefly summarises the key findings of this dissertation, outlines the insights gained from the analyses, and concludes with a broader outlook of the topic.

9.1 Summary of key findings

The main outcomes of this dissertation can be summarised chronologically by presenting the core findings of the Chapters 3-8 individually.

1) ***The concept of competitiveness:*** By critically reflecting on the existing literature on microeconomic and macroeconomic competitiveness, two insights can be distilled.

First, firm level competitiveness requires to take non-price factors and, most importantly, the relative nature of the concept into account. It is thus crucial to use indicators reflecting the relative performance of firms compared to its peers, for instance, market share growth.

Second, considering competitiveness on the country level needs to take the existence of market failures, price measures as well as non-price measures, country and firm level indicators, welfare creation, and institutional quality into consideration. While it has to be acknowledged that no perfect set of indicators for macroeconomic competitiveness exists, such issues should be accounted for in future analyses.

2) ***Dimensions of costs and benefits of material productivity:*** Applying the comprehensive cost-benefit framework in Chapter 4 illustrates the trade-offs firms could be confronted with when deciding on material productivity investments. Accordingly, their incentives to invest in material productivity tends to increase when externalities are internalised, thus when the environmental dimension of materials is monetised and relevant from a financial perspective.

   Additionally, the results suggest that firms could be more likely to improve their material productivity once secondary effects are considered, and, crucially, the longer their investment horizons are. In short, there could be a trade-off between short term financial (not societal) gains of inaction and long term benefits from investing in material productivity.

3) ***Material use triggers GHG emissions in the short and long term:*** Empirical results in this dissertation provide evidence for a short and long term impact of material use on GHG emissions in Europe. Considering the various material subgroups individually, the findings suggest that the overall effect is mainly driven by fossil fuel use. There is substantial country heterogeneity, implying the importance of country specific approaches. Heterogeneity across material indicators is additionally studied, suggesting that RMC based material use results in fewer GHG emissions compared to the DMC indicator.

   A simple linear prediction shows that reducing material use by around 5% per annum could enable the EU to reach its climate change mitigation target of reducing GHG emissions by 40% by 2030 compared to 1990. It is further shown that reducing material use today requires 4-6 years to unfold its full effect on GHG emissions, thus illustrating a trade-off between reducing material use now by less compared to reducing it later by more.

4) ***Economic growth drives material use in Western Europe:*** This dissertation provides new evidence that increasing the GDP growth rate causes an increase in the DMC growth rate for Western Europe, whereas the effect is insignificant for Eastern European economies. A more disaggregated analysis shows that minerals and biomass materials are the main material subgroups affected by increases in the GDP growth rate for Western Europe, suggesting that infrastructure investments and an increase in food production might be the result of the increased income growth. Furthermore, this dissertation shows that there is significant heterogeneity across countries, again underlying the importance of country specific policy approaches. Moreover, the effect becomes insignificant when RMC data are used.

   Two possible explanations are found that are consistent with these results. Lower energy prices in Western Europe compared to the rest of Europe could increase the demand for materials through its complementarity to energy, and higher labour cost in Western Europe compared to the rest of Europe could have stimulated substitution from labour to materials. This hints to the notion that relative price changes between labour and materials could reduce material use and increase the use of labour, i.e. employment.

5) ***Material productivity leaves most competitiveness indicators and GHG emissions unchanged on the country level:*** This dissertation also shows that increasing the material productivity growth rate causes (i) the wage growth rate to increase, (ii) with lower confidence, the current account growth rate to improve, while other competitiveness indicators are insignificantly affected, and (iii) no statistically significant effect on GHG emissions. The causal impact on the wage rate is robust and relevant, raising the question whether higher wages increase or decrease competitiveness.

   The results are tested against country heterogeneity, suggesting that higher-income countries could benefit more from material productivity improvements in terms of higher wages compared to lower-income economies. Additionally, the model is estimated with the alternative material indicator RMC which fails relevant statistical tests. Furthermore, this chapter discusses policy options to reduce the magnitude of potential rebound effects triggered by higher wages and thus GHG emissions, arguing in favour of channelling the gains from material productivity improvements into eco-innovations.

