Creating innovation incentives through environmental policies: An economic analysis

vorgelegt von

Vera Zipperer, M.Sc.

von der Fakultät VII – Wirtschaft und Management
der Technischen Universität Berlin

zur Erlangung des akademischen Grades
Doktorin der Wirtschaftswissenschaften
– Dr. rer. oec. –

Genehmigte Dissertation

Promotionsausschuss:

Vorsitzender:	Prof. Dr. Marco Runkel, TU Berlin
Gutachter:	Prof. Karsten Neuhoff, Ph.D., TU Berlin
Gutachter:	Prof. Simone Borghesi, Ph.D., EUI Florence

Tag der wissenschaftlichen Aussprache: 10. September 2019

Berlin, 2019

To my parents

Acknowledgements

I would like to thank my main supervisor, Karsten Neuhoff, for fruitful supervision, providing helpful comments to my work with his smart and sharp mind, and for challenging me and my work throughout my time as PhD student. Further, I am grateful to my second supervisor, Simone Borghesi, for accepting to be part of my dissertation committee – providing a full circle back to my first thoughts about conducting a PhD back in time at a meeting of the Italian Association of Environmental and Resource Economists in Milan.

My invaluable thanks go to my co-authors Greg, Martina, Misato, Silvia, and Tomasz for sharing laughter and sweat, for showing and receiving respect and appreciation. Specifically, I would like to thank Greg for his contagious enthusiasm about innovation policy and for being an inspiring co-author who shaped my mind like no one else to think in a consistent and concise way. Further, I am indebted to Misato for being a great role-model and for hosting me at the Grantham Research Institute in London which provided an unforgettable and immensely enriching experience to me – not only from an academic point of view but far more than this, with special thanks to the whole joyful GRI team, and Elisabeth, Tobias and Isa for introducing me to the adventure of climbing. I also gratefully acknowledge financial support from the DIW Graduate Center and the Stiftung der Deutschen Wirtschaft which allowed me to conduct this research stay but mostly allowed me to fully concentrate on my research throughout my time as PhD student.

I owe special thanks to my colleagues from the DIW, especially the climate policy department, the GC-cohort of 2014, and the yoga group. Particularly, I would like to thank Nils for guiding me through the PhD-jungle, whether these were the complexities of being a PhD-student or whether this was our green office-oasis filled up with plants. No words can express my gratitude to Olga C. who always ensured that I would not loose my motivation for finishing this thesis. Thank you for being such a wonderful person, always cheering up your environment, for having and showing faith in me. A very special thanks also goes to Jan for being the best sparrings-partner I could have wished for, far beyond PhD-related topics.

Last but not least, I would like to thank my family and friends. Special thanks go to Cortnie for turning our PhD-life not only into one study trip but into many more shared journeys, to Antonia for sharing the PhD-experience with me in which it is invaluable to know that there is a special someone out there, going through the same ups and downs of a dissertation, to Rabea and Anke for having their doors always open for me, to Victoria for grounding and motivating me throughout the last years, to Julia for not getting tired of showing me the 'real' world beyond academia. Far beyond all, and from the bottom of my heart, I would like to thank my family for their understanding, their patience, and their endless support without which this thesis would never have been possible.

Summary

Environmental policies are often considered as burden to firms as these face additional costs in order to comply with the regulations. However, by adapting to new regulatory frameworks, firms might reconsider their previous production processes and thereby reap additional gains, e.g. in terms of productivity through resource reallocation within the firm, or enhanced innovation activity. In four chapters, the present thesis examines whether environmental policy is able to create incentives for innovation and how appropriate measures could be designed. In the framework of the innovation concept of technology-push and demand-pull instruments, the potential of different environmental policies to create innovation incentives is assessed.

The first chapter takes a bird's eye view of the topic by examining the relationship between an aggregated indicator of environmental policy stringency and the productivity of firms. The analysis confirms that a tightening of environmental policy is able to provide benefits in terms of productivity gains – but only for already highly productive firms. Less productive firms are experiencing productivity losses as environmental policy becomes more stringent.

The second chapter deals with public innovation funding for low-carbon demonstration plants as an example of a technology-push policy and identifies learning, knowledge dissemination, gradual upscaling, financial engagement of the private sector, and the generation of a robust demand-pull for low-carbon technologies as key design aspects for the success of public innovation funding.

The third chapter looks at green public procurement as an example of a demand-side policy. The analysis shows that the inclusion of environmental criteria in the

selection phase of the procurement process is associated with an increased innovation activity in form of product innovations for firms that have been able to win such procurement contracts.

The fourth chapter investigates design aspects of another demand-side policy instrument – namely the pricing of environmental externalities from production processes. The analysis characterises general principles for the design of the benchmark-based free allowance allocation mechanism in the European Emissions Trading System and underlines the importance of including indirect emissions in such a system.

Zusammenfassung

Umweltpolitikmaßnahmen werden häufig als Belastung für Unternehmen angesehen, da sich die betroffenen Unternehmen mit zusätzlichen Kosten konfrontiert sehen, um neue Vorschriften einzuhalten. Durch die Anpassung an neue regulatorische Rahmenbedingungen können jedoch auch Produktivitätsgewinne für Unternehmen entstehen, da bisherige Produktionsprozesse überdacht werden müssen, und dadurch eine Ressourcenumschichtung innerhalb des Unternehmens oder verstärkte Innovationstätigkeiten entstehen können. Die vorliegende Dissertation untersucht in vier Kapiteln, ob Umweltpolitik in der Lage ist, Innovationsanreize für Unternehmen zu schaffen und wie geeignete Maßnahmen gestaltet werden können. Im Kontext des Innovationskonzepts von Technologie-Push und Nachfrage-Pull-Instrumenten wird das Potenzial verschiedener Umweltpolitikmaßnahmen zur Schaffung von Innovationsanreizen bewertet.

Das erste Kapitel nimmt eine Vogelperspektive auf das Thema ein, indem es den Zusammenhang zwischen einem aggregierten Indikator für die Stringenz von Umweltpolitik und der Produktivität von Unternehmen untersucht. Die Analyse zeigt, dass eine Verschärfung der allgemeinen Umweltpolitik Vorteile in Form von Produktivitätssteigerungen für ohnehin bereits sehr produktive Unternehmen mit sich bringt. Weniger produktive Unternehmen verzeichnen Produktivitätsverluste mit zunehmender Stringenz der Umweltpolitik.

Das zweite Kapitel befasst sich mit öffentlicher Innovationsförderung für kohlenstoffarme Pilotanlagen als Beispiel für eine Technologie-Push-Politik und identifiziert Lernerfahrungen, Wissensweitergabe, schrittweise Hochskalierung, finanzielle Beteili-

gungen privater Unternehmen, sowie die Erzeugung von anhaltender Nachfrage nach kohlenstoffarmen Technologien als erfolgsentscheidende Designaspekte der Innovationsfinanzierung.

Das dritte Kapitel befasst sich mit nachhaltiger, öffentlicher Auftragsvergabe als Beispiel für eine nachfrageseitige Politikmaßnahme. Die Analyse zeigt, dass die Einbeziehung von Umweltkriterien in der Auswahlphase des Beschaffungsprozesses mit einer erhöhten Innovationstätigkeit in Form von Produktinnovationen von Unternehmen einhergeht, welche diese Beschaffungsaufträge für sich gewinnen konnten.

Das vierte Kapitel befasst sich mit den Gestaltungsaspekten eines weiteren nachfrageseitigen Politikinstruments, der Bepreisung externer Umweltauswirkungen von Produktionsprozessen. Die Analyse charakterisiert Grundsätze für die Ausgestaltung der Referenzwert-basierten, kostenlosen Emissionszertifikatszuteilung im Rahmen des Europäischen Emissionshandelssystems und unterstreicht die Notwendigkeit der Einbeziehung indirekter Emissionen in ein solches System.

List of publications included in this dissertation

Chapter 1: Environmental policies and productivity growth: Evidence across industries and firms

- Co-authors: Silvia Albrizio, Tomasz Kozluk
- Published in *Journal of Environmental Economics and Management* (2017), January 2017, Volume 81: 209-226, available under DOI: https://doi.org/10.1016/j.jeem.2016.06.002
- The version included in this thesis is the post-print version.

Chapter 2: The valley of death, the technology pork barrel, and public support for large demonstration projects

- Co-authors: Gregory Nemet, Martina Kraus
- Published in *Energy Policy* (2018), August 2018, Volume 119: 154-167, available under DOI: https://doi.org/10.1016/j.enpol.2018.04.008
- The version included in this thesis is the post-print version.

Chapter 3: Green public procurement and the innovation activities of firms

- Single authored
- Published as DIW Discussion Paper No. 1820 (2019), available under https://www.diw.de/documents/publikationen/73/diw_01.c.676416.de/dp1820.pdf
- The version included in this thesis is the post-print version.

Chapter 4: Benchmark design for emissions trading schemes

- Co-authors: Misato Sato, Karsten Neuhoff

- A previous version of this chapter was published as DIW Discussion Paper No. 1712 (2017), available under https://www.diw.de/documents/publikationen/73/diw_01.c.574078.de/dp1712.pdf and as GRI Working Paper No. 287 (2017), available under http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2017/12/Benchmarks_for_emissions_trading_general_principles_for_emissions_scope.pdf

- The version included in this thesis is a revised version of the previously published working papers.

Contents

General Introduction

Global warming poses one of the major challenges to today's societies. Despite political efforts and commitments, an enhanced effort in climate policy is needed to keep global warming below one and a half degrees Celsius above pre-industrial temperature levels in order to limit damages to biodiversity, ecosystems, and climate-related risks like food and human security (IPCC, 2018). While countries around the world have begun to implement various environmental policy tools, such as emissions trading schemes or environmental regulation, the projections of CO_2 emissions without any further policy changes over the next decades are still alarming, as keeping global warming below the necessary threshold becomes more and more unlikely (UNEP, 2018).

One crucial ingredient to achieving a low-carbon economy in the future, is technological innovation. Without immense reductions of consumption patterns, significant emission reductions can only be achieved if new technologies are developed and implemented. While incremental innovations, such as energy efficiency measures in the industrial sector, are important along the transition pathway, they will not be sufficient to achieve a deep decarbonisation of the industry (see Lehne and Preston (2018) for an example of the cement sector). Breakthrough technologies are urgently needed but seem to have difficulties of reaching the commercial market stage.

This thesis examines the effect of environmental policies on the innovation activities of firms. While the reason for implementing environmental policies is achieving certain environmental objectives, these policies will at the same time have effects on the economy as consumer and producer behaviour will adapt to the new policy framework. The overarching research question of this thesis is whether firms react to new environmental policies through changes in their innovation activities, focusing on the effects in the industrial sector. While Chapter 1 provides an analysis of a composite index of environmental policy stringency and productivity, the following chapters study more specific environmental policies. The environmental policies considered include public innovation funding for low-carbon technologies (Chapter 2), green public procurement (Chapter 3), and emissions trading schemes (Chapter 4).

The first chapter of the thesis starts from an evolutionary perspective which underlines the potential benefits of additional environmental regulations to firms (Jaffe et al., 2002). While environmental regulations are often considered to create additional costs to firms as these have to comply to new rules, there might also be benefits from such regulations: assuming that firms are subject to bounded rationality, they might reconsider their production processes in order to produce in accordance with the new regulation and thereby unlock previously overseen potentials. Incentives for innovation, efficiency improvements and resource reallocation within firms might thus lead to enhanced productivity. This argument is widely known as the so-called Porter Hypothesis (Porter, 1991, Porter and Linde, 1995) and has sparked considerable interest of both academia and policy makers over the past decades. While understanding the economic effects of environmental policies is crucial for designing future environmental policies, the empirical evidence on the Porter Hypothesis has so far been limited to country, sector or policy-specific analyses as comparable cross-country measures of environmental policy stringency were not readily available (Kozluk and Zipperer, 2014).

Chapter 1 of this thesis, joint work with Silvia Albrizio and Tomasz Kozluk, provides the first large cross-country study on the strong version of the Porter Hypothesis[1], based on a newly developed indicator of environmental policy stringency. The

[1] Jaffe and Palmer (1997) distinguished three versions of the Porter Hypothesis, namely the weak, the strong and the narrow version. According to the weak version, more stringent environmental

chapter evaluates the effect of environmental policy stringency on multi-factor productivity in a panel of OECD countries, combining an industry-level with a firm-level analysis. A neo-Schumpeterian productivity model is used as basis for the econometric analysis (Acemoglu et al., 2006, Aghion and Howitt, 2006). The contribution to the literature in the field is twofold. First, the use of the new cross-country measure of environmental policy stringency (EPS) overcomes previous obstacles such as single-country studies or single-sector studies (see Brunel and Levinson (2016) for a discussion of different measures; see Cohen and Tubb (2015) and Kozluk and Zipperer (2014) for a literature overview of the Porter Hypothesis). The use of the EPS indicator allows a global perspective on the Porter Hypothesis over more than two decades, even though it has be be acknowledged that the coverage is limited to OECD countries and thus only covers industrialised economies. Second, the combination of a industry-level and firm-level analysis allows drawing more robust conclusions about the channels at work behind potential effects: the industry analysis provides insights on aggregate effects by taking into account entry and exit of firms but might miss insights in terms of heterogeneous effects on firms. The firm analysis thus allows a more detailed look at heterogeneous effects while being limited in terms of representation of the firm population. The results of the analysis show that a tightening of environmental policy is associated with a short-term increase in industry-level productivity growth for countries near the global technology frontier. The effect diminishes and vanishes the further away industries are from the global productivity frontier. A similar pattern is found in the firm-level analysis: the most productive firms in an industry see a temporary boost in productivity growth when environmental policy stringency is tightened, while the less productive firms experience a productivity slowdown.

The second chapter takes a more detailed look at a specific technology-push policy for environmental innovations, namely public innovation funding for low-carbon

policies stimulate innovation, the strong version suggests that tighter environmental policies might lead to productivity gains for firms. The narrow version claims that only well-designed environmental policies will lead to the effects suggested by the weak and strong version.

technologies. While productivity gains, like the ones analysed in the context of the Porter Hypothesis, might often be achieved through incremental innovations, additional breakthrough technologies are needed to achieve a deep decarbonisation of the industry (Neuhoff et al., 2015). Moving these non-incremental innovations from the initial pilot scale to full commercial scale is, however, not trivial due to technical risk of upscaling, uncertain market demand and the need for large investments (Murphy and Edwards, 2003). This implies that many inventions never become widely available in the market – a phenomenon which is known as the 'technology valley of death' in the innovation literature. This valley of death might be overcome through either technology-push policies or demand-pull policies. Examples of technology-push policies include R&D grants, tax credits for firms, the creation of knowledge networks, and public innovation funding.

Chapter 2 of this thesis, joint work with Gregory Nemet and Martina Kraus, investigates the characteristics of well-designed public innovation funding for low-carbon demonstration projects. Collecting a new dataset of 511 case studies on publicly funded demonstration projects in the energy and materials sector, the chapter provides new evidence on factors important in designing public innovation funds. Nine technology areas were coded, ranging from solar thermal electricity, wind power, CCS (industrial and power) low-carbon steel and cement, and synthetic fuels to cellulosic biofuels. Information on the timing, motivation, scale, and share of public funding of projects was gathered in order to quantitatively analyse the factors contributing to successfully overcoming the valley of death for these projects. The chapter also contributes to the literature by providing a conceptualisation of the literature surrounding the valley of death with a specific regard towards low-carbon innovations. Combining the analysis of the case studies and the literature yields several main insights for the effective design of innovation funding to overcome the valley of death for low-carbon demonstration projects: first, learning through such demonstration projects should be prioritised, paired with knowledge transmission of the projects through well-documented failures and successes. Second, enough time should be provided for iterative upscaling as the successful set-up of ever larger demonstration projects needs time. Third, the private sector should be kept engaged financially to align incentives for long-term objectives. Last, a robust demand-pull mechanism should be put in place to ensure that new technologies reach the commercial stage eventually.

The third chapter looks at the possibility of creating a robust demand-pull effect through an enhanced use of environmental selection criteria in public procurement. As mentioned above, next to technology-push policies, demand-pull policies might also be implemented to overcome the valley of death. Such policies create more predictable market environments for innovations reaching the commercial scale. Examples include intellectual property rights, technology standards, subsidised demand, externality pricing, and public procurement. Government spending in form of public procurement accounted for 12% of GDP on average in OECD countries in 2015 (OECD, 2017), making governments a substantial buyer in the market. By making use of their market power, governments could achieve certain normative policy objectives, such as sustainability, through procurement by adding e.g. environmental criteria to procurement tenders. So-called 'green public procurement' (GPP) might have a direct environmental effect by lowering the carbon footprint of the public sector, but also an indirect effect through induced innovations by creating lead markets for new environmentally friendly products. While green public procurement is high on the international policy agenda[2], little is known about whether the desired innovation effect of green procurement might work at all.

Chapter 3 of this thesis provides first empirical evidence on whether and how environmental criteria used in procurement tenders, i.e. green public procurement, are able to trigger innovation activities within firms. The analysis is based on a

[2]Green public procurement is one of the six priorities of the European Commission in its 2017 procurement strategy (European Commission, 2017b). The United Nations anchored sustainable procurement as target 12.7 in their Sustainable Development Goals (UNEP, 2017).

novel dataset which is the first one to combine data from large-scale green public procurement contracts with firm-level innovation data for a sample of German firms from 2006 to 2016. By using actual procurement contract-level data, it is possible to analyse the direct relationship between GPP and innovation, instead of having to rely on proxy measures of procurement as other studies have done (e.g. Aschhoff and Sofka (2009)). The empirical analysis uses a binary-response model to evaluate whether winning a GPP contract increases the probability of firms' innovations. The chapter thereby adds to the literature on procurement as demand-side innovation policy instrument (see Appelt and Galindo-Rueda (2016) for a review and Czarnitzki et al. (2018) for a recent addition to the literature) by looking specifically at *green* public procurement. The results of the analysis show some support for a demand-pull effect of GPP: winning a GPP contract is related to a higher probability of general product innovations. However, no significant correlation is found with general process innovations of firms. Looking specifically at environmental innovations, investigating whether GPP could be a driver of environmental innovations, the results show no significant correlation between winning a GPP contract and environmental process or product innovations.