6) ***Eco-innovation induced material productivity increases boost competitiveness and reduce GHG emissions on the firm level:*** Additional findings provide evidence for a positive and causal impact of increases in material productivity on microeconomic competitiveness for those firms that had an eco-innovation stimulated by public funding. These results are particularly strong in Eastern European countries and material-intensive sectors such as manufacturing, construction, retail trade, food production, and transport. It is further shown that such material productivity improvements also reduce the firms' GHG emissions.

   These results provide the important insight for policymakers in the EU that they could focus their efforts on enabling eco-innovation through providing sufficient and adequate finance as well as reducing barriers for and within firms. Streamlining eco-innovations that result in material productivity improvements are consistent with these results.

In addition to the summary of concrete and novel findings, this dissertation also provides more general insights across the various investigations.

9.2 Insights gained from this dissertation

This dissertation draws nuanced conclusions as to how material use and productivity relates to and whether it can reconcile competitiveness and climate change mitigation objectives. Going beyond the individual findings of each empirical analyses, this dissertation provides evidence for more general insights that can be drawn from findings across the various chapters of this thesis:

1) ***(Limited) reconciliation between competitiveness and climate change mitigation:*** The results and insights gained across the various chapters of this dissertation provide a nuanced picture as to whether material use and material productivity can reconcile competitiveness and climate change mitigation objectives. Since the results in this thesis suggest that material use, and in particular the use of fossil fuels, increases GHG emissions in the short and long term (Chapter 5) and material use is driven by economic growth in Western Europe (Chapter 6), it appears that the ever-increasing use of materials seems incompatible with climate change mitigation objectives. However, as Chapters 7 and 8 show, material productivity can reconcile competitiveness and climate change mitigation objectives for particular firms,

especially those that had an eco-innovation, but not across the entire economies of Europe. This leads to three conclusions.

i. Mainly certain firms, i.e. (eco-)innovative firms in material-intensive sectors in Eastern Europe, seem to benefit from material productivity increases, both in terms of gaining competitiveness and reducing GHG emissions.
ii. This means that there are other firms that are likely to be negatively affected by material productivity increases since there is no evidence presented in this dissertation suggesting that material productivity is a setback in achieving these objectives on a macroeconomic level. Essentially, this suggests that material use and material productivity cannot fully reconcile competitiveness with climate change mitigation objectives.
iii. Accordingly, material productivity can only partially compensate for the low levels of labour productivity increases ('productivity puzzle'), as increased competitiveness resulting from higher (material) productivity predominantly applies to certain sectors only, without having a significant macroeconomic effect. However, the complementarity or substitutability between materials and labour (and thus material and labour productivity) needs to further investigated.

2) ***Potential distributional effects:*** As the previous point illustrates, increases in material productivity can boost competitiveness and reduce GHG emissions of certain firms in Europe, but such benefits are likely to be unequally distributed across firms, sectors, and countries. Therefore, the results of this dissertation are coherent with the notion that not all firms, sectors, or countries are likely to benefit (equally) from increases in material productivity. A further and more detailed investigation is necessary to better identify sectors and regions that are potentially negatively affected in order to support such sectors and areas in successfully managing the effects of a transition towards more resource efficient and sustainable economies.
3) ***Importance of eco-innovations:*** The dissertation's results indicate those eco-innovations that increase material productivity are likely to increase a firm's competitiveness and reduce its GHG emissions, in particular in material-intensive sectors in Europe. This is an enormously important result in support of enabling and financing eco-innovations. Moreover, wage gains from material productivity improvements on the country-level might lead to rebound effects. Channelling wage increases into eco-innovations are found to decrease the magnitude of such effects. Thus, eco-innovations that increase material productivity could serve as an important

strategy for policymakers and firms to achieve competitiveness and climate change mitigation objectives.