The fourth chapter investigates the design of another demand-side innovation mechanism, namely externality pricing. Emissions trading schemes (ETS) are a popular way of pricing greenhouse gases such as CO_2 and are rapidly spreading around the world (ICAP, 2018). However, as the geographic coverage of trading schemes is only local or regional, policy makers and industry are often afraid of so-called carbon leakage: the re-location of industrial production to areas without carbon pricing as reaction to increased production costs due to the externality pricing. Carbon leakage prevention measures thus remain a key part of unilateral carbon pricing instruments – the new standard policy tool to prevent carbon leakage being benchmark-based free allowance allocation. As the coverage of emissions trading schemes increases, both in terms of sectors as well as countries, it becomes crucial to better understand the incentives put in place through benchmark-based free allocation.

Chapter 4 of this thesis, joint work with Misato Sato and Karsten Neuhoff, analyses the design of emission benchmarks used to allocate free allowances in the European Emissions Trading Scheme (EU ETS) with a specific focus on the basic materials sector. Using an analytic model, the chapter is the first to analyse the effects of the scope of benchmark design with regard to direct and indirect emissions covered, adding to the literature on free allocation mechanisms in emissions trading schemes (see Branger and Sato (2017) for an example of misaligned incentives in the cement sector). While emission benchmarks aim to provide a technology-neutral basis for carbon leakage protection in order to incentivise innovative technologies, the results of the analysis show that the current design of benchmarks creates distortions in terms of abatement incentives as indirect emissions attributable to inputs and outputs are not adequately accounted for. General principles for setting the benchmark scope are developed in the chapter, arguing that a systematic adjustment of the scope of emissions covered in benchmarks is necessary to drive efficient input and output choices and achieve significant emission cuts. The chapter also highlights the important role of getting benchmarks right when supplementing output-based free allocation with a consumption tax for emission-intensive goods as demand-side carbon leakage mitigation.

Table 1: Overview by chapter: topic, pre-publication and author's contribution

Ch.	Title	Co-Authors	Pre-Publication	Contribution
I	Environmental policies and productivity growth: evidence across industries and firms	Silvia Albrizio, Tomasz Kozluk	Journal of Environmental Economics and Management 81 (2017): 209-226; Prior version: OECD Eco. Dep. Working Papers No. 1179 (2014).	Author was responsible for parts of the firm-level econometric analysis. Data collection and cleaning, model development, analysis and interpretation of results, as well as writing was collaborative.
II	The valley of death, the technology pork barrel, and public support for large demonstration projects	Gregory Nemet, Martina Kraus	Energy Policy 119 (2018): 154-167; Prior version: DIW Discussion Paper No. 1601 (2016).	Author collected case studies on biofuels and CCS, and conducted econometric analysis. Analysis of case studies, interpretation of results, and writing was collaborative.
III	Green public procurement and the innovation activities of firms	Single author	DIW Discussion Paper No. 1820 (2019).	The author is responsible for all parts of the research.
IV	Benchmark design for emissions trading schemes	Misato Sato, Karsten Neuhoff	DIW Discussion Paper No. 1712 (2017); GRI Working Paper No. 287 (2017).	Author developed analytic details of the model and is responsible for writing the manuscript. Research idea and overall framing was collaborative.

Chapter 1

Environmental policies and productivity growth: evidence across industries and firms*

1.1 Introduction

Over the past twenty years, governments in OECD countries have implemented a wide range of environmental policies with the aim of improving environmental conditions. Policy instruments are often based on price mechanisms (market based instruments), increasing the opportunity costs of pollution and environmental damage, or take the form of command-and-control policies, enforcing environmental standards (non-market instruments). Inevitably, environmental policies affect production processes,

*This chapter is joint work with Silvia Albrizio and Tomasz Kozluk. The paper is published in the Journal of Environmental Economics and Management 81 (2017), available under https://doi.org/10.1016/j.jeem.2016.06.002. An earlier version was published as OECD Economics Department Working Paper No. 1179 (2014). It should not be reported as representing the official views of the OECD or of its member countries. The authors would like to thank Jean-Luc Schneider, Giuseppe Nicoletti, Shardul Agrawala, Nick Johnstone, Chiara Criscuolo, Peter Gal, Carlo Menon, Jehan Sauvage, Oystein Skeie, Enrico Botta and two anonymous referees for their useful comments and suggestions. Special thanks go to Catherine Chapuis for statistical assistance.

resource reallocation, capital investment, labour intensity and innovation incentives. Therefore, the ongoing tightening of environmental regulation is likely to affect not only environmental outcomes but also economic performance.

This paper focuses on the effects of environmental policy stringency on multi-factor productivity (MFP) growth. More stringent environmental policies imply an additional burden for firms, inducing a shift of resources from the traditionally "productive" uses towards pollution abatement. Hence, firm-level productivity growth may slow down, at least in the short term. At the same time, incentives for innovation, efficiency improvements and within-firm reallocation may lead to higher productivity, as suggested by the so-called Porter Hypothesis (PH; Porter (1991); Porter and Linde (1995)). Jaffe and Palmer (1997) characterise three variants of the Porter Hypothesis: the weak version implies that tighter environmental policies stimulate innovation, whereas the strong version claims that environmental policy may lead to higher overall productivity of firms. Finally the narrow version of the PH states that gains in productivity and innovation redirection are more likely under certain types of environmental policies, such as flexible, market based instruments. At the industry-level, the direction of the effect of environmental policies on productivity will also depend on the resulting resource reallocation among firms: polluting firms may exit or enter the market, decrease or increase their production or outsource part of their activities or relocate abroad (in line with the pollution haven hypothesis, see for example Levinson and Taylor (2008)). Furthermore, if environmental policies increase barriers to entry, competition or trade, competitive pressures will be reduced, firms' entry-exit dynamics will slow and industry productivity will decrease. Hence, understanding the impact of environmental policies on MFP growth is crucial for the design and choice of policy packages. Yet, empirical evidence on such effects has been rather country- and context-specific and thus inconclusive. The two main constraints on empirical work so far are poor data availability, as good cross-country proxies for environmental policy stringency are hard to come by (Botta and Kozluk, 2014, Brunel and Levinson, 2016), and the fact that identification strategies based on the introduction of one policy in several countries at the same time are not feasible due to a scarcity of such examples and multiple interfering factors.

In an attempt to fill this gap, we focus on the strong version of the PH and conduct an empirical analysis of the effect of environmental policy stringency (EPS) on productivity growth. The contribution of this analysis is twofold. First, we employ a new cross-country proxy of environmental policy stringency, developed by Botta and Kozluk (2014).[1] This allows a panel analysis of OECD countries over two decades giving a more global perspective to the literature on the Porter Hypothesis. Second, we combine industry and firm-level results. The industry analysis considers aggregate effects on the full firm population, that is, including entry and exit and the relative importance of effects across firms weighted by their size, but may suffer from aggregation bias: different effects of environmental policy stringency on firm-level MFP growth may cancel out on the industry-level. The firm-level analysis can address this heterogeneity directly, but has limitations in terms of population representation and tracking firm entry and exit dynamics. Thus a combination of analysis at the two levels offers additional insights on the channels at work.

The results suggest that a tightening in environmental policies has a positive short-term effect on industry productivity growth in the most technologically advanced country-industry pairs. This positive effect diminishes with the distance to the global technology frontier and vanishes completely for the least productive ones. This finding is only partially reflected in the results at the firm-level: only one-fifth of the firms are able to reap productivity gains after a tightening of environmental regulation. About half of the firms, the least productive ones, face a negative effect on productivity growth in the short run. This negative effect, for less technologically advanced firms, is lost at the industry-level due to aggregation. Moreover, empirical

[1] The OECD's Environmental Policy Stringency indicator was developed as part of the same project as this empirical work. Details on the indicator, updates and the underlying data can be found at http://oe.cd/eps.

results across the two levels of analysis yield some support for the narrow version of the Porter Hypothesis: market based environmental policies are found to be more productivity-friendly than non-market instruments.

The paper is structured in the following way. Section 1.2 provides an overview of the relevant empirical literature on the effects of environmental policies on productivity growth. Section 1.3 presents the EPS index used in the analysis, followed by Section 1.4, providing some descriptive statistics. Section 1.5 explains the empirical methodology, details about the data used, the main results, and discusses potential channels of the effects. Section 1.6 provides additional tests and Section 1.7 robustness checks. The final section concludes.

1.2 Literature review

Empirical studies about the PH can be broadly divided into two main strands: analyses of the "strong" version look at productivity growth, while analyses of the "weak" version focus on innovation. The "narrow" version is less frequently analysed.

At the industry-level, empirical studies of the effects of environmental policies on productivity growth provide rather inconclusive evidence on the significance and direction of the effect (Cohen and Tubb, 2015, Kozluk and Zipperer, 2014, Ambec et al., 2013). This may be because they often analyse rather context specific set-ups, such as single countries, industries or specific environmental laws. Older industry-level studies, which tend to find negative effects of environmental regulations on productivity growth, suffer from problems of identification and are generally not very robust. Notable contributions include attempts to explain the US productivity slowdown in the 1970s with environmental regulation (Gray, 1987, Barbera and McConnell, 1990), as well as Dufour et al. (1998) who looks at Canadian industries in the 1980s. More recent work, based on longer time series or case studies, finds an aggregate positive or nil effect. Hamamoto (2006) finds that environmental command and control regulations led to an increase in innovation (R&D spending) and consequently to an increase in productivity growth in a sample of five Japanese manufacturing sectors over 20 years. Yang et al. (2012) find similar effects of environmental policy tightening on Taiwanese manufacturing sectors; while for Quebec, Lanoie et al. (2008) find a short-run negative effect, due to the additional costs imposed by the tighter environmental regulation, outweighed by a subsequent positive effect. An early study with an international dimension, Alpay et al. (2002), finds no effect on productivity growth in the US food manufacturing sector (where environmental policies are proxied by pollution abatement and control expenditures) but a positive effect in Mexico (with environmental policies proxied by the frequency of environmental inspections). More recently, Franco and Marin (2017) find a positive effect of environmental taxes on productivity in European countries in the early 2000s, but no effect on innovation (measured by patent counts), suggesting a direct effect of environmental policies. Rubashkina et al. (2015) find the opposite effects in a panel of 17 European manufacturing sectors using abatement cost data as the environmental policy proxy: industry productivity seems unaffected by abatement costs whereas patenting activity increased.

Evidence from firm or plant level studies shows a negative but also not very robust effect of environmental regulation on productivity growth (Cohen and Tubb, 2015, Kozluk and Zipperer, 2014). Most of the studies compare productivity growth between regulated and non-regulated firms or plants, finding negative (Gollop and Roberts, 1983, Smith and Sims, 1985) or insignificant (Berman and Bui, 2014) results. These early studies often neglect including firm or plant specific characteristics in the analysis. Becker (2011) and Gray and Shadbegian (2003) show the importance of including such characteristics and find negative effects of environmental regulation on productivity growth. The effect of environmental regulation can also depend on the type of pollutant regulated. In this respect, Greenstone et al. (2012) identify a negative effect of ozone and particulates emission regulations, no effect of sulphur dioxide emission regulations and a positive effect of carbon monoxide regulations.

Aside the aforementioned methodological issues, the firm and plant level studies suffer from a lack of generality, as they usually analyse very specific regulations or industries in a single country setting.

Empirical studies on the Porter Hypothesis, strong or weak version, rely on a vast range of measures of environmental policy stringency. Most studies focusing on the effects in a single country look at the introduction, or significant change, in a particular environmental policy, or the difference between regulated and unregulated firms. Such approaches can be more precise in capturing causal relationships, but at the sacrifice of the generality of conclusions. Cross country (or state) studies are limited by the availability of cross-country measures of environmental policies. The proxies used range from pollution abatement expenditures (Gray, 1987, Morgenstern et al., 2002, Gray and Shadbegian, 2003), survey-based policy perceptions (Kalamova and Johnstone, 2011, Johnstone et al., 2010, Johnstone and Labonne, 2006, Lanoie et al., 2011), environmental treaties signed (Javorcik and Shang-Jin Wei, 2004, Yörük and Zaim, 2005, Wu and Wand, 2008), "green" voting records (Gray, 1997) or environment-related inspection frequency (Alpay et al., 2002, Testa et al., 2011, Brunnermeier and Cohen, 2003). In addition, some papers use revealed performance measures, such as energy or pollution intensity or environmental compliance (Cole and Elliott, 2003, Beers and Bergh, 1997, Harris et al., 2002, Mcconnell and Schwab, 1990, Javorcik and Shang-Jin Wei, 2004).

1.3 EPS – a new measure of environmental policy

Our paper's contribution is to provide a cross-country panel analysis of the strong version of Porter's Hypothesis using a new composite index of environmental policy stringency (EPS) developed by the OECD (Botta and Kozluk, 2014). The EPS index covers 24 OECD countries over the period 1990–2012 and summarises environmental policy stringency across selected instruments. The indicator is based on the taxonomy developed by De Serres et al. (2010) and consists of two components, a market based and a non-market one. The market based component groups instruments which assign an explicit price to the externalities (taxes: CO_2, SOX, NOX, and diesel fuel; trading schemes: CO_2, renewable energy certificates, energy efficiency certificates, feed-in-tariffs, and deposit-refund-schemes), while the non-market component clusters command-and-control instruments, such as standards (emission limit values for NOX, SOX, and PM, limits on sulphur content in diesel), and technology-support policies, such as government R&D subsidies. The indicator ranges from 0 to 6 with higher numbers being associated with more stringent environmental policies. The novelty and advantage of this indicator is that it reduces a complex set of multi-dimensional policies into a comparable country-specific proxy. While the indicator focuses on regulation in upstream activities, such as energy and transport, and covers primarily climate and air pollution policies, the intention is to proxy overall environmental policy stringency. Botta and Kozluk (2014) argue that the advantage of focusing on policies affecting upstream activities is that such activities are present and of comparable economic importance across countries. Both energy and transport are generally characterised by high pollution intensity and regulated by well-identified and comparable types of policy instruments. The key idea is that the stringency in this sub-sample of sectors and pollutants implies a similar degree of policy control for the same externalities in other sectors.[2] Moreover, from an econometric perspective, using an EPS proxy based on sectors that are not directly included in the analysis (such as energy, transport and waste) helps to avoid some endogeneity concerns.[3] In practice, the credibility of the EPS as proxy for the country's overall environmental policy stringency is confirmed by a comparison with other available measures of environmental policy stringency (e.g. World Economic Forums Executive Opinion Survey responses, EBRD's CLIMI).[4]

[2]An idea that seems confirmed by Rubashkina et al. (2015).

[3]See section 1.7 for a detailed discussion.

[4]Three main cross-country measures of environmental policies are available: responses to World Economic Forum's Executive Opinion Survey (on perceived stringency), a composite indicator based

1.4 Environmental policies and productivity – what the descriptive statistics say

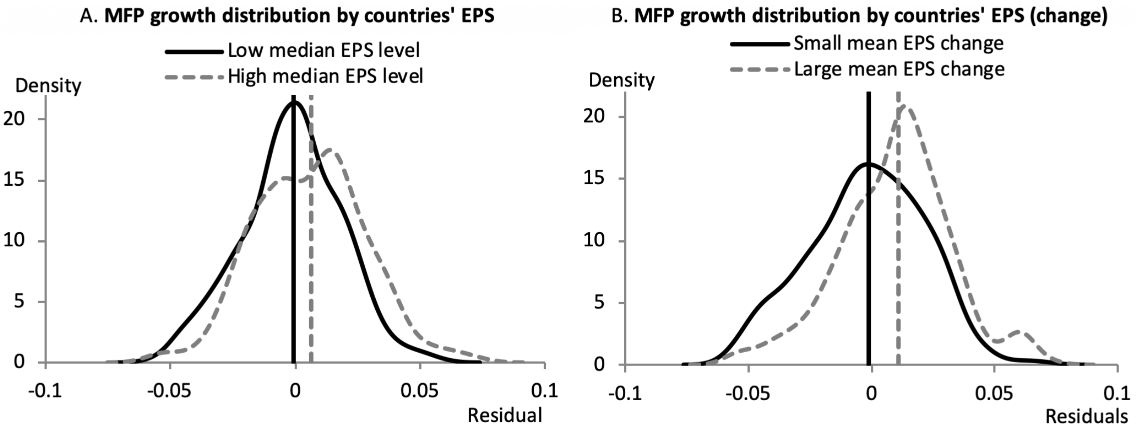
Over the period of 1990–2009, countries with the most stringent environmental policies have generally seen higher industry MFP growth than those with the most lax policies. Figure 1-1, left panel, shows that the median of annual industry-level MFP growth rates for the most stringent countries is on average higher (i.e. located more to the right) than for the less stringent countries. A similar finding holds when looking at tightening in environmental policies (Figure 1-1, right panel). Countries that experienced a stronger tightening have, on average, experienced higher MFP growth than countries with less tightening. While this would suggest that environmental policy stringency is associated with higher productivity growth, it can only serve as a motivation for a rigorous analysis, as many factors can influence productivity. Section 1.5.1 and Appendix 1.9.1 provide additional information and statistics of the main variables of interest.

1.5 Econometric model

Our empirical analysis is based on a standard Neo-Schumpeterian model of multifactor productivity growth, where productivity growth depends on the industry's (or firm's) ability to adopt innovative and efficient technologies available in the market (technological catch-up) and on firms' ability to innovate (technological pass-through) (Acemoglu et al., 2006, Aghion and Howitt, 2006, Nicoletti and Scarpetta, 2003). As

on different policy aspects (Dasgupta et al., 1995) and the EBRD's Climate Laws, Institutions and Measures Index (CLIMI (EBRD, 2011)). These indicators either lack a meaningful time-dimension, or lack one at all, which renders them less suitable for empirical analyses of effects of policy stringency (see Botta and Kozluk (2014) and Brunel and Levinson (2016) for a detailed discussion). Correlations for the EPS reported by Botta and Kozluk (2014) are: with WEF 0.44 (p-value 0.00), with CLIMI 0.56 (p-value 0.01).

Figure 1-1: Distribution of MFP growth by countries' environmental policy stringency (EPS) 1990-2009



Note: The left-hand graph presents the MFP growth distribution of the three countries with highest median EPS levels (dotted line) versus the distribution in the three countries with the lowest median EPS levels. The right-hand graph shows the MFP growth distribution of the three countries with the highest average EPS increases over the sample versus the three countries with the lowest. Source: Authors' calculations based on OECD STAN database and OECD PDBi database.

stressed in a more general context by Bourlès et al. (2013), regulations may have a heterogeneous effect on firm and industry productivity growth depending on the level of countries' and firms' technological advancement. A similar distinction is suggested by Porter and Linde (1995) for effects of environmental policies. Following this argument, we augment the model of Bourlès et al. (2013) with environmental policies, allowing the latter to have different effects on MFP growth depending on the country's/firm's distance to the global frontier. The most technologically advanced firms are likely to have more resources to invest into R&D or knowledge-based capital, and scale up energy efficiency gains from abatement. They may also be better suited to adapt to changes in the business environment – in this case provoked by an EPS tightening – having better access to technology, markets or managerial capacity. Less advanced firms may find it burdensome to comply with the new regulation, and may require higher investments to adopt cleaner technologies, exchanging equipment, etc.

The identification strategy is based on the fact that environmental policy is likely to affect industry productivity heterogeneously depending on the industry's exposure to the regulation. A higher 'environmental dependence' (proxied by pollution intensity in our main specification) increases the industries' exposure to the country-level environmental policies and hence the potential economic effects of the latter. Thus, in the empirical specification, the EPS index is interacted with the pollution intensity of the industry. This approach is common in the analysis of impacts of national-level policies and developments at the industry and firm levels, and was popularised by Rajan and Zingales (1998), who looked at the role of financial development using financial dependence as the exposure variable. See section 1.5.1 and Appendix 1.9.1 for more details on the environmental dependence variable.

The resulting specification for the industry and firm analysis is the following:

$$\begin{gathered}\Delta lnMFP_{cit} = \alpha_1 + \alpha_2 \frac{1}{n}\sum_{j=1}^{n}(ED_{i1987}\Delta EPS_{ct-j}) + \\ \alpha_3 gap_{cit-1}\frac{1}{n}\sum_{j=1}^{n}(ED_{i1987}\Delta EPS_{ct-j}) + \alpha_4 gap_{cit-1} + \\ \alpha_5 \Delta lnMFP_{it}\widehat{MFP}_{it} + X_{cit}\gamma + \eta_t + \delta_{ci} + \epsilon_{cit}\end{gathered} \tag{1.1}$$

where $\Delta lnMFP_{cit}$ is the multi-factor productivity growth for each combination of country c and industry/firm i at time t. ΔEPS is the change of the country EPS and captures the tightening of country's environmental policy interacted with pre-sample industry pollution intensity, ED, and used here as n-year moving average. The second term allows for a heterogeneous effect of the policy depending on the technological gap, defined as the distance to the country-industry frontier $gap = ln(\frac{MFP_i\widehat{MFP_i}}{MFP_{ci}})$. The rest of the terms follow directly from Bourlès et al. (2013). The third term is the distance to the productivity frontier which allows for technological catch-up effects. The global frontier is defined as the highest MFP across countries by industry and year – corrected for outliers, following Bas et al. (2016). In the firm-level estimation, the global frontier is defined as the average MFP of the top 5% firms across countries, by industry and year. The fourth term is the growth in the leader MFP, $\Delta ln(MFP_{it})$, and represents the technological pass-through. X_{cit} is a vector of additional country and industry/firm controls.

We use three different specifications in terms of controls. The 'Baseline' specification includes the output gap (to control for the business cycle), an additional dummy for particular effects of the financial crisis and a common time trend.[5] In the 'Baseline+Regulation' specification, we follow Bourlès et al. (2013) and Bassanini and Duval (2009) by including domestic regulations that are likely to affect MFP growth: employment protection legislation (OECD's EPL) and product market regulation (OECD's PMR). Higher employment protection may hinder the reallocation of workers across firms, thereby implying lower productivity growth (Bourlès et al., 2013), but it may also encourage investment in workers' human capital, boosting MFP growth (Gal and Theising, 2015). Anti-competitive product market regulations can hamper productivity by reducing competitive pressures, impeding efficient resource allocation and thereby raising production costs (Bourlès et al., 2013).[6] Thirdly, in the 'Full specification' we additionally control for the fact that R&D-intensive industries are more likely to have higher productivity growth, (including lagged R&D expenditure over value added). Finally, we control for a time trend η_t and country-industry fixed effects δ_{ci} or, alternatively, country and industry fixed effects: δ_c and δ_i.[7] At the firm-level, we also control for firm specific factors by including standard controls such as demand proxied by total assets turnover, and firms' size (lagged log number of employees).[8]

[5]We test three alternative specifications to account for the structural breakdown due to the latest financial crises: a dummy equal to 1 from 2007 to 2009; three dummies, one for each year of crisis; and a single dummy in 2008 to capture beginning of the Euro crisis. Results are robust throughout these specifications.

[6]We distinguish between high and low regulated countries using a dummy variable which takes the value 1 for PMR levels above the median and 0 below. The distribution of the 1998 PMR is used to construct a dummy for 1990–2000, while the indicator values of 2003 and 2008 are attributed to the time periods 2001-2005 and 2006-2010, respectively, given that the PMR is only calculated every 5 years.

[7]Country-time fixed effects are not included in the analysis, but we use the mentioned comprehensive range of time and country-level controls.

[8]Given the unbalanced firm sample, we substitute the PMR dummy with the OECD regulatory impact (RI) indicator in the firm-level specification. While the PMR is an economy-wide indicator of product market policy regimes, the RI quantifies the potential knock-on effects of anti-competitive

The analysis focuses on the change of the EPS indicator rather than levels. Even though the level of environmental policy stringency may have economic effects, for instance on trade patterns, effects on productivity growth are likely to be driven by changes in the environmental policy stringency. When only considering one country, a static level of environmental regulation per se (seen as a difference in relative prices of inputs) will not induce changes in the production processes of firms. However, firms are likely to react to new policy implementations by investing into abatement capital or reorganising their production. Moreover, from an econometric perspective, EPS levels empirically resemble a non-stationary process, which may be problematic, while the first differences are stationary.[9]

Effects of environmental policy changes can be lagged in time. The timing can depend on the type of instrument – e.g. it can be delayed with taxes, while immediate with bans or standards as well as its characteristics: announcement, derogation, delayed implementation of legislative processes, or specific characteristics of the reaction (time to build, learning by doing, etc.). Firms may invest into new capital, decide to exit the market or outsource, and hence see economic effects both before or after the policy's exact implementation date. Therefore, after testing for different lag structures, a three-year moving average has been chosen for the change in EPS and has been adopted for both the industry and firm-level. This moving average is defined as the unweighted average of the first, second and third lag of the change in EPS. This moving average is also used in the interaction term with the distance to frontier.[10]

regulation in upstream network sectors on 39 manufacturing sectors which rely on the network sector outputs as intermediate inputs. This indicator has the advantage of having more variability than the PMR, which makes it more suited for firm analysis where the time spell is short.

[9] We also test the impact of EPS in levels (in a similar setup), which turns out not to be significant.

[10] An introduction or a change in stringency of environmental policy instruments is often known or expected in advance – before the actual implementation. Thus the effect of a tightening in EPS on MFP growth in period t might not be captured by looking only at the following periods. If policymakers credibly announce the upcoming change of an environmental policy, firms may start investing into the capital and labour to comply with the new policy before the actual implementation. Tests on forward looking behaviour are reported in the OECD working paper Albrizio et al. (2014), which also includes a macro-level analysis where there is some evidence of such effects.

1.5.1 Data

Industry MFP is constructed using the OECD Structural Analysis database (STAN) and the Productivity Database By industry (PDBi). It is calculated as the residual from a log Cobb–Douglas production function for capital and labour, with the capital share set to 1/3. MFP growth is estimated as a two-year moving average for a panel of 17 OECD countries and 10 manufacturing sectors over the time period 1990–2009.[11]

Firm MFP is constructed using the OECD-ORBIS database developed by Gal (2013) based on the Bureau Van Dijk (BvD) ORBIS dataset. It follows the approach of Wooldridge (2009).[12] The panel consists of 11 OECD countries and 22 manufacturing sectors over the time period 2000–2009.[13] The selection is based on the number of observations, the stability of the number of observations over time, and the representation of the firm size distribution with respect to national business registries (Gal, 2013).

Environmental dependence is measured as pollution intensity, constructed for each industry using the IPPS Pollution Intensity and Abatement Cost World Bank dataset which collects data for the US manufacturing sector in 1987. Appendix 1.9.1 describes the methodology for the construction of the pollution intensity measure and reports related cross country statistics along with two alternative proxies used (see also section 1.7).

[11] The countries included are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Italy, Japan, the Netherlands, Norway, Spain, Sweden, the United Kingdom and the United States. The manufacturing industries covered in the sample are food, beverages and tobacco (ISIC Rev.3.1 code 1516), textiles and footwear (1719), wood (2000), pulp, paper and printing (2122), chemical, rubber, plastics and fuel products (2325), other non-metallic mineral products (2600), basic metals and fabricated metal products (2728), machinery and equipment (2933), transport equipment (3435) and manufacturing n.e.c. and recycling (3637).

[12] MFP figures are built based on Levinsohn and Petrin (2003). Woodridge's production function estimation is a one-step procedure that attempts to solve the capital measurement issue (Ackerberg et al., 2006). See Gal (2013) for a detailed and comprehensive discussion of the construction of the MFP measures.

[13] The countries included are: Belgium, Finland, France, Greece, Italy, Japan, Korea, the Netherlands, Spain, Sweden and the United Kingdom. The industry coverage is 2-digit manufacturing (NACE Rev. 1.1 industries 15 to 37). The baseline specification covers 191 597 firms.

1.5.2 Main results

Industry analysis

A tightening in environmental policy stringency is found to have a positive short-term effect on industry-level productivity growth, in countries where the industry is close to the global technological frontier. This can be interpreted as support for the strong version of the Porter Hypothesis on the industry-level. The effect diminishes as the distance to the frontier increases and becomes insignificant far from the frontier.

Table 1.1 reports the results across the different specifications, with different fixed effect structures as specified in the table. Frontier observations are excluded from the sample in all the specifications.

In line with previous literature, the coefficient on the MFP growth of the leader is positive, indicating a pass-through effect from the leader to the lagging industries. Moreover, there is evidence of catch-up effects (positive and significant coefficient of the gap), namely country-industry pairs that are further from the technology frontier tend to grow faster. The time trend captures the slowdown of MFP growth in advanced economies (Gordon, 2012), while the business cycle and lagged R&D expenditure are positively correlated with productivity growth. Other controls have expected signs, but turn out mostly insignificant.

Across the specifications the tightening of environmental policy is associated with a short-term, positive effect on industry-level productivity growth and with a negative effect coming from the interaction term with the distance to frontier. Therefore, the overall estimated marginal effect of a tightening in environmental policy on industry productivity growth depends on the technological advancement of the country-industry pair with respect to the global frontier:

$$\frac{\partial \Delta ln(MFP_{cit})}{\partial \frac{1}{3}\sum_{j=1}^{3}(ED_{i1987}\Delta EPS_{ct-j})} = \alpha_2 + \alpha_3 gap_{cit-1} \tag{1.2}$$

To check for the magnitude and significance of the estimated marginal effect

Table 1.1: Industry-level: main estimation results

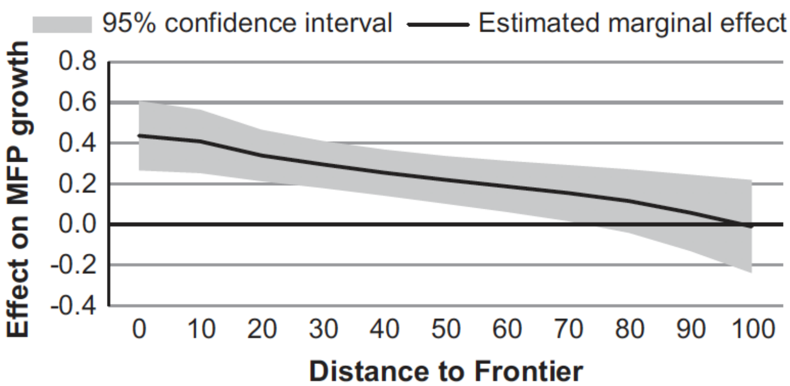
MFP growth	1 Baseline	2 Baseline	3 Baseline + Regulation	4 Baseline + Regulation	5 Full	6 Full
Leader MFP growth	0.14***	0.16***	0.14***	0.16***	0.12***	0.14***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Gap (t-1)	0.089***	0.17***	0.089***	0.17***	0.088***	0.16***
	(0.01)	(0.03)	(0.01)	(0.03)	(0.01)	(0.03)
EPS tightening[1]	0.1***	0.11***	0.11***	0.12***	0.12***	0.12***
	-(0.02)	(0.030)	(0.02)	(0.03)	(0.02)	(0.03)
Gap * EPS tightening[1]	-0.14**	-0.17*	-0.14**	-0.18*	-0.15***	-0.16**
	-(0.07)	(0.09)	(0.07)	(0.09)	(0.05)	(0.07)
output gap	0.36***	0.37***	0.38***	0.39***	0.40***	0.41***
	-(0.09)	(0.10)	(0.10)	(0.10)	(0.09)	(0.10)
year trend	-0.0024***	-0.0025***	-0.0025***	-0.0025***	-0.0029***	-0.0030***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
crisis	-0.0029	-0.0010	-0.0030	-0.0012	-0.0043	-0.0028
	-(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
EPL (t-1)			0.012	0.013	0.012	0.013
			(0.01)	(0.01)	(0.01)	(0.01)
PMR (t-1)			-0.0093	-0.0073	-0.0067	-0.0037
			(0.01)	(0.01)	(0.01)	(0.01)
R&D intensity (t-1)					0.0012**	0.0035**
					(0.00)	(0.00)
constant		4.94***		4.89***		5.96***
		(1.17)		(1.17)		(1.20)
Fixed effects						
Country*Industry	No	Yes	No	Yes	No	Yes
Country	Yes	No	Yes	No	Yes	No
Industry	Yes	No	Yes	No	Yes	No
N	2084	2084	2084	2084	1954	1954
Adjusted R2	0.165	0.115	0.166	0.115	0.184	0.117

Note: Robust standard errors in parentheses and they are clustered at country-industry-level; *** denotes statistical significance at the 1% level, ** significance at 5% level, * significance at 10% level. [1] denotes the moving average of the EPS change over three-years-lags.

we calculate the annual MFP effect for high polluting industries over the observed distance to frontier range, including the corresponding confidence intervals, for an average change of EPS of 0.12 points, which is the mean in-sample change of EPS. Figure 1-2 shows that the annual effect of tightening in industry-EPS on industry-level MFP growth is positive throughout most of the distance to frontier, leading overall to a permanently higher MFP level. This effect fades away only for countries far from the frontier.

This heterogeneous effect suggests that in each industry the most productive countries benefit most in terms of productivity growth. One reason may be that in these countries firms have access to top technologies and are most capable to adapt to the new regulations, for example by improving production technology. They may also have the best access to financial markets, networks etc., hence being better suited to accommodate the policy change. In this respect, our result points towards the Porter Hypothesis. However, the effect could also be due to a reallocation effect, with productivity gains due to a more rapid axing of less productive firms or outsourcing of less-productive activities as a result of additional costs imposed by environmental policies. This reallocation and entry-exit effect is not identifiable at the industry-level, but would likely inflate the observed productivity gains. To shed further lights on these dynamics we (i) study the effects of a tightening of environmental policy at the firm-level, and (ii) we compare the aggregate firm and industry results over a common sample (time and countries).

Figure 1-2: Marginal effect of an EPS tightening by the distance to frontier (industry-level)



Note: Annual MFP effect of a 0.12 point increase in environmental policy stringency (mean in-sample change of EPS) for highly polluting industries. 95% confidence intervals are reported.

Firm analysis

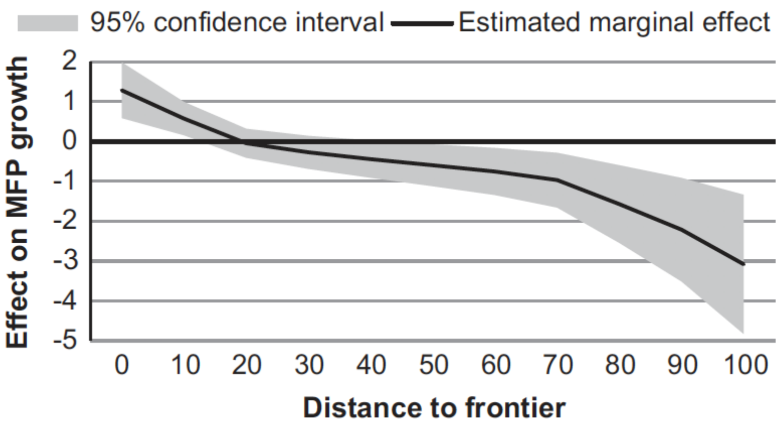
The positive finding at the industry-level is only partially confirmed in the firm analysis. Table 1.2 reports the results for the main specification at the firm-level, which augments the industry model with firm-level controls (see section 1.5). Overall, only one fifth of the firms are estimated to reap productivity gains after a change in environmental regulation, while about a half of the least productive firms face a negative effect. Figure 1-3 reports the annual effect of a mean tightening of EPS on firm multi-factor productivity growth, for firms in high polluting industries.