4) ***Endogeneity matters (most of the time):*** Addressing the potential problem of endogeneity is at the heart of this dissertation. For instance, researching the effect of economic growth on material use, the 'endogeneity bias' for Western Europe is that the effect of a 1% increase in the GDP growth rate causes the DMC growth rate to increase by 2.7% using a 2SLS approach, compared to 0.9% as suggested by OLS. However, the median value of the OLS results for Western Europe lies within the 95% confidence interval of the 2SLS result. Nevertheless, the differences in the coefficients might lead to contrary conclusions about the income elasticity of material use.

   Moreover, investigating the effect of material productivity on competitiveness on the country level shows that the causal effect on wages is significant, while not addressing endogeneity leaves the impact statistically insignificant. Even though no lessons can be drawn about the type of endogeneity (i.e. omitted factors, simultaneity, or measurement errors), it clearly shows that taking endogeneity into account provides different results.

   Furthermore, considering the impact of material productivity on microeconomic competitiveness, the results provide evidence that material productivity improvements cause microeconomic competitiveness to increase by around 12%, which is statistically different from the OLS results by a factor of four.

   The conclusions drawn from this insight is that not addressing endogeneity tends to underestimate the 'true' effect between economic growth and material use as well as material productivity and competitiveness. Since endogeneity plays an important part in the findings of most estimations in this dissertation, it is not only a *potential* but a *real* issue of concern for academics, international organisations, and policymakers.

5) ***Heterogeneity across firms, sectors, or countries matters:*** Throughout Chapters 5-8, country, sector, or firm heterogeneity is explicitly taken into account. In all investigations, this heterogeneity is shown to be significant and relevant, thus demonstrating the importance of considering heterogeneity.

   The conclusions being drawn from this is that not all firms, sectors, or countries experience the same effects, for instance, mainly material-intensive sectors are likely to benefit from material productivity improvements. This requires a nuanced approach towards material use and productivity as well as firm, sector, or country specific policies in trying to alternate the estimated effects in this dissertation. In short, one-size-fits-it-all thinking would undermine the stark heterogeneity in Europe.

6) ***The type of material indicator matters:*** This dissertation further shows that heterogeneity across material indicators is relevant. By discussing the differences between the DMC and RMC indicators, substantial differences become apparent.

   Acknowledging that different timespans are considered, the effect of RMC on GHG emissions is significantly lower compared to DMC by a factor of three. Moreover, while the effect of economic growth on DMC is statistically significant, the effect becomes insignificant when RMC data is used. Lastly, the effect of material productivity on macroeconomic competitiveness using RMC data fails the conventional statistical tests, thus preventing any inference to be made, confirming that the choice of material indicator has important implications on the conclusions drawn.

   It should be acknowledged that the way RMC data are approximated in this dissertation, i.e. by using averages, might be one reason for these differences. Also, the transnational *indirect* material use that the RMC indicator covers could explain why these two variables produce different results. Future research could focus on using more sophisticated ways to calculate RMC data for empirical analyses.

7) ***More data, better quality:*** Every empirical analysis crucially depends on data availability and quality. Accordingly, the broad availability of DMC data in Europe is one of the core reasons for considering the timespans and countries in this dissertation. Global analyses over longer periods are restricted by the current lack of coherent data.

   Thus, to test the findings of this dissertation across other continents and time horizons would require an international effort to standardise existing databases and develop new ones. For example, extending the RMC-based material indicator for OECD countries would be an important first step. This insight is particularly important for the firm level, as only very limited data sources currently exist. This bottleneck makes it difficult, for example, to identify potential 'losers' of moving towards more material productive economies – an insight that would be important to understand for academics, international organisations, policymakers, and firms.

8) ***Future research areas:*** Besides extending the analyses in this dissertation with regards to their timespan, country coverage, and alternative material indicators, the following are initial ideas on how to build on the findings of this dissertation.

- A more detailed analysis on the environmental implications of material use and productivity going beyond GHG emissions and focusing on local pollution could be addressed by future research projects.
- Future research could focus on better understanding the types of firms and sectors that are potentially adversely affected by material productivity improvements. This would help to inform policymakers to find adequate responses for particularly affected sectors.
- An investigation on the complementarity or substitutability of materials with other inputs such as labour and capital would significantly improve the understanding of welfare creation by the various inputs of the production function. This would further increase the understanding of the contribution material productivity could play in addressing the 'productivity puzzle'.
- The approaches of this dissertation could be complemented by considering the social dimension of materials, for instance, by estimating the distribution of wages increases by material productivity improvements or the health benefits from reducing environmental pressures from increasing material productivity.