Table 1.2: Firm-level: main estimation results

MFP growth	1	2	3	4	5	6
	Baseline	Baseline	Baseline + Regulation	Baseline + Regulation	Full	Full
Leader MFP growth	0.14***	0.16***	0.14***	0.17***	0.13***	0.16***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Gap (t-1)	0.21***	0.24***	0.20***	0.24***	0.21***	0.28***
	(0.02)	(0.01)	(0.02)	(0.01)	(0.03)	(0.01)
EPS tightening[1]	0.42***	0.46***	0.39***	0.43***	0.34***	0.34***
	(0.09)	(0.10)	(0.09)	(0.10)	(0.08)	(0.09)
Gap * EPS tightening[1]	-0.19***	-0.22***	-0.18***	-0.21***	-0.15***	-0.18***
	(0.05)	(0.06)	(0.05)	(0.06)	(0.05)	(0.05)
output gap	1.78***	1.91***	1.50***	1.54***	1.96***	2.03***
	(0.37)	(0.37)	(0.32)	(0.31)	(0.38)	(0.36)
year trend	-0.018***	-0.020***	-0.018***	-0.022***	-0.021***	-0.026***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
crisis	-0.043***	-0.043***	-0.042***	-0.044***	-0.054***	-0.059***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
EPL (t-1)			0.018	0.0051	0.0016	-0.037
			(0.07)	(0.08)	(0.07)	(0.08)
RI (t-1)			-0.63	-1.33*	-1.25**	-2.68***
			(0.44)	(0.71)	(0.48)	(0.70)
R&D intensity (t-1)			0.0040***	-0.0044***	0.0047***	-0.0055***
			(0.00)	(0.00)	(0.00)	(0.00)
Size (t-1)					0.028***	0.039***
					(0.01)	(0.00)
Asset turnover (t-1)					0.0085*	0.017***
					(0.01)	(0.00)
constant		39.8***		44.3***		57.6***
		(4.24)		(6.85)		(7.31)
Fixed Effect						
Country	No	Yes	No	Yes	No	Yes
Industry	Yes	No	Yes	No	Yes	No
Country*Industry	Yes	No	Yes	No	Yes	No
N	1578262	1578262	1473422	1473422	1062460	1062460
adj. R-squared	0.104	0.123	0.104	0.123	0.104	0.132

Note: Robust standard errors in parentheses and they are clustered at country-industry-level; *** denotes statistical significance at the 1% level, ** significance at 5% level, * significance at 10% level. [1]defined as the moving average of the EPS change over three years (lagged).

Figure 1-3: Marginal effect of an EPS tightening by the distance to frontier (firm-level)



Note: Annual MFP effect of a 0.12 point increase in environmental policy stringency (mean in-sample change in EPS) for highly polluting industries. 95% confidence intervals are reported.

Comparison industry versus firm results

Figure 1-4 reports the estimated effects of a change in environmental policy on industry and firm-level productivity growth disentangling the effect as function of two dimensions: country/firm productivity (distance to frontier) and industry pollution intensity. In particular, the chart shows the point estimate and the confidence interval for a change in the EPS index equal to the mean cross-country tightening over the period considered. The left hand panel refers to the industry case: highly productive countries experience a temporarily increased MFP growth regardless of the level of pollution intensity. The right hand panel reports firm-level results for the same category matrix (high versus low pollution; high versus low productivity) with less productive firms experiencing a slowdown in MFP, especially if they belong to pollution intensive industries.

The significant negative effect for almost half of the firm sample is not found for country-industry pairs in the industry-level analysis. This discrepancy may be the outcome of at least two different mechanisms. First, it may come from the difference in sample composition between industry and firm-level analyses either in terms of countries or years considered. The first two columns in Table 1.5 and Table 1.6 in Appendix 1.9.2, report the estimations over a common year and country sub-sample and show that the different samples have little role in explaining the industry-firm differences – the results are similar to those obtained in the original samples.

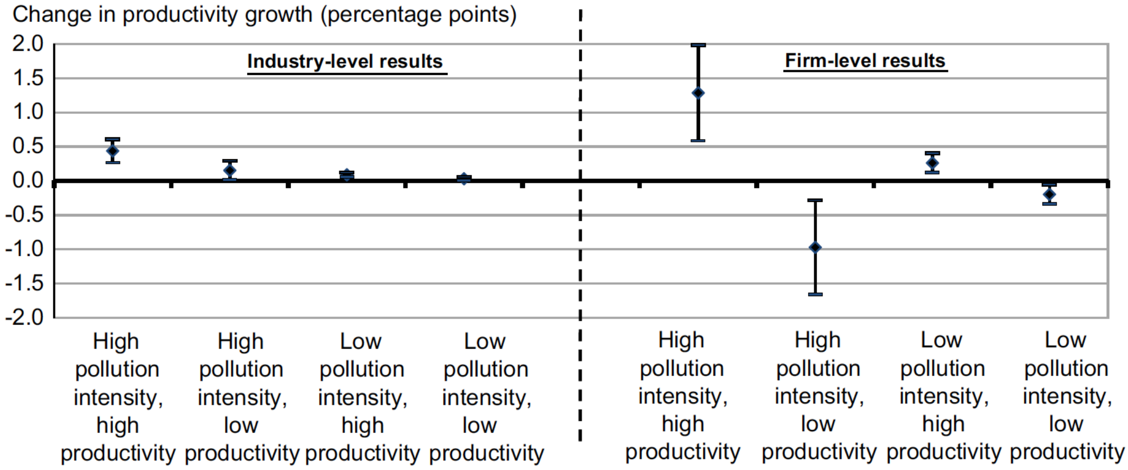
Second, the discrepancy between industry and firm-level results may come from entry/exit dynamics of firms. Particularly the less technologically advanced firms may end up exiting the market or reducing activity scale. The exit of the least efficient firms would raise overall industry productivity, offsetting the negative productivity effects observed in surviving less-technologically advanced firms. Testing for entry/exit dynamics is problematic due to the lack of data. ORBIS includes information on the incorporation date, but this variable suffers from some measurement issues (Gal, 2013). At the same time, exit is not observable as the company may remain active but no longer be included in the database. Keeping these shortcomings in mind, we find some evidence that firm in-sample survival (proxied by the age of a firm) is negatively and significantly correlated with the distance to the technological frontier - which points to a higher turnover among the firms further away from the frontier and implies that the entry/exit story is plausible.[14]

Potential channels

The heterogeneity found at the firm-level, may be the outcome of different channels of transmission of environmental policy. A potentially important channel is via innovation, i.e. the 'weak version' of the Porter Hypothesis. The increase in innovation activity can then potentially lead to efficiency gains and productivity increases (strong PH). Additional tests of this channel did not allow us to draw a decisive conclusion, and were seriously limited by the lack of adequate data. Two recent and

[14]The incorporation data are not available for each firm, which reduces the sample to 944,061 observation and 162,073 firms. In our sample, the unconditional correlation between age and technological advancement is 0.18 (p-value of 0.00). Additionally, looking at the average age of firms across the percentiles of the distribution of the distance to frontier, we find a negative trend.

Figure 1-4: Effects of a tightening of Environmental Policy Stringency on productivity growth (industry and firm-level) – economic significance



Note: (1) One year effects of a median increase in environmental policy stringency, i.e. 0.12 change in the value of the EPS index in one single year (equivalent to the change in annual average tightening from the level in Italy or Greece to that of the Nordic countries). Effects are estimated to last for three years after the policy change and then fade away. No lead effect is found. (2) High (low) pollution intensity is defined as an industry with the highest (lowest) pollution intensity on seven selected key pollutants with respect to value added. (3) High productivity is defined as the country-industry pair (or firm) on or close to the estimated global industry (or firm) productivity frontier. Low productivity is defined as country-industry pair (or firm) at the 75th percentile of distance to the global industry (or firm) productivity frontier. 90% confidence intervals are reported.

focused studies report mixed findings on the weak version of the PH: no effects of environmental policies on patenting (Franco and Marin, 2017) or positive significant effects (Rubashkina et al., 2015).

In any case, these results must be treated with caution. There are various problems of using patents as a proxy for innovation, more generally and in this particular exercise. Most ‘innovations’ are not patented – firms tend to introduce innovations that improve production processes or products, without necessarily patenting them; partly because this is costly, partly because many of the innovations are not really patentable. In practice, this means that most firms in the population do not patent at all (in our sample, just over 1% of firms patent in each year). Moreover, the transmission channel of environmental policy through patented (or any breakthrough) innovation might be subject to relatively long time lags. In fact, the process from the incentive (policy change) to increased innovation efforts (e.g. R&D spending), actual development of the technology, patenting it and, finally, adoption which has commercial effects (productivity), is likely to take many years (see David and Wright (2003), Andrews et al. (2014), Popp (2015)). Therefore, the impact that we find on multi-factor productivity is more likely to be the outcome of small process innovations, technological diffusion, resources reallocation and off-shoring.

The most productive firms are more likely to be involved in international trade or be part of a multinational group. Therefore, they have more resources and capacity to adapt rapidly to changes in the regulation, to innovate, exploit intra-group R&D and know-how in efficient and cleaner technologies, which lowers costs and speeds up technological implementation. Therefore, highly productive firms may be best suited to profit rapidly from changing conditions, seizing new market opportunities, rapidly deploying of new technologies or reaping previously overseen efficiency gains as implied by the Porter Hypothesis. They are also likely to be in a better position to offshore part of the production or substitute inputs profiting from access to global value chains. The role of the internationalisation channel is confirmed by Albrizio (2016), who uses a similar specification on the same dataset, and finds a stronger (positive) effect of a tightening of EPS for multinationals than for domestic firms.

1.6 Additional hypotheses tested

We use our datasets to test two additional hypotheses: the importance of EPS levels and the differential effect of market versus non-market EPS instruments.

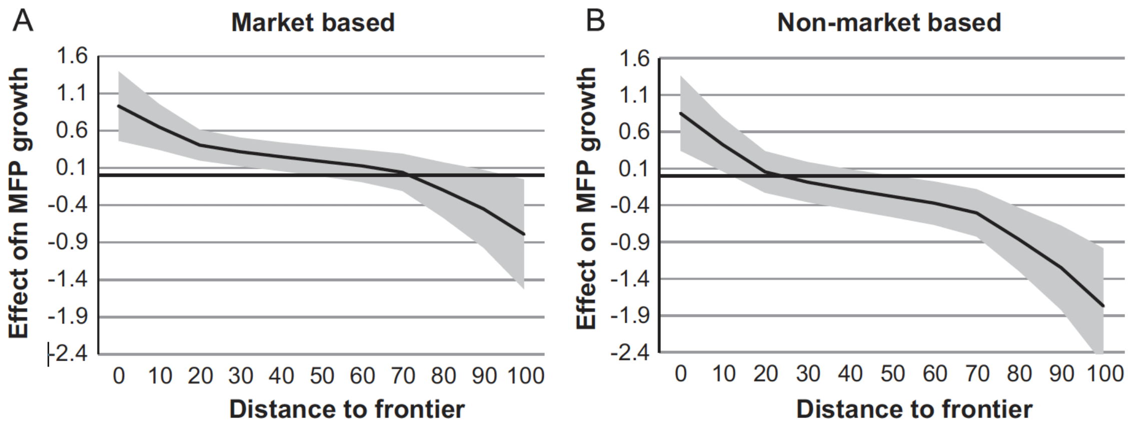
The economic effect of the same change in environmental policy stringency may depend on whether a country already has lax or tight environmental policies. On the one hand, further tightening in an already highly regulated country can be expected to be more detrimental than in a set-up where almost no regulation exists. On the other hand, the marginal effect of the tightening may be smaller if environmental policies are already stringent. To verify these conjectures the change in the EPS variable is interacted with a dummy indicating whether the country is above or below the sample median level of environmental policy stringency. No evidence is found that the country's level of environmental policy stringency affects the results: the temporary effect in productivity growth resulting from policy tightening is similar across countries, regardless of whether they have a high or low level of environmental regulation.[15]

The *narrow* version of the Porter Hypothesis suggests that it is more likely that environmental policies, which focus on the outcome rather than on the production process, lead to more innovation or higher productivity. This boils down to a differentiation of market based versus non-market environmental policies. Market based environmental policy instruments, which are based on explicit price signals, are generally considered to be more cost effective than non-market ones (De Serres et al., 2010). For instance, under an emission trading scheme firms have more flexibility in choosing the technology and timing of adjustment than in a scheme of rigid technology standards. Hence, firms subject to market based instruments can be expected to experience less detrimental effects on productivity growth. To investigate whether the effect of EPS changes on MFP growth varies with the design features of the environmental policy instruments, the country-level EPS index is split into market based and non-market policies. Empirical results across the two level of analysis yield some support for the narrow version of the Porter Hypothesis. At the firm-level, the market based instruments show a positive significant coefficient whereas the non-market instruments have no significant effect on productivity growth when using the full set of controls (Appendix 1.9.2, Table 1.6, column 2). The effect of the interaction with the distance to frontier is negative and strongly significant for the market component, while less robust for the non-market one. The average annual effects differ considerably for the two groups of instruments (Figure 1-5).

At the industry-level (Appendix 1.9.2, Table 1.5, column 2) the effect of non-

[15]Complete results can be obtained from the authors upon request.

Figure 1-5: Average annual marginal effect: market based versus non-market EPS tightening – firm-level



Note: Panel A shows the effect of a 0.12 point increase in the stringency of market based instruments (mean in-sample EPS change), for highly polluted industries. Panel B shows the MFP effect of a 0.12 point increase in the stringency of non-market based instruments (mean in-sample EPS change). 95% confidence intervals are reported.

market policies is still significant. The magnitude of the estimates is similar across the two sub-components. The interaction term with the distance to frontier is not robust anymore for the market based instrument, suggesting that market based instruments do not penalise less productive industries.

1.7 Robustness checks

Three further robustness checks were performed at each level of analysis (industry and firms). These specifications test (i) the robustness of our results to the choice of the policy exposure variable, namely the environmental dependence measure, (ii) the ability of the EPS indicator to represent economy wide environmental policies and (iii) the importance of cross-country differences in policy enforcement. Additional tests supporting the proposed identification are also provided.

Sensitivity to the choice of the exposure variable

Appendix 1.9.2 reports the re-estimated results when alternative definitions of environmental dependence are used: the industries energy dependence (in sample) and energy cost share (pre-sample). In each of the cases the results are not significantly affected, implying the results do not hinge on the exact definition of environmental dependence applied (Appendix 1.9.2, Table 1.5, columns 3 and 4; Appendix 1.9.2, Table 1.6, columns 3 and 4).[16]

Representativeness of the EPS proxy

The identification strategy is based on the assumption that overall stringency of environmental regulations can be approximated by looking at policy instruments that regulate environmental externalities in selected sectors. A large part of the policy instruments used for constructing the EPS proxy relate primarily to fossil-fuel electricity generation; hence the EPS measure may be less representative for countries with a low share of fossil fuel based electricity generation. To the extent such countries may score lower than expected on the EPS proxy (e.g. lower stringency of the particular policies captured by the EPS proxy), this may imply erroneous estimates. However, re-estimating the equations excluding countries that have a fossil-fuel electricity generation capacity share below 30% (Norway, France, Sweden and Canada) does not affect our results significantly (Appendix 1.9.2, Table 1.5, column 5; Appendix 1.9.2, Table 1.6, column 5).

Differences in policy enforcement

The EPS indicator is a de jure measure and does not capture differences across countries in the implementation and enforcement of policies. The responses to the World

[16]Note that one of the channels through which regulation may affect industry and firm multifactor-productivity is by rising energy prices. However, our aim is to quantify the overall effect, rather than its directness.

Economic Forum's survey on how environmental regulation is enforced can be used to test for the importance of the differences in policy enforcement. We divide countries into high (dummy=1) and low (dummy=0) enforcement countries, relative to the median value over the entire available sample. This dummy has no time dimension, hence is interacted with the EPS. At both layers of analysis, the interaction term is not significant, suggesting no additional effects, while the main explanatory variables remain significant and stable in term of the coefficient estimate (Appendix 1.9.2, Table 1.5, column 6; Appendix 1.9.2, Table 1.6, column 6).

Endogeneity concerns

Potential endogeneity of the EPS index due to reverse causality or simultaneity may question our identification strategy. This could be a problem if, for instance, good performance in given industries (in terms of MFP growth) facilitates adoption of more stringent environmental policies or if firms that are performing poorly are able to successfully lobby against more stringent policies. In order to reduce these concerns we adopt the following precautions. First, the EPS index used is a proxy of overall stringency, based largely on out-of-sample upstream sectors, which makes it less likely that specific industries and firms are able to directly influence the regulatory process. Second, we consider lagged values of the index, which reduces the simultaneity issues. Third, the results are robust to the different fixed effect structures used to control for unobservable confounding factors. Moreover, we explicitly test the potential endogeneity of the EPS index by assessing whether past industry MFP growth can predict current levels of EPS. In a simple regression framework we control for fixed effects (time, industry, country), with a general aim to account for factors such as political economy potentially driving the changes in EPS in response to past industry performance. None of the lags of MFP growth can predict the current changes in EPS. Finally we run an ordered probit estimation on macro-level data to test whether past MFP growth can help to forecast future EPS changes (based on methodology from

Mertens and Ravn (2012), among others). The indicator variable takes the value one if there is a tightening of EPS, zero if there is no change and minus one if there is a negative change. Assuming that the regulator would base policy stringency decisions on the level of the emissions, the growth of the economy and on technical change, we include the additional covariates to the model: lagged economic growth (GDP growth rate), lagged greenhouse gas emissions, shifts in the technological frontier capturing the availability of new and more efficient technologies (proxied by lagged MFP growth of the leader – top performer country by year), as well as the domestic ratio of green patent applications (relative to total, 2-year moving average) a variable to account specifically for the innovation effort in cleaner technologies. Country fixed effects are included and one to two-lags specifications are tested. Results lead to rejecting the hypothesis that past MFP growth can help to explain future EPS changes (Table 1.3). On the contrary, past innovation efforts (green patents), and past economic growth seem good predictors of future environmental policy tightening, as expected.

Table 1.3: Ordered probit: macro level

Indicator variable: EPS tightening											
	GDP growth (L2)	GDP growth (L3)	GHG per capita (L2)	GHG per capita (L3)	MFP growth leader (L2)	MFP growth leader (L3)	MFP growth (L2)	MFP growth (L3)	Green patent ratio	Year	N.Obs
β	0.423*	0.22	0.32	-0.46	-12.25	-9.62	-20.40	-11.49	599.0***	-1.198***	179
SE	0.169	0.163	0.39	0.36	9.62	8.035	12.45	10.69	168.7	0.311	

Note: The dataset considers 23 OECD countries from 1990 to 2009. Data included are: country multi-factor productivity index Johansson et al. (2012) from which the MFP growth of the leader is calculated as the country with the highest MFP in each year; the ratio of green patents over the total patents application in each country (OECD); per capita GHG emissions is expressed in billions of tons of CO2 equivalent (OECD). *** Denotes statistical significance at the 1%-level. ** Significant at 5%-level. * Significant at 10%-level.