9.3 Outlook

It is essential to further research the effects of material use and productivity on competitiveness as well as climate change mitigation objectives. What becomes clear from this contribution is that existing shortcomings matter and need to be addressed to better understand the implications of moving towards more sustainable economies.

Against this backdrop, increasing material productivity might be an important first step in the 'right' direction to meet the goals outlined in the Paris Agreement, the SDGs, and the Addis Ababa Action Agenda (UN 2015a; UN 2015b; UN 2015c). There are encouraging signals to meet such ambitious objectives across the world led by many policymakers, development banks, and the private sector – despite current political uncertainties.

For instance, the OECD is working on practical policy solutions to showcase the importance of policy in the transition towards more resource efficient economies, underpinned by efforts to make coherent and comprehensive data available on these issues (OECD 2014; OECD 2016). The EU continues to shape the agenda towards more resource efficiency and a circular economy, also by supporting research projects on subjects related to this dissertation (EC 2016d; EC 2017f). Development banks additionally provide finance and expertise to further showcase the potential of improving material productivity (EBRD 2015a; EIB 2015; World Bank 2015).

In closing, besides such efforts, one has to keep in mind that there might be 'losers' from this transition (as it is the case for every structural change) and that productivity gains may need to be complemented by continuous, comprehensive, and innovative efforts to ensure a 'fair' transition for all actors involved. In this regard, the on-going communication strategy on the political level that mostly emphasises the benefits could in the long run lead to a deterioration of trust in the very political and institutional structures necessary to enable the transition to a more resource efficient economy. After all, transforming our economy to one that generates welfare while respecting the environmental boundaries of our planet is a task worth pursuing.

10 Bibliography

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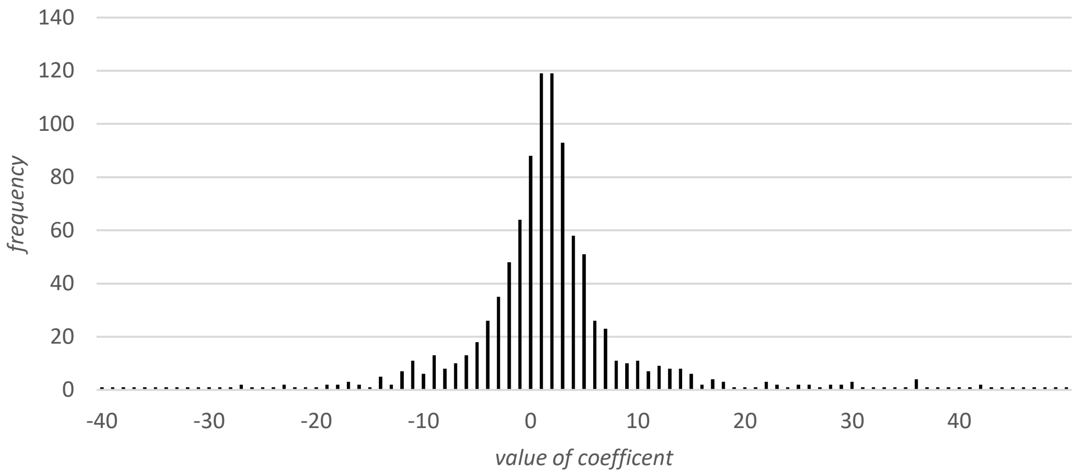
11 Appendix

Table A1: Countries grouped into 'Europe', 'Western Europe', and 'Eastern Europe'