1.8 Conclusion

Over the last twenty years, governments in OECD countries have implemented a wide range of environmental policies with the aim of improving environmental conditions. Inevitably, these policies affect production processes, resource re-allocation, capital investment, labour intensity and innovation incentives. Therefore, the ongoing tightening of environmental regulation is likely to affect not only environmental outcomes, but also economic performance. According to the strong version of the Porter Hypothesis environmental policy may lead to higher overall productivity of firms.

We test the effect of a change in environmental policy stringency on productivity growth at two different aggregation levels (industry and firm) in a panel of OECD countries over the last 20 years. We find that a tightening in environmental policy stringency is associated with a subsequent short-run increase in productivity growth for the most productive industries and firms, providing empirical support for the strong version of the Porter Hypothesis. However, this positive effect may come from process improvement as well as from off-shoring. At the same time, less productive firms experience a fall in MFP growth, suggesting that the increase in productivity found at the industry-level partly reflects the exit of least productive firms from the market. The effect on productivity growth does not depend on whether countries already have a high or low level of environmental regulation.

Finally, market based environmental policy instruments are found slightly more productivity growth friendly than non-market instruments, as suggested by the narrow version of the Porter Hypothesis. This may be because they provide firms with higher flexibility in the abatement process, by allowing them to choose either the most suitable technology solution or the timing of the adjustment.

1.9 Appendix

1.9.1 Data description

Table 1.4: Descriptive statistics

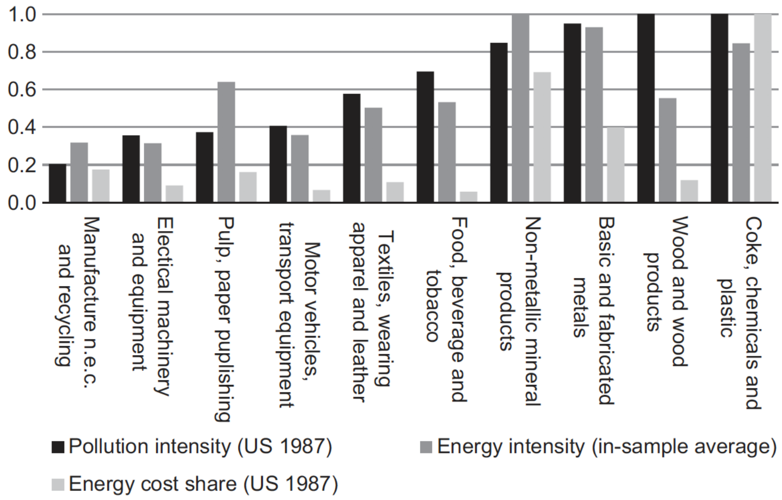
Industry dataset					Firm dataset				
	MFP growth			EPS[1]		MFP growth			EPS[1]
Industry	Mean	Std. Dev.	Freq.	3-y MA	Country	Mean	Std. Dev.	Freq.	3-y MA
1516	0.003	0.062	205	0.082	BEL	0.009	0.304	110397	0.076
1719	0.020	0.055	212	0.066	ESP	-0.019	0.327	556936	0.112
2000	0.012	0.068	208	0.114	FIN	0.046	0.281	47561	0.096
2122	0.015	0.045	209	0.043	FRA	0.014	0.256	244648	0.097
2325	0.022	0.060	205	0.118	GBR	0.025	0.457	72537	0.075
2600	0.012	0.057	209	0.102	GRC	-0.021	0.378	34728	0.041
2728	0.012	0.061	209	0.112	ITA	-0.035	0.368	388681	0.060
2933	0.038	0.069	211	0.041	JPN	0.002	0.101	61277	0.029
3435	0.017	0.073	207	0.046	NLD	0.023	0.394	8693	0.122
3637	0.011	0.084	209	0.024	SWE	0.044	0.095	141810	0.127
Total	0.016	0.065	2084	0.075	Total	-0.006	0.317	1667268	0.090

Note: [1]denotes the moving average of the weighted EPS*ED change over three years, averaged across the time period considered. The number of observations varies depending on the controls included in the specification. These statistics consider the basic specification, as reported in the industry and firm model section.

Environmental dependence

Industries are ranked based on pollution intensity (relative to value added) on seven pollutant categories (two water pollutants, four air pollutants, one toxic substance). The 'environmental dependence' is then the simple average of these seven scores, and it can take values from zero (least polluting industry) to 1 (most polluting industry). We use two alternative proxies for industry exposure to environmental policy: the energy dependence index based on OECD STAN Input-Output tables, and the energy cost share based on World KLEMS tables for US 1987 (Figure 1-61). The robustness checks are reported in Appendix 1.9.2, Table 1.5, columns 3 and 4, and Appendix 1.9.2, Table 1.6, columns 3 and 4. Details on the advantages and disadvantages of each of the environmental dependence measures are discussed in Albrizio et al. (2014).

Figure 1-6: Exposure variable by industry



Note: Authors calculation based on WB pollution intensity data on US manufacturing sectors for 1987, the OECD Input-Output (average across vintages), and the ratio between energy inputs and intermediate inputs at current purchasers' prices (both in millions of US Dollar) for US manufacturing sector in 1987. All three indicators are re-scaled between 0 and 1.

1.9.2 Additional hypothesis tested

Table 1.5: Industry-level: robustness checks and additional hypothesis tested

MFP growth	1 Common sample industry and firms	2 Market versus non-market instruments	3 Exposure variable: energy dependency	4 Exposure variable: energy cost share	5 Representativeness of the EPS proxy	6 Differences in policy enforcement
Leader MFP growth	0.11**	0.12***	0.13***	0.13***	0.13***	0.12***
	(0.05)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Gap (t-1)	0.11***	0.088***	0.090***	0.086***	0.082***	0.088***
	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
EPS tightening[1]	0.089***				0.13***	0.096***
	(0.03)				(0.02)	(0.03)
Gap * EPS tightening[1]	-0.16**				-0.16**	-0.14**
	(0.07)				(0.05)	(0.06)
output gap	0.54***	0.39***	0.40***	0.38***	0.39***	0.42***
	(0.19)	(0.09)	(0.09)	(0.09)	(0.10)	(0.11)
year trend	-0.0028**	-0.0028***	-0.0029***	-0.0025***	-0.0029***	-0.0029***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
crisis	-0.012	-0.0038	-0.0045	-0.0075	-0.0011	-0.0042
	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
EPL (t-1)	0.013	0.011	0.013	0.014	0.018	0.013
	(0.06)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
PMR (t-1)	-0.0012	-0.0070	-0.0072	-0.0044	-0.0076	-0.0064
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
R&D intensity (t-1)	0.00091	0.0012**	0.0012**	0.0011**	0.0013*	0.0012**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Market EPS tightening[1]		0.096***				
		(0.02)				
Gap(t-1)*M EPS tightening[1]		-0.12***				
		(0.04)				
Non-Market EPS tightening[1]		0.027				
		(0.02)				
Gap(t-1)*NM EPS tightening[1]		-0.038				
		(0.04)				
EPS tightening[1] (En.Dep)			0.14***			
			(0.03)			
Gap(t-1)*EPS tightening[1] (En.Dep)			-0.16***			
			(0.06)			
EPS tightening[1] (En.Cost)				0.42***		
				(0.11)		
Gap(t-1)*EPS tightening[1] (En.Cost)				-0.046**		
				(0.19)		
EPS tightening[1]*Enforcement						0.028
						(0.04)
Gap(t-1)*EPS tightening[1]*Enforcement						-0.0055
						(0.08)
Fixed effects						
Country*Industry	Yes	Yes	Yes	Yes	Yes	Yes
N	833	1954	1954	1954	1399	1954
Adjusted R2	0.170	0.188	0.184	0.179	0.165	0.184

Note: Robust standard errors in parentheses, clustered at country-industry-level; ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively. [1]denotes the moving average of the EPS change over three years (t-1 to t-3). Each of the columns represents specifications derived from column (6) in Table 1.1. Column 1 shows results for a common firm and industry-level sub-sample (overlapping). Column (2) shows results from market based and non-market instruments; (3) and (4) show results with alternative definitions of the exposure variable; (5) shows results with countries with small shares of fossil-fuel based electricity excluded; and (6) shows results when attempting to account for enforcement.

Table 1.6: Firm-level: robustness checks and additional hypothesis tested

MFP growth	1	2	3	4	5	6
	Common sample industry and firms	Market versus non-market instruments	Exposure variable: energy dependency	Exposure variable: energy cost share	Representativeness of the EPS proxy	Differences in policy enforcement
Leader MFP growth	0.13***	0.071***	0.12***	0.12***	0.12***	0.13***
	(0.02)	(0.03)	(0.02)	(0.02)	(0.03)	(0.02)
Gap (t-1)	0.21***	0.21***	0.22***	0.21***	0.22***	0.22***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
EPS tightening[1]	0.34***				0.50***	0.42***
	(0.08)				(0.10)	(0.09)
Gap (t-1)*EPS tightening[1]	-0.15***				-0.22***	-0.18***
	(0.05)				(0.07)	(0.05)
Output gap	1.96***	4.98***	2.03***	1.81***	1.90***	1.89***
	(0.38)	(0.83)	(0.37)	(0.38)	(0.40)	(0.39)
Year trend	-0.021**	-0.027***	-0.021***	-0.021***	-0.023***	-0.021***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Crisis	-0.054***	-0.10***	-0.057***	-0.057***	-0.054***	-0.053***
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
EPL (t-1)	0.0016	-0.23**	-0.017	-0.0056	-0.25***	0.047
	(0.07)	(0.10)	(0.08)	(0.09)	(0.09)	(0.07)
RI (t-1)	-1.25**	-0.91*	-1.36***	-1.51***	-1.21**	-1.16**
	(0.48)	(0.46)	(0.48)	(0.48)	(0.53)	(0.47)
R&D intensity (t-1)	0.0047***	0.0064***	0.0052***	0.0047***	0.0072*	0.0047***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Size (t-1)	0.028***	0.024***	0.028***	0.028***	0.031***	0.028***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Asset turnover (t-1)	0.0085*	0.015**	0.0096*	0.0091*	0.014***	0.0083
	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)
Market EPS tightening[1]		0.28***				
		(0.07)				
Gap(t-1)*M EPS tightening[1]		-0.13***				
		(0.03)				
Non-Market EPS tightening[1]		0.29***				
		(0.05)				
Gap(t-1)*NM EPS tightening[1]		-0.080***				
		(0.02)				
EPS tightening[1] (En. Dep)			0.42***			
			(0.06)			
Gap(t-1)*EPS tightening[1] (En.Dep)			-0.12***			
			(0.02)			
EPS tightening[1] (En.Cost)				0.52***		
				(0.17)		
Gap(t-1)*EPS tightening[1] (En.Cost)				-0.16***		
				(0.06)		
EPS tightening[1]*Enforcement						-0.16
						(0.11)
Gap(t-1)*EPS tightening[1]*Enforcement						0.0034
						(0.05)
Fixed effects						
Country*Industry	Yes	Yes	Yes	Yes	Yes	Yes
N	1062460	562814	1072550	1072550	850509	1062460
Adjusted R2	0.104	0.105	0.106	0.104	0.105	0.105

Note: Robust standard errors in parentheses, clustered at country-industry-level; ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively. [1]denotes the moving average of the EPS change over three years (t-1 to t-3). Each of the columns represents specifications derived from column (6) in Table 1.2. Column 1 shows results for a common firm and industry-level sub-sample (overlapping). Column (2) shows results from market based and non-market instruments; (3) and (4) show results with alternative definitions of the exposure variable; (5) shows results with countries with small shares of fossil-fuel based electricity excluded; and (6) shows results when attempting to account for enforcement.

Chapter 2

The Valley of Death, the Technology Pork Barrel, and Public Support for Large Demonstration Projects*

2.1 Introduction

A prominent claim in innovation literature, and in practice, is that a technology 'valley of death' exists, from which promising technologies fail to emerge due to weak incentives for investment, e.g. due to technical risk, uncertain markets, and the need

*This chapter is joint work with Gregory Nemet and Martina Kraus. The paper is published in Energy Policy 119 (2018), available under https://doi.org/10.1016/j.enpol.2018.04.008. An earlier version was published as DIW Discussion Paper No. 1601 (2016). A case study protocol and a dataset with the basic characteristics of the case studies have been published as Supporting Information Documents in Mendeley Data and are available at http://dx.doi.org/10.17632/mf8v7jg7ts.1. The authors are grateful for funding from German Federal Ministry for Economic Affairs and Energy contract #03MAP316. The authors received helpful comments during presentations at: the Association for Public Policy Analysis and Management, DIW-Berlin, Economics for Energy-Madrid, ETH-Zurich, IAEE-Bergen, OECD, SPRU, and the Technical University of Berlin.

for large chunky investments. Market failures and innovation system failures lead to under-investment at this intermediate stage of innovation. While governments might address this problem, a second metaphor holds that a 'technology pork barrel' also exists, in which technology support will inevitably fail due to politicians diverting program goals to trade favours and improve reelection prospects. A related notion holds that even beyond these problems with representative democracy, poor access to information implies that 'governments should not pick winners.' The strong version of these latter arguments, predominant in some countries today, is that even if market and system failures set up a technology valley of death, it is not worth addressing because government failures are so inherent in democracies that they will undermine efforts to make technologies commercially viable.

That the extent of government failures may exceed market failures has important implications for technologies facing real valley of death problems; they may simply never become widely adopted. This outcome is particularly relevant for technologies needed to address climate change. For example, achieving the ambitious climate change mitigation targets that 196 countries agreed upon in Paris in December 2015 will require near complete decarbonisation of developed countries' economies during this century (Rogelj et al., 2015). This transformation will necessarily involve not only sectors such as electricity and transportation, which are already decarbonising, but also substantial emission reductions in industrial sectors such as steel and cement in which the core production process produces emissions (Woertler et al., 2013, Ahman et al., 2199, Denis-Ryan et al., 2016). While some opportunities remain for picking low hanging fruit, such as emission reductions through energy efficiency improvements, they are not sufficient to achieve the envisaged climate goals (OECD, 2015, Arens and Meister, 2016). Adoption of radical low-carbon innovations in the production process, combined with electrification (IEA, 2014), is crucial to decarbonising the materials sector (Neuhoff et al., 2015). And because industrial facilities are large to reap scale economies, industrial low-carbon technology needs similar scale to fit into the broader technological system. Large-scale radical innovations with payoffs that depend on uncertain future policies seem especially prone to the valley of death problem. To help improve the prospects of meeting ambitious goals, governments around the world are considering substantial increases in their support for innovation, including demonstration projects. One example is the Mission Innovation initiative, in which 21 governments have committed to double their energy R&D investment over the next five years (Karlsson, 2016, Sivaram and Norris, 2016). Further the European Commission has proposed a New Entrants' Reserve (NER) 400 program, which would use the revenue from auctioning 400 million emissions permits to fund projects in the 2020s focused on decarbonising industry (Borghesi et al., 2016). How this support will be structured, allocated, and coordinated are crucial open questions – ones that need more sophisticated guidance than following heuristics such as removing 'barriers' and avoiding 'picking.' Just letting 'markets decide' ignores the reality of substantial market and system failures, while simply beefing up government funding does not adequately address the perceived poor track record of previous government programs. Further, the potential for high-profile failures heightens the stakes involved in that they may create lasting legacies that affect the political feasibility of future efforts.

The paper thus addresses the broad question of *how public support for low-carbon technology demonstration projects can be structured to be most effective in overcoming the valley of death?* This is done in two ways. First, starting with a simple model of government support for innovation based on technology-push and demand-pull, the literature is reviewed to more precisely understand the conditions that can produce a technology valley of death. Second, built on this reassessment, important aspects of a large sample of past demonstration projects are characterised. A new data set of 511 demonstration projects is collected, for which the following characteristics are coded: timing, motivations, contributions, scale-up, performance, and markets. Our primary motivation is to contribute to a (hopefully) growing set of studies about technologies that face the challenges of this awkward intermediate stage, between technology-push and demand-pull. The aim of the paper is to help structure thinking, beyond heuristics, about the policy decisions at stake because the policy outcomes have broad ramifications beyond the sums involved, even if those are substantial (Iyer et al., 2015).

This paper is structured as follows. First, the state of the literature on technology-push and demand-pull is reviewed, linking the valley of death with the technology pork barrel. Second, specific aspects of large-scale, low-carbon demonstration projects are described and hypotheses around several characteristics are developed, based on the existing literature. Third, these hypotheses are tested with the help of a newly assembled data set of previous large scale demonstration projects. Fourth, a response to our research questions is developed with an empirical assessment of the data set. Fifth, the limitations of the data set are outlined. The paper concludes with a discussion of the implications for policy making.

2.2 Literature and theory

Informing decisions about public investments in demonstration projects starts with understanding insights from previous research about government involvement in this particularly challenging stage of the innovation process.

2.2.1 Technology-push and demand-pull

While more sophisticated theories have emerged, it is difficult to completely discard the nearly century-old notion of the process of innovation as progress along a sequence of stages from scientific research to applied research to commercialisation, and diffusion – with various names and fineness in distinctions to describe the stages (Schumpeter, 1947, Usher, 1954). Crucial to moving this model from aged caricature to useful depiction of reality are the feedbacks involved in this sequence. Knowledge created in the process is used to inform thinking and decisions in previous stages. For example, experience in production can identify bottlenecks that require new designs to address; consumer use of new technologies can inform how they can be improved. Once feedbacks of knowledge are included in the previously *linear* process it takes on the attributes of a system – with complexity, emergent properties, increasing returns, and stochastic outcomes as defining features.

The literature on "technology-push" and "demand-pull" implies that governments can interact with this system in two ways. In the most succinct terms: technology push policies *reduce the costs* of innovation for private sector actors while demand-pull policies *increase the payoffs* to private sector actors for successful innovations (Nemet, 2009). In the technology-push approach, the government's goal is to increase the availability of new knowledge while in demand-pull the goal is to increase the size of markets for commercialised knowledge. Examples of technology-push policies include: public R&D funding, R&D tax credits, subsidising education, and supporting knowledge networks. Examples of demand-pull include: intellectual property rights, pricing externalities, subsidising demand, government procurement, and technology standards. The innovation literature involves a lengthy debate about this dichotomy including both descriptively about which has been the dominant driver of innovation (Schmookler, 1962, Mowery and Rosenberg, 1979, Godin and Lane, 2013) and normatively about whether governments should focus on creating knowledge or creating markets (Bush, 1945, Veugelers, 2012, Peters et al., 2012). A general consensus has emerged around the following four aspects of innovation. First, technology-push and demand-pull are both necessary and neither is sufficient; given substantial variation among technologies. Second, technology-push is important in early stages and demand-pull in later stages. Third, incremental innovations depend on demand-pull while radical innovations require technology-push. Fourth, successful innovations tend to be those that "couple" a technical opportunity with a market opportunity (Freeman, 1974, Pavitt, 1984, Arthur, 2007, Di Stefano et al., 2012).

This framework is particularly useful for assessing demonstration projects as it illustrates what makes support for them challenging. First, demonstration projects fit awkwardly into this framework as they lie *between* the research oriented areas associated with technology-push and market oriented stages of demand-pull. Second, in the context of low-carbon technologies, demand-pull may be weak due to low credibility that policymakers will create future markets making the resulting incentives *fragile*.

2.2.2 Demonstration projects

Demonstration projects sit at an awkward stage, in the middle of the innovation process; they are well beyond research but not yet commercial products (Kingsley et al., 1996, Mowery, 1998, Spath and Rohracher, 2010, Hendry and Harborne, 2011). As such, it's not even clear whether government funding for demonstrations involves reducing innovation costs or increasing commercial payoffs. To small suppliers of innovation, a billion dollar demonstration project *is* the payoff; to large ones it is part of the cost of bringing an innovation to the market. Ultimately, if one were to choose, the latter description seems more representative.

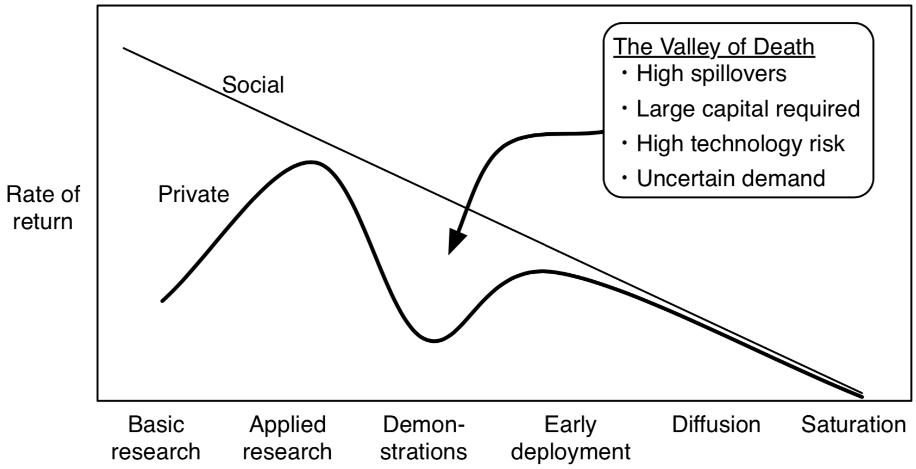
In an excellent review of what they term "pilot and demonstration" projects, Frishammar et al. (2015) make clear that this term has been used in several different ways and thus suggest the rather general definition of "a tool used to progress knowledge so that an effective organisation, design, and management of commercial facilities can be achieved at a lower risk for the stakeholders involved." This definition reveals that demonstrations often involve multiple objectives. Most fundamentally, their goals can diverge between demonstrations 1) as exemplars, proving reliability and performance and 2) as experiments from which to learn. Demonstrations provide opportunities for collaboration, for example among component suppliers, universities, partner firms, and in some cases customers, so that process and interactions can be standardised and improved. These interactions make clear that the challenges involved are not purely technical, encompassing alignment of institutions, rules, standards, codes, and public attitudes. They are also about creating knowledge about technical possibilities, not just creating those possibilities (Weyant, 2011). All of these functions are supportive of a recurring challenge in innovation, scaling up unit size (Wilson, 2012). The scale-up might be needed to achieve some minimum efficient scale, or to fit into a larger technological system.

2.2.3 Valley of death: 'between' and fragile

The notion of the technology valley of death is that technologies at the demonstration stage face particular challenges that lead to under-investment and ultimately to premature deaths of otherwise promising innovations (Murphy and Edwards, 2003, Watson, 2008, Weyant, 2011). Figure 2-1 portrays the valley of death by showing the shift in funding over the course of the innovation lifecycle, from the public to private, is in part due to declining social returns and increasing private ones. At any stage at which social returns exceed private ones, there will be under-investment unless the public sector plays a role. For example, at early stages the widespread availability of new knowledge as scientific research makes social value high and easy to access for all. At late stages, there are diminishing returns to adoption and firms are able to protect what value remains via brands, patenting, and optimised proprietary production processes.

Why don't firms pay for their own demonstrations? At either end of the innovation sequence, the optimal roles of the public sector and firms are clear: basic research requires public funding; adoption of commercial technologies are best funded by the private sector, including consumers. However, in between, at the demonstration stage, a troublesome combination of factors is typically involved: the potential for knowledge about outcomes to be highly beneficial to companies other than those making an investment; a substantial increase in the scale of investment required; unproven technical reliability; and uncertain market receptiveness. Because knowledge about performance may have high value, but may also be non-excludable, social returns to

Figure 2-1: Innovation stages and the technology valley of death



investment at this stage may far exceed private returns. A lack of investment by both the public and private sector has been a frequent result. The main four reasons for this are described in more detail in the following.

Appropriability Low appropriability is the most widely accepted explanation for why firms will be unwilling to fully fund their own demonstration projects (Teece, 1986, Cohen et al., 2002, Hall et al., 2009). Appropriability is low when knowledge created as a result of a firm's investment 'spills over' to other firms. Such spillovers might be very tangible e.g. when firms reverse engineer the products of others, or take less tangible forms, e.g. when employees who accumulate tacit knowledge in developing technology, take that knowledge with them when they move to a new firm. Firms might also observe the behaviour of other firms directly, for example in the case of a large demonstration project like a large industrial facility, a rival might be able to determine how often the facility operates, and whether the firm builds more of the same design. In all of these example, firms have an incentive to free-ride on the innovation investments of others. The result in aggregate is under-investment in technology development.

Scale The scale required for innovations to become profitable depends on the production process, the sector, whether the innovation involves a process or product, among other factors. Proving reliability at scale is a challenge, particularly for radical innovations which might depend on large demonstration projects for subsequent commercialisation (Wilson, 2012, Funk, 2013). For example, upscaling typically identifies new problems that are not apparent at smaller scales (Sahal, 1985). The capital required for a single demonstration project can be in the 100s of millions of dollars, or even billions. It may even be the case that several demonstration plants will need to be built to sufficiently learn or prove to de-risk the technology and move to commercial production. The required investment may rival the value of the firms themselves making them a potentially unacceptable risk. The under-investment problem due to spillovers is exacerbated if the scales required are large relative to the size of the firms involved.

Radicalness Incentives for private investment in demonstration projects also hinge on the novelty of the innovations. Incremental improvements to existing technologies are more likely to attract financial investment than radical innovations. Radical innovations likely involve more uncertainty over whether they will prove feasible, economical, and reliable (Verhoeven et al., 2016). Radical innovations also have bigger knowledge spillovers than incremental ones, as the latter can often be protected by patents or embedded in unobservable production processes (Hurmelinna-Laukkanen et al., 2008).

Fragile demand-pull Incentives to invest in demonstrations may also be weak because expectations about the payoffs are uncertain. This issue is especially problematic for innovations that depend highly on government actions for their payoffs, for example environmental technologies. If future policies are uncertain, investment can be reduced (Nemet et al., 2017). It is quite clear that weak credibility about government commitments to future policies has been a problem in climate policy (Koch et al., 2016). Where payoffs depend on policies, and especially if lags between investment and payoffs are long, weak policy credibility can make demand-pull 'fragile' and thus weaken incentives for demonstration investments.

As the above discussion suggests, the interactions among these factors may be especially problematic. Scale and radicalness may simply exacerbate appropriability problems. Large firms may be able to absorb the risk of investing in billion dollar demonstration programs, but if knowledge spillovers exist, the scale of investment may be too much to overcome. Fragile demand-pull may be more of government failure than a market failure. This stage of the technology innovation process is particularly amenable to cost sharing between governments, private firms, and industrial consortia. Investment by the public sector is made difficult however by the need to concentrate substantial funds in a small number of projects. This concentration has made investments at the demonstration stage vulnerable to shifting political support and, conversely, prone to regulatory capture that may excessively prolong programs and funding.

2.2.4 Government failures and the technology pork barrel

As a result, government support of demonstrations involves not only market failure problems but potentially also government failures. The basic argument is that government failures exist that lead to suboptimal implementation of policies to address innovation-related market failures. Several specific mechanisms can result in government failure (Weimer and Vining, 2015). Concentrated interest groups in a technology have strong incentives to lobby and thus policy decisions are made with excess weight placed on the costs and benefits of those groups. Because they face elections, representatives have strong incentives to secure and maintain government technology investments in their own districts. This particular mechanism has earned colourful metaphors such as 'log-rolling' and 'pork barrel' politics. Elections may lead representatives to be especially focused on securing funding in the near term, possibly without regard to broader and long term impacts. Problems in bureaucratic supply may also exist. In part because governments do not face competitors, X-inefficiency may lead to programs not performed at least cost. Also, incentives within bureaucracies may create agency problems, which in an innovation context may result in programs implemented above the most efficient least cost method. This is especially problematic in innovation where the private sector is already likely risk averse so that government need to be risk-seeking to avoid crowding out private investment. Their lack of participation in the marketplace may also give governments poor access to information, for example about pricing, competing technologies, and consumer preferences. Finally, decentralised government decision making – in which countries and sub-national governments make independent decisions – inadequate information, poor coordination, and inefficient duplication of programs raise implementation challenges.

This literature establishes the multitude of challenges that new technologies face at a crucial phase in their development, demonstrations. Both market failures and government failures exist. Our premise is that the design of future demonstration programs can benefit from understanding this literature and from understanding what configurations have been tried in the past. Our approach is thus to study the characteristics of previous demonstration projects.

2.3 Large-scale, low-carbon demo projects

This section focuses on four main aspects of demonstration plants, namely the motivation for building demonstration plants, the timing of upscaling, the role of the public sector, and the role of market conditions. Using claims from the literature about these aspects of demonstration projects, hypotheses for several characteristics of demonstration projects are developed and tested with a new data set in the next section.

2.3.1 Motivation for demonstration plants

Demonstration projects are undertaken to achieve diverse social goals. These goals create a form of demand-pull, but by themselves they do not reveal whether projects might determine that the technology is unfeasible, unreliable, too expensive, or too immature for commercial adoption.

More immediately the projects themselves may be undertaken with varied motivations that affect their success. An important distinction is between projects meant to serve as exemplars to encourage commercialisation or as experiments from which to learn (Frishammar et al., 2015). Strong arguments emphasise that the real social value is in learning rather than in proving (Reiner, 2016). Still other motivations exist, e.g. given the large public funds being used, they are often used to pursue a social goal itself, such as production, or environmental benefits.

A broad set of literature discusses the benefits of clarifying program objectives (Harborne and Hendry, 2009) and making sure 'learning' is a prominent one (Reiner, 2016). Demonstrations are best seen as experiments (Lefevre, 1984), part of a process of continuous experimentation (Hellsmark, 2199) where risk and failure are crucial to learning (Anadon et al., 2199). Making mistakes should not just improve chances of hits, but should be used to learn from what did not work (Grubler and Wilson, 2014). Consequently, appropriate metrics for project selection or continuation are maximising learning or minimising cost per learning, rather than in terms of performance or cost per performance, which was a problem in NER300, a previous carbon capture and storage (CCS) demonstration solicitation (Lupion and Herzog, 2013).

In the empirical analysis of this paper, the main motivations of demonstration projects will be analysed and it will be tested whether the objective of learning is prioritised over others.

2.3.2 Upscaling

Given learning as a prime objective, the programs of the past make clear that there are benefits to sequential iteration to enhance learning. Iteration enables learning and technology improvement (Wright, 1936, Sheshinski, 1967). Sequential construction of projects allows for opportunities from learning by doing; knowledge generated in producing one demonstration can be used to inform subsequent plants. Iteration enables successful learning by allowing for responses to failure (Frishammar et al., 2015) and thus enhancing the ability to assume and manage risk. Further iteration allows for a progression of technical to organisational to market learning (Bossink, 2015).

Increasing the scale of plants is a central function of the demonstration phase (Rai et al., 2010, Herzog, 2011, Zhou et al., 2015, Frishammar et al., 2015). Upscaling however involves overcoming obstacles (Rosenberg and Steinmueller, 2013) and consequently takes considerable time, going through a 'formative phase' of experimentation (Wilson, 2012). More bluntly it is clear that building to full commercial size immediately is asking for trouble, as we've seen in wind (Garud and Karnoe, 2003) and to some extent in CCS (Lupion and Herzog, 2013). As previous work has shown, a sequence of technical, organisational and market demo is needed (Bossink, 2015).

Using the new data set of this paper, it will be evaluated how the previous experience in upscaling looked like and whether this differs across technologies.

2.3.3 The role of the public sector

Typically, some form of public funding is essential for demonstrations (Foxon, 2010). The presence of knowledge spillovers mean public funding is needed (Foxon, 2010), in addition to private participation (Macey and Brown, 1990). Nonetheless, experiential learning, in which knowledge is created by participants, implies that the private sector must play an active role in developing new technologies and demonstration plants (Hendry et al., 2010). However, part of the technology pork barrel argument is that the firms see securing government funding as their primary objective and consequently have little incentive to implement projects effectively (Cohen and Noll, 1991).

An important development in the past decades has been much more careful consideration of risk and reward for participants (Baer et al., 1976, Dosi et al., 2006, Markusson et al., 2011, Scarpellini et al., 2012, Russell et al., 2012). Crucially, involvement of firms provides opportunities for experiential learning (Baer et al., 1976, Hendry et al., 2010, Schreuer et al., 2010, Russell et al., 2012) and can stimulate networks of cooperating firms (Bossink, 2015). Moreover, success of the projects often depends on the private sector assuming a large share of both funding and management (Lefevre, 1984, Macey and Brown, 1990).

The empirical analysis of this paper will evaluate how big the share of public funding is and whether this differs according to technologies. Furthermore, it will be explored whether the involvement of the public sector is related to specific project characteristics.

2.3.4 The role of market conditions

The ultimate (but not immediate) goal of supporting demonstrations is to facilitate widespread adoption, and thus demand and markets are of course key (Kingsley et al., 1996). Especially in climate change and thus low-carbon technology areas, policies and their credibility are a central determinant of market conditions (Taylor et al., 2003, Zhou et al., 2015, Rai et al., 2010, Finon, 2012, Nemet et al., 2014). Previous literature has emphasised the need to connect demonstration projects to adopters and the markets in which they will ultimately compete (Kingsley et al., 1996, Sun et al., 2014). This importance is bolstered by demand-pull arguments about the importance of demand for innovation (Di Stefano et al., 2012).

The example of the EU's NER300 program shows how important market conditions are for the development of new demonstration projects. Lupion and Herzog (2013) attribute the failure of the NER300 program to stimulate the construction of any CCS projects to four factors: competition with renewables, project complexity, low carbon prices, and a combination of fiscal austerity and weak climate policy around the global financial crisis. Note that three of the four problems involved future demand, not the funding structure itself. Demonstrations need markets that pay off innovation investments not just under a steadily increasing Hotelling-style market, but under a broad range of market conditions.

Supplementing the dataset with additional data on prices of competing technologies, the analysis of this paper will investigate the empirical evidence for demonstration projects and their surrounding market conditions.

2.4 Dataset for empirical analysis

On the basis of a unique dataset collected for this study, the empirical relevance of the four aspects of large scale demonstration projects which were discussed in the previous section, namely the motivation of projects, the upscaling phase, as well as the role of the public sector and of the market are investigated. More than 500 case studies in low-carbon technology areas over the past several decades are examined, coding each demonstration project on the factors described in more detail in the next section.

2.4.1 Dataset and methodology

The focus in the collection of case studies lies on demonstration projects of low-carbon technologies in the following three sectors: electricity, industry, and liquid fuels. In total, 511 cases are examined in nine low-carbon technology areas. Technologies are selected that are analogous to large demonstration plants in low-carbon industry due to similarities in scale, complexity, markets, and integration into a broader technological system:

Electricity: 1) solar thermal electricity, 2) nuclear power, 3) wind power, 4) carbon capture and storage (CCS) for power plants;

Industry: 5) CCS for industry, 6) steel, 7) cement; and

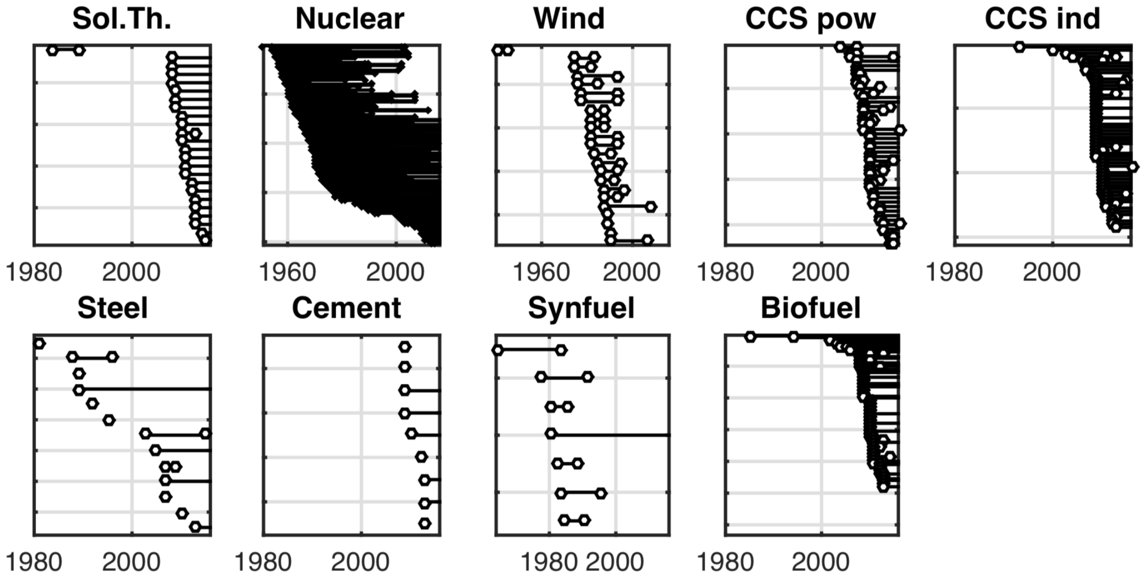
Liquid fuels: 8) synthetic fuels, and 9) cellulosic biofuels.