Europe – 32 countries	Western Europe – 19 countries	Eastern Europe – 13 countries
Belgium	Belgium	
Bulgaria		Bulgaria
Czech Republic		Czech Republic
Denmark	Denmark	
Germany	Germany	
Estonia		Estonia
Ireland	Ireland	
Greece	Greece	
Spain	Spain	
France	France	
Croatia		Croatia
Italy	Italy	
Cyprus	Cyprus	
Latvia		Latvia
Lithuania		Lithuania
Luxembourg	Luxembourg	
Hungary		Hungary
Malta	Malta	
Netherlands	Netherlands	
Austria	Austria	
Poland		Poland
Portugal	Portugal	
Romania		Romania
Slovenia		Slovenia
Slovakia		Slovakia
Finland	Finland	
Sweden	Sweden	
United Kingdom	United Kingdom	
Norway	Norway	
Switzerland	Switzerland	
Serbia		Serbia
Turkey		Turkey

Figure A1: 'Pseudo' 1,000 2SLS regressions for Western Europe.



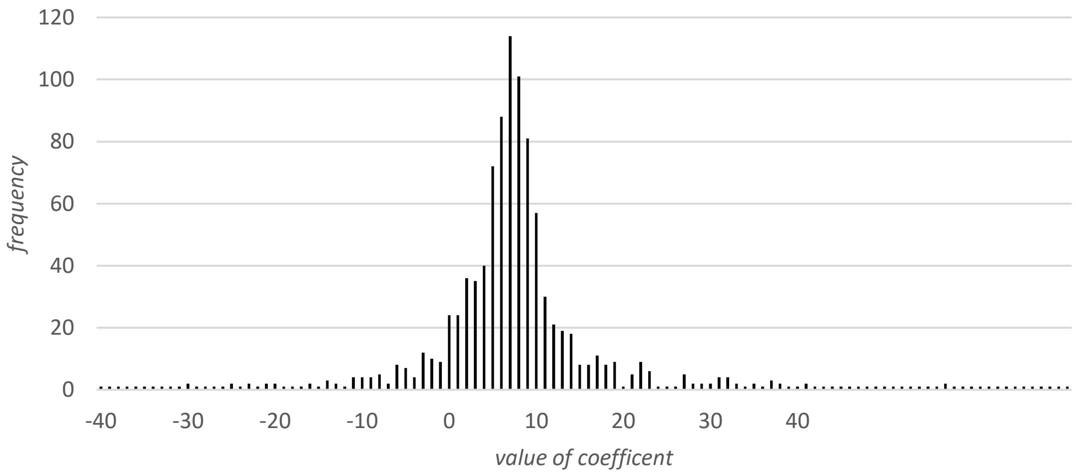
Notes: To increase readability, the range has been limited to -40 and 40, thereby excluding 11 coefficients.

Table A2: 'Pseudo' regression statistics for Western Europe.

	π_1' from Eq (7)
Mean	5.19
Std. dev.	101.23
Median	0.97
5th percentile	-11.55
95th percentile	-11.56

Notes. Statistics of 1,000 π_1' coefficients of 'pseudo' 2SLS regressions. Model is from Eq (7).

Figure A2: 'Pseudo' 1,000 2SLS regressions for Eastern Europe.



Notes: To increase readability, the range has been limited to -40 and 40, thereby excluding 32 coefficients.

Table A3: 'Pseudo' regression statistics for Eastern Europe.

	π_1' from Eq (7)
Mean	13.86
Std. dev.	251.48
Median	0.47
5th percentile	-15.23
95th percentile	24.61

Notes. Statistics of 1,000 π_1' coefficients of 'pseudo' 2SLS regressions. Model is from Eq (7).

Table B1: Countries of the sample.

12 countries	Frequency	Percentage
Bulgaria	4,581	8.69
Cyprus	1,024	1.94
Czech Republic	6,351	12.04
Germany	4,278	8.11
Estonia	1,903	3.61
Hungary	1,720	3.26
Italy	14,919	28.29
Lithuania	1,365	2.59
Latvia	800	1.52
Portugal	6,114	11.59
Romania	8,750	16.59
Slovakia	926	1.76
Total	52,731	100.00

Table B2: Sectors of the sample.