Each case involves a well-documented government effort to demonstrate the technology, e.g. wind power (Gipe, 1995), CCS (Herzog, 2016), and synthetic fuels (Anadon and Nemet, 2014).

Demonstration projects in each of these technologies are identified by using the general definition of demonstrations by Frishammar et al. (2015). These are projects for which: 1) there is an element of novelty, e.g. a first-of-a-kind, or nth-of-a-kind, 2) development is advanced enough that scale and maturity are beyond the laboratory and prototype stage, e.g. operating in a real environment, but 3) not yet commercially available, e.g. for sale to a third party.

Every database entry and coding of a demonstration project case in the dataset can be identified by a unique ID (see Supporting Information on more details about data collection). Additional identifiers that are coded for each case include the full project name, sector and technology area. The time period for each demonstration

Figure 2-2: Timing of demonstration projects included in analysis.



project is coded according to the project begin and end dates, as well as the year a project became operational. Budget data is coded in standardised US Dollars of the year 2015 as well as original budget currency for each demonstration project. Data is mainly collected from online databases in each technology sector.[1] Additionally, the dataset is made up of information from other academic publications and data of individual project homepages and various websites. The case study protocol presents a detailed overview of these different data sources. The resulting dataset spans start dates from 1940–2015 (see Figure 2-2).

[1]Data on solar thermal electricity is collected from the database by the National Renewable Energy Laboratory (NREL). NREL compiled data on concentrating solar power (SCP) projects in collaboration with Solar Power and Chemical Energy Systems (SolarPACES). Gipe (1995) is the main data source for wind power. Data on carbon capture for power plants is mainly collected from the MIT Carbon Capture and Sequestration Technologies (CC and ST) Program. The MIT CC and ST Program also provides data on carbon capture projects for the industry. The Global CCS Institute provides data for carbon capture plants as well as demonstration plants in the cement and steel sectors. The data for synthetic fuels cases is taken from Anadon and Nemet (2014). Demonstration project data in the sector of cellulosic biofuels is provided by the online database of Task 39 IEA Bioenergy 2020.

2.4.2 Coding characteristics of case studies

Given that all projects are part of a portfolio, no attempt is made to classify each as a success or failure. Rather a data set of characteristics of each project is assembled and the focus lies on evaluating four areas which the literature has pointed to as important attributes of government support for innovation at the demonstration stage.

1. Motivation: Each project is coded on the stated motivations including: production, creating knowledge, scale-up, proving technology, and other motivation. The category 'other motivation' i.a. includes environmental protection, job creation, and energy independence.

2. Timing and upscaling: The timing of each project is coded by the year the project was begun, when it became operational, and when it ended. Furthermore, the scale of production for each project is coded, using equivalent units within each technology area.

3. Role of public sector: For each project where information on the public involvement was available, the total project cost and the public and private sector shares of those costs are calculated.

4. Role of markets: Each demonstration project is connected to market indicators (prices) over time at the technology level. This allows comparing decisions to initiate, operate, and cancelled projects with market expectations at the time.

2.4.3 Methodology

The data collected from the demonstration projects is used to inform the hypotheses developed in the previous section. The qualitative analysis is based on descriptive statistics of the data set as well as it explores the time dimension of the data set. Correlations of project characteristics are presented, as well as characteristics are set into context of market developments.

2.5 Results of empirical analysis

Based on coding these demonstration projects, results on project motivations, timing and scale-up, private sector contributions, and connections to markets are reported.

2.5.1 Motivation

Table 2.1 shows the motivations expressed by each project for which information was available. The motivations are arranged in terms of timing of impact: the most near-term focused objective is to produce a product while the most long-term would be to learn, which serves a broader goal (such as production) in the longer term. The three main motivational drivers in the category 'others' were environmental protection, job creation, and energy independence.

In aggregate, the four categories are at quite similar levels. However, the technology specific mixes are quite distinct. Steel, cement, and synthetic fuels have prioritised learning in more than half of the projects. Scale up has been important for wind, cement, and synfuels; proving technology for power plant CCS, steel, and cement. More than half of projects in power plant CCS, cement, and synfuels see production as a motivation. Note that some projects stated more than one motivation so that they sum to more than 100%. Figure 2-11 in Appendix 2.8.1 shows trends over time in the occurrence of each motivation. There is no distinct shift notable, although a broader mix of motivations (and thus lower shares for all) toward the end of the time period can be noticed.

Table 2.1: Stated motivations in demonstration projects

Technology	Production	Proving	Scale up	Learning	Other	N
1) Sol. Th. Elec.	29%	33%	21%	17%	29%	24
3) Wind Power	43%	26%	78%	13%	0%	23
4) CCS Power	52%	64%	45%	50%	25%	44
5) CCS Industry	29%	40%	31%	34%	19%	62
6) Steel	46%	62%	38%	54%	15%	13
7) Cement	56%	89%	67%	89%	33%	9
8) Syn. fuels	56%	56%	56%	56%	44%	7
9) Cell. biofuels	6%	12%	6%	13%	2%	126
All Sectors	27%	34%	28%	29%	14%	308

Note: More than one response possible per project.

This question was approached with the prior hypothesis that projects tend to overemphasise production as an objective, at the expense of learning. The results however do not provide support, the shares of motivations are quite similar, at least across all projects. Solar thermal electricity, biofuels, and wind power have been least focused on learning as a motivation. This result fits with the prominence of demand pull policy instruments for these technologies, as well as below-median levels of public investment, which are discussed next (Figure 2-5). One possible explanation is some selection in terms of which cases provided information on motivations; for 60% of the cases information on motivation is available. A second possibility is related to the option of multiple responses. In a secondary analysis the responses are weighted inversely by the number of objectives provided, e.g. each motivation weighted by 1/4 if four motivations were provided. This results in similar outcomes with the additions that production is important for wind power and proving technology is important for industrial CCS.

2.5.2 Timing and upscaling

As shown in Figure 2-2, the projects span a 75 year period. Having coded the project start, completion, and cancellation dates (see Appendix 2.8.2 Table 2.2), the following findings emerge: Average time from beginning of a project to coming on-line was 1.9 years for all projects, highest in CCS power plants and synfuels. In contrast to prominent literature on commercial plants, nuclear demonstrations were only slightly above the average (2.5 years), although it also had the most variation. For all projects, 36% were cancelled, with the highest cancellation rate in nuclear power plants. For nuclear, lifetimes of < 30 years are considered as cancellations rather than end of life shutdowns since many reactors operate after 50 years. For projects that were cancelled, the average time on-line before project cancellation was 11.4 years. Of the projects that were ultimately cancelled, 27% were cancelled before they ever came on-line. For the projects that were cancelled after they came on-line, average time to complete construction was 5.3 years, more than double the mean construction time.

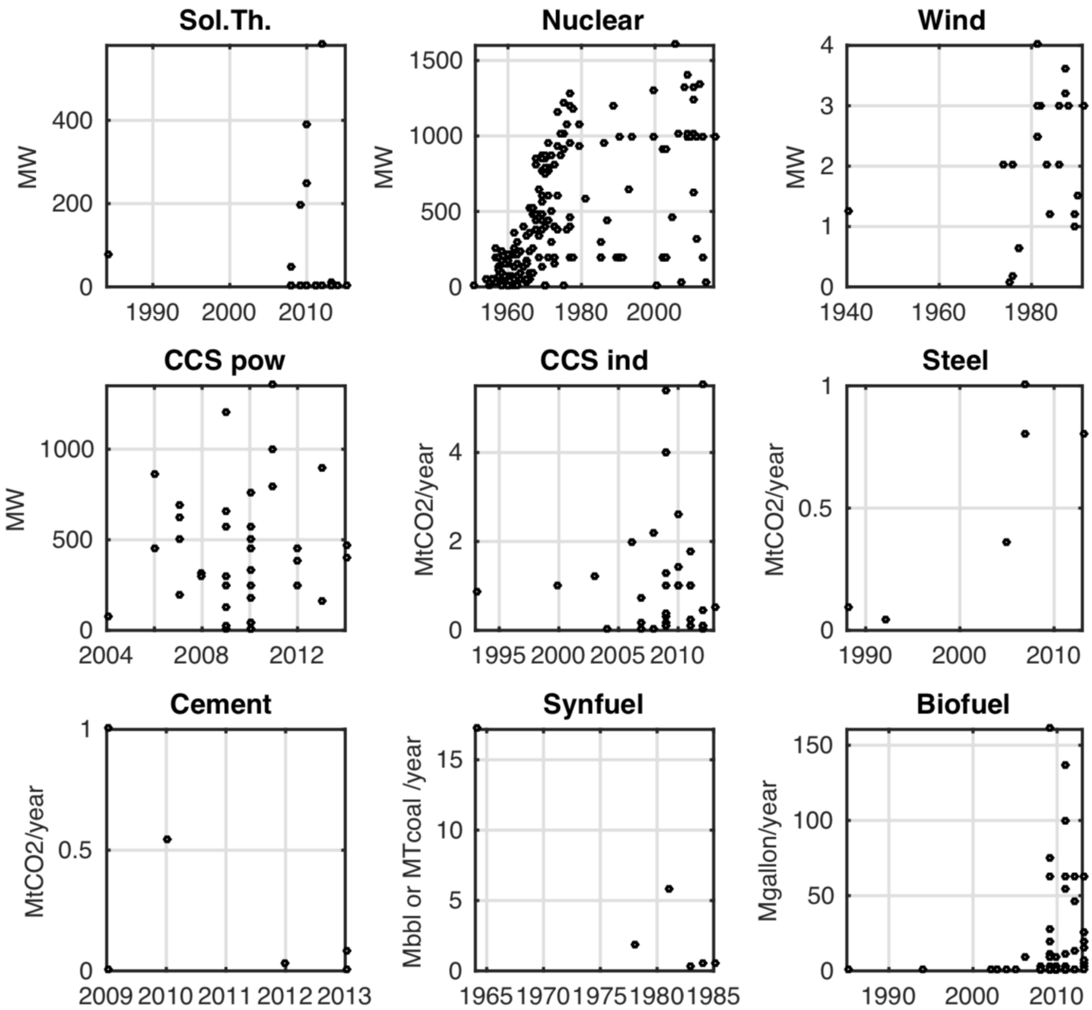
Looking at the size of projects within a technology area over time, it is clear that upscaling is a central outcome. In every case, one can see a trend to larger projects over time (Figure 2-3). These nine technology areas are in part selected based on the technologies needing to function at large scale to be commercially viable. Yet, there is no case in which demonstrations were built at a commercial scale at the beginning. It is known that the process of upscaling takes years and involves iterative improvement (Wilson, 2012), and that is certainly the case with these projects. For a closer look, consider the example of nuclear fission power plants, for which there is comprehensive data for over 65 years available (Figure 2-4). It took 15 years to go from the first demonstrations to commercial scale plants; and that is for the technology that has been deployed more rapidly than any other. One sees a similar pattern in wind turbines. In that case, it was quite clear in the early 1970s that wind turbines would need to be built at MW scale to be economically competitive (Vargo, 1974). As a result, the U.S. and Germany developed several demonstrations with a capacity of over 1MW using technology from the aerospace industry (Gipe, 1995). Yet, these approaches failed compared to the Danish approach which was to gradually upscale their turbines, so that it took over 20 years to reach 1 MW scale. The Danish approach of gradual upscaling with iterative improvement led them to dominate the wind power industry (Garud and Karnoe, 2003).

2.5.3 Public contribution

In Figure 2-5 the public share of expenditures for each project for which data was available is shown. Across all projects, there is a median public contribution of 64%, with a 25-75th percentile range of 29–80%. Every technology area shows a wide dispersion in public contribution, with many including both completely publicly and completely privately funded projects. Notably the data shows substantially higher public sector participation in industrial CCS projects compared to power-sector CCS; the 25–75 ranges do not overlap. It should be noted that some firms may be in a regulated environment that allows them to pass on all or some of their share to ratepayers (Averch and Johnson, 1962). However, even in the power sector in a single country there is inconsistent treatment of cost recovery in these projects so no attempt is made to code them in this way.

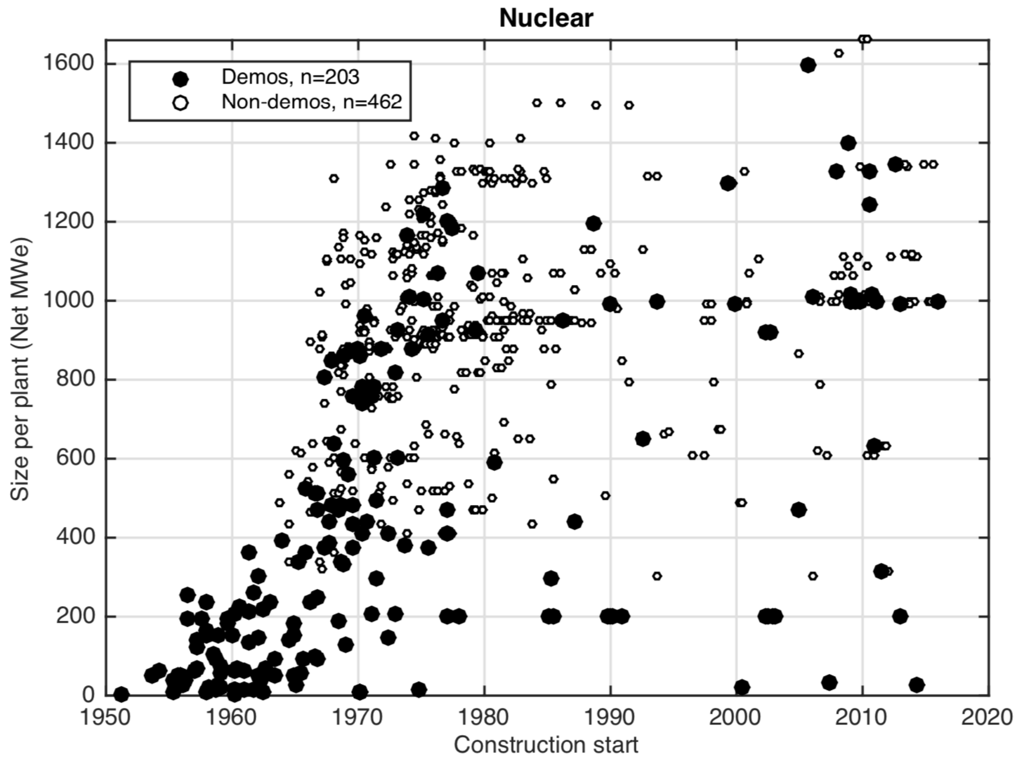
To explore some of the possible factors affecting this wide dispersion, Figure 2-6 shows bi-variate comparisons of public share with: start year, sequence, budget, and market prices in which the technologies would ultimately compete. Note that this figure does not include data on nuclear projects where data on the public share was

Figure 2-3: Scale of demonstration projects by project start year



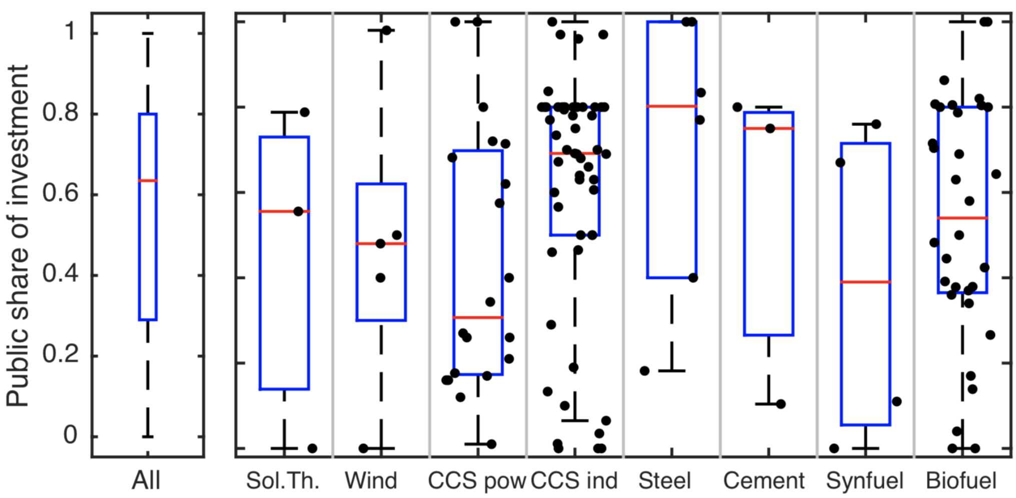
unavailable. Linear fits show only weak relationships, e.g. there appears to be a trend toward higher public share. Notably there are very little indications of a relationship between project size (in terms of budget) or in terms of prices. To further assess these possible relationships, a fractional logit model is used to estimate the determinants of the public sector share of funding (see 2.8.3). No significant results are found, although the budget coefficient is negative and slightly significant at the ten percent level in two out of seven estimations. There is however only full data for about 100

Figure 2-4: Nuclear power plants: scale of demo projects compared to commercial plants (non-demos)



Note: Demonstrations defined as: 1) first of a kind reactor type by supplier, 2) built at < 50% of minimum commercial scale (500MW), or 3) operating for < 25% of 60 year life.