Nace code	13 sectors	Frequency	Percentage
B	mining and quarrying	696	1.32
C	manufacturing	24,659	46.76
D	electricity, gas, steam and air conditioning supply	790	1.5
E	water supply; sewerage; waste management and remediation	1,687	3.2
F	construction	3,940	7.47
G	wholesale and retail trade; repair of motor vehicles and motorcycles	8,154	15.46
H	transporting and storage	3,463	6.57
I	accommodation and food service activities	1,220	2.31
J	information and communication	2,713	5.14
K	financial and insurance activities	2,043	3.87
L	real estate activities	189	0.36
M	professional, scientific and technical activities	2,461	4.67
N	administrative and support service activities	716	1.36
B-N	***Total***	52,731	100.00

Table B3: Instrument properties.

Dependent: PFS_i	
constant	0.013
Country	
Bulgaria	reference
Cyprus	0.003
Czech Republic	0.040***
Germany	0.025***
Estonia	0.014***
Hungary	0.006
Italy	0.095***
Lithuania	0.020***
Latvia	0.009
Portugal	0.024***
Romania	0.021***
Slovakia	0.040***
Sector	
mining and quarrying	reference
manufacturing	-0.004
electricity, gas, steam and air conditioning supply	0.050***
water supply, sewerage, waste management and remediation activities	0.079***
construction	0.023**
wholesale and retail trade; repair of motor vehicles and motorcycles	-0.025***
transporting and storage	0.013
accommodation and food service activities	-0.025*
information and communication	-0.035***
financial and insurance activities	-0.024**
real estate activities	-0.025
professional, scientific and technical activities	-0.000
administrative and support service activities	-0.040***
Largest market	
locally	reference
nationally	0.010***
Europe	-0.007**
outside Europe	0.006
Employment, 2006	
<50 employees	reference
50-250 employees	0.010**
>250 employees	0.033***
Employment, 2008	
<50 employees	reference
50-250 employees	0.019***
>250 employees	0.026***
turnover, 2006	0.000
turnover, 2008	0.000
R^2	0.030
N	52,713

Notes. Dependent variable is PFS_i. Estimated with OLS. SEs are robust against heterogeneity. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table B4: Probit estimations.

	(1)	(2)	(3)	(4)
ΔMP_i	1.4687***	1.5483***	1.4687***	1.4683***
	(0.0167)	(0.0396)	(0.0419)	(0.0420)
$\Delta product_i$		0.1943***	0.1564***	0.1616***
		(0.0241)	(0.0252)	(0.0253)
$\Delta MP_i * \Delta product_i$		-0.1712***	-0.1678***	-0.1689***
		(0.0377)	(0.0398)	(0.0399)
$\Delta process_i$		0.3663***	0.3019***	0.3011***
		(0.0233)	(0.0246)	(0.0246)
$\Delta MP_i * \Delta process_i$		-0.2478***	-0.2449***	-0.2432***
		(0.0389)	(0.0411)	(0.0412)
$\Delta organisational_i$		0.3571***	0.2904***	0.2921***
		(0.0223)	(0.0234)	(0.0234)
$\Delta MP_i * \Delta organisational_i$		-0.1179***	-0.1348***	-0.1351***
		(0.0380)	(0.0400)	(0.0400)
$\Delta marketing_i$		0.1944***	0.1890***	0.1881***
		(0.0227)	(0.0237)	(0.0238)
$\Delta MP_i * \Delta marketing_i$		-0.0962***	-0.0668*	-0.0684*
		(0.0362)	(0.0381)	(0.0382)
$environmental\ programme_i$			0.5173***	0.5197***
			(0.0179)	(0.0179)
$turnover_{i,2008}/turnover_{i,2006}$			0.0000	0.0002
			(0.0093)	(0.0093)
$size_{2006,i}$			0.0970***	0.1078***
			(0.0131)	(0.0135)
$\Delta size_i$			0.0195	0.0245
			(0.0294)	(0.0296)
$national_i$				-0.0426**
				(0.0191)
$europe_i$				-0.0988***
				(0.0295)
RoW_i				-0.0898**
				(0.0488)
Country dummies	YES	YES	YES	YES
Sector dummies	YES	YES	YES	YES
Pseudo R^2	0.24	0.28	0.30	0.29
N	58,478	58,478	54,401	54,234