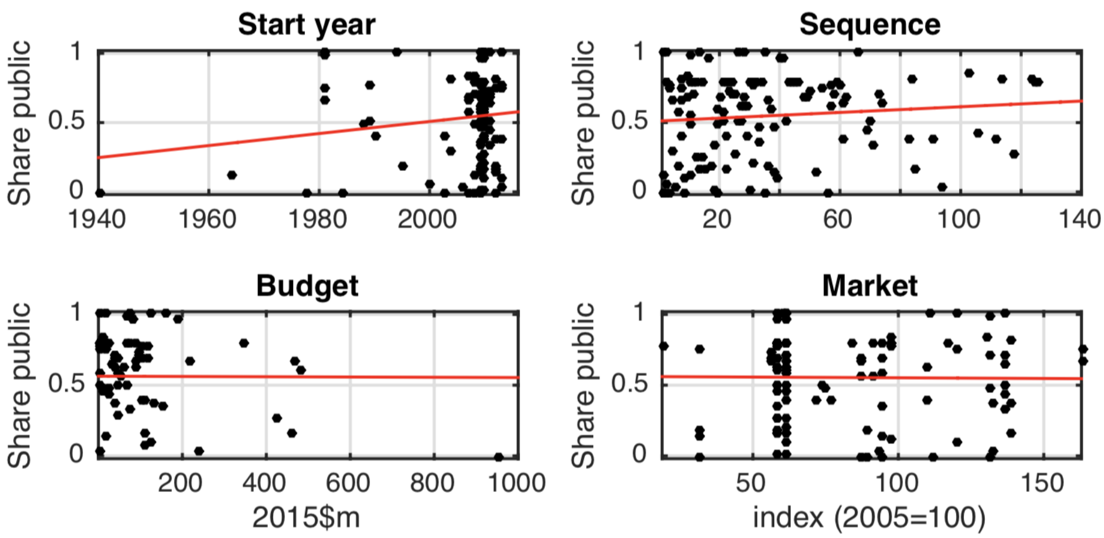
Figure 2-5: Contributions of public sector to demonstration projects



Note: Boxes represent 25–75th percentile ranges, red line is median, and dashed lines indicate full range.

observations, and we are careful to include 8 technology dummies in every estimation, so there is some risk of a type II error. Nonetheless it is somewhat surprising to see no effect of public share given the large range of project budgets included and the notion that scale affects incentives. These results are included in 2.8.3.

Figure 2-6: Contributions of private sector to demonstration projects

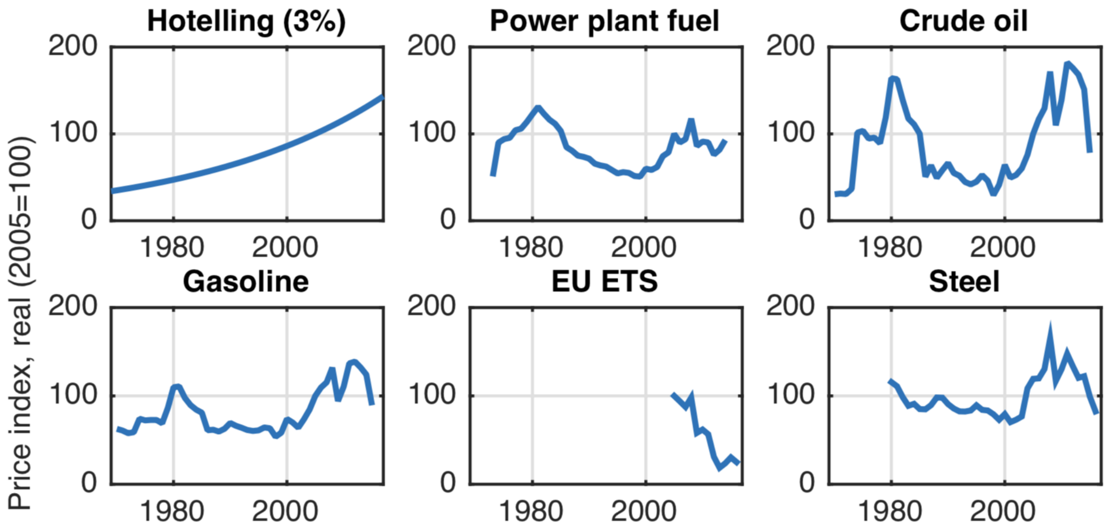


Note: Horizontal axes show: year project began, nth plant for each technology, total project budget, and price index for relevant market

2.5.4 Markets and expectations

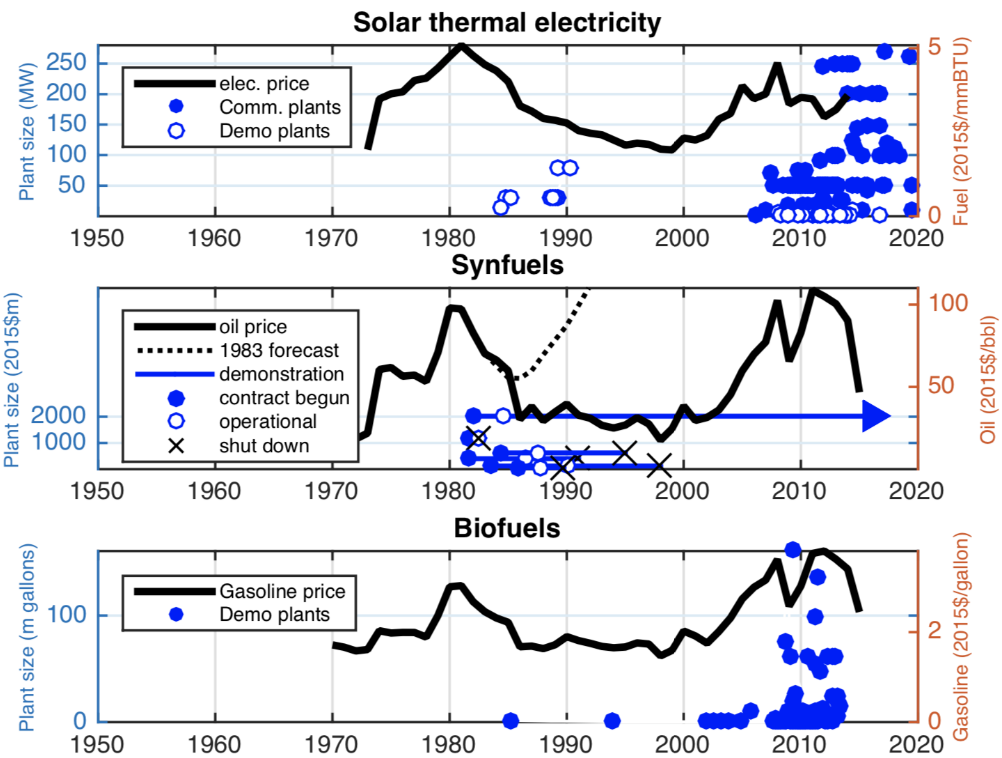
To assess the markets in which these demonstration projects were ultimately to compete, price indices are created for each of the markets in which each of these 9 technologies competes (Figure 2-7). Prices are in real dollars and indexed so that 2005=100. In addition, a Hotelling curve is added using a typical social discount rate of 3% to give a sense of the general expectation of a long term price path for a non-renewable resource (Hotelling, 1931). A Hotelling price path predicts that prices of an exhaustible resource (e.g. oil, atmospheric storage of CO_2) rise at a constant pure rate of time preference for the time of project duration. It is important to consider that Hotelling is not merely an academic construct, it shapes expectations about future prices in a variety of contexts. This descriptive comparison supports what is clear from the literature (Krautkraemer, 1998, Zaklan et al., 2016), that price paths following Hotelling are the exceptions rather than the rule – it is more likely to see shocks and boom-bust cycles, as the prices related to each demonstration project in Figure 2-7 show.

Figure 2-7: Price indices for markets relevant to each technology



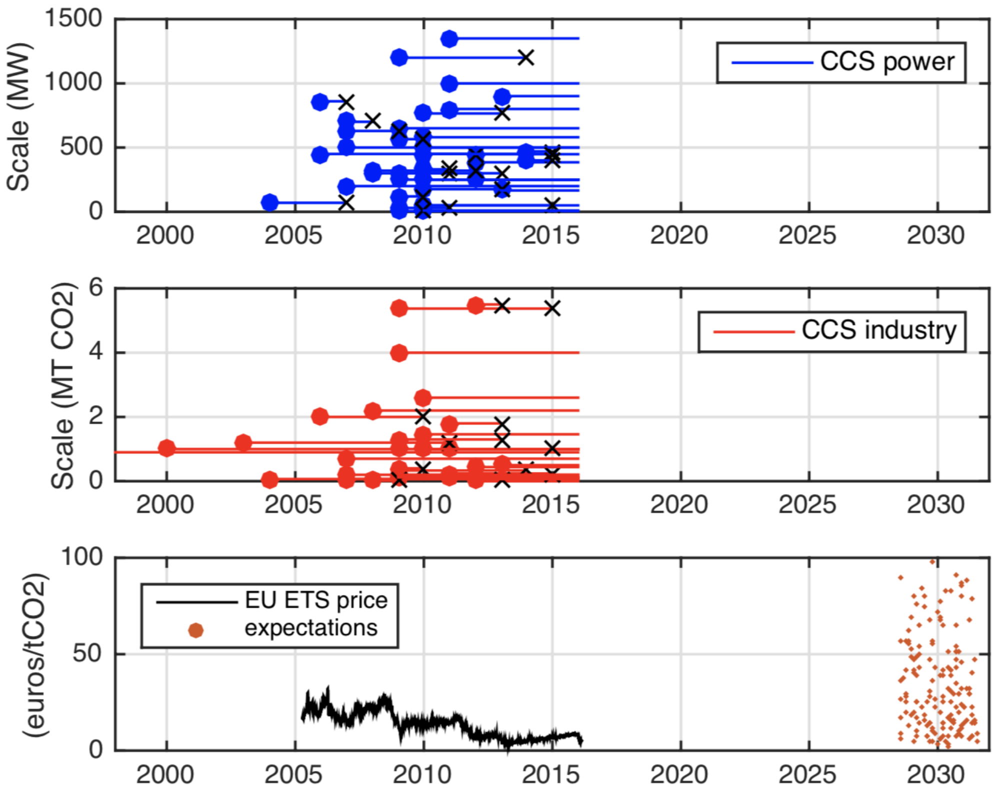
Looking at market prices in the context of previous demonstrations shows a recurring outcome; demonstration project often come on-line just as markets for them are heading in the wrong direction. The projects were planned when prices and expectations rose, and only came on-line when prices crashed. The lags between project initiation and on-line make them vulnerable to volatile markets. This is clearly seen in synfuels (Figure 2-8), in which projects came on-line just as the market was disappearing. Similar outcomes are observed in solar thermal electricity and cellulosic biofuels. In the synfuels case, only one project survived; this more than any other outcome led to the notion of the technology pork barrel. It was not that technology did not perform according to projections, but the unexpected drop of global oil prices that eliminated the commercial viability of the projects. This outcome created the impression of a failure of the innovation policy.

Figure 2-8: Markets for demonstration projects: solar thermal electric, synthetic fuels, and cellulosic biofuels



CCS projects show a similar pattern; projects have come on-line just as the EU ETS price has crashed (Figure 2-9). Taking a more future oriented perspective, expectations of future carbon prices in 2030 (Usher and Strachan, 2013) are plotted. Expectations of prices seem higher than current prices, but the wide dispersion of expected prices imply considerable uncertainty, even as to whether prices will be higher or lower than today's. It seems possible that CCS markets could look similar to those of synfuels and others, such that projects coming on-line may need to survive multiple years selling into a low price regime before prices rise. The persistent pattern of unstable energy markets suggests that demonstration programs need a plan for robustness, so that projects have a chance to proceed to commercial adoption under a range of market outcomes, not just optimistic ones.

Figure 2-9: Markets for demonstration projects in CCS

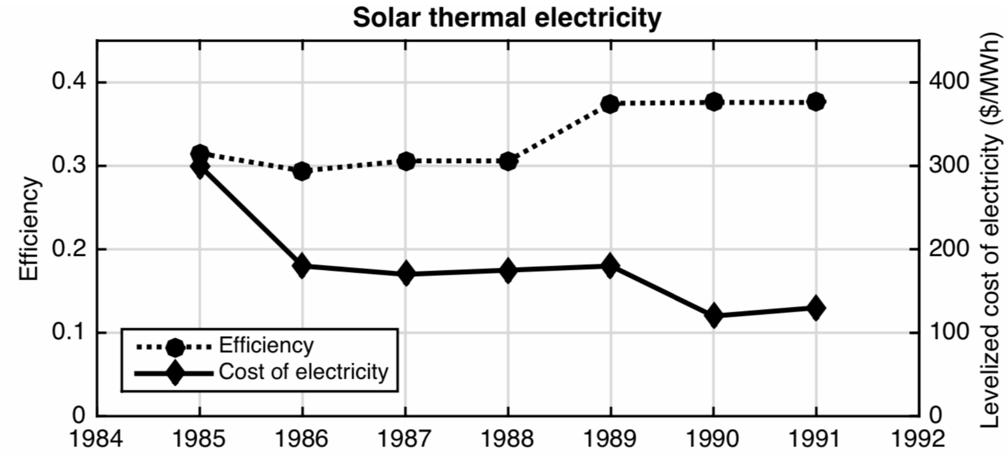


2.6 Discussion and limitations

The dataset collected for this analysis relies on publicly available information. Evidently, this limits the scope of data collection and thus the analysis, especially with respect to performance, knowledge dissemination, and broader project contexts.

A project focus on learning means that management of knowledge is central;

Figure 2-10: Performance of solar thermal electricity demonstration projects



how it is produced but also how it is codified, stored, and transmitted (Grubler and Nemet, 2014). Dissemination is even more important given the global public good aspect (atmospheric greenhouse gas storage capacity) of the problems to be addressed. Performance review of demonstrations helps (Frishammar et al., 2015), including especially reporting of results (Gallagher et al., 2006).

We were unsuccessful in obtaining performance data and details about knowledge dissemination for anything close to a representative sample of the projects which were coded. However, as an exception, results from the first solar thermal electricity plants in California in the 1980s (Figure 2-10) are shown. These results show impressive cost reductions over sequential plants, including scale-up. Perhaps even more relevant to this paper is that this improvement was only observable due to a 50:50 cost shared post-demonstration assessment by the private firm who developed the plants and the U.S. Department of Energy (Nemet, 2014). Performance was assessed systematically over time and made publicly available (Lotker, 1991). From the projects that were reviewed in this paper, this post-project assessment represents the gold standard for knowledge codification and dissemination for demonstration plants.

Another factor which was not feasible to code in a comprehensive manner was the broader context of demonstration projects. The strong effects of scale economies for the technologies under consideration imply a need for diversity support (Markusson et al., 2012) to avoid lock in (Shackley and Thompson, 2012). Given multiple pathways available for large scale low-carbon technologies, premature focus can be risky (Nemet et al., 2013). This creates a need to support variety while evolutionary mechanisms impose selection pressure (Kemp et al., 1998). However, this analysis cannot provide insights on these broader project contexts.

2.7 Conclusion

Looking at a a broad set of previous demonstration projects provides insights for how to make the most out of future government support for demonstrations. Our review of past demonstration projects reveals five main conclusions which are important policy design elements to include as several countries consider how to support innovation for large scale decarbonisation.

First, there is still scope to prioritise learning as a motivation for such projects. Our review of past projects identified a wide range of motivations. Only 60% of the projects for which motivation information was obtained, stated something related to learning as an explicit objective. To enhance the social returns of these government investments, all of them should consider learning as part of their objectives at the very least. They thus should be monitored and reported on to facilitate learning. Milestone payments provide help in this direction as they raise the importance of defining meaningful milestones. Basing milestones e.g. on knowledge created, could offer a promising direction for the design of public innovation funds to ensure the importance of knowledge creation.

Second, iterative scale up is important for the development of new technologies. Our data show achieving full commercial scale takes considerable time. For example, one can clearly see two decades of demonstrations and upscaling in nuclear. That may be an extreme example given the complexity of that technology. Still, it points to the need for sequencing and iterative learning, and perhaps most importantly, some urgency in initiating projects. Policy makers need to learn from failures and successes of the past in order to design a demonstration strategy that itself can both generate new knowledge and learn from that which is created.

Third, the role of the public sector is independent of projects characteristics. A very heterogenous mix of public-private financial contributions was found in the data set. The share of public contribution in the overall budget of demonstration projects seems to be unrelated to other project characteristics like technology, scale, motivation, or market environment. Experiential learning, in which knowledge is created by participants, mean that the private sector must play an active role. Managing public-private relations in innovation funding is nontrivial, including not only funding and risk, but also knowledge.

Fourth, knowledge dissemination is essential in contributing to overall learning objectives. A focus on learning means that management of knowledge is central; how it is produced but also how it is codified, stored, and transmitted. Performance review of demonstrations helps, including especially reporting of results. Policymakers must carefully weigh the benefits of knowledge dissemination against private claims of proprietary access to knowledge created. The benefits of widespread access to knowledge created is not something to give up easily in negotiations to secure private funding.

Fifth, a robust demand-pull policy environment helps sustain the on-going viability of projects once initial capital investment has been made. Pairing our dataset of demonstration projects with market conditions, it is striking how many demonstration programs competed in markets that involved negative shocks around the time that projects came on-line – this is observable in synfuels, biofuels, solar thermal electricity, and CCS. The time lag from project initiation to time on-line, an average of 1.9 years in our sample, is thus crucial in times of changing market conditions. Our data suggests that relying on a Hotelling path for future payoffs is a risky bet and that it is more likely to see booms and busts of relevant prices over the duration of projects. This large uncertainty about the price development of competing technologies creates the need for a robust demand-pull policy in addition to public financial support of demonstration projects. Features of robust demand-pull include for example niche markets (Kemp et al., 1998), hedging across jurisdictions (Nemet, 2010), and flexible production (Sanchez and Kammen, 2016). Last but not least, government price guarantees have played an important role as was seen in the case of synfuels, solar thermal electricity, and on a smaller scale, photovoltaics.

There are however additional factors which should be considered when setting up a demonstration strategy and we touch on three aspects providing direction for further research. First, policy makers are ultimately concerned about two questions: 1) *How big a demonstration plant should we build?* and 2) *How many demonstration plants do we need?* Our take on the first question is that iterative upscaling implies that the budget should increase over time. The median cost of all projects in our data set is \$64m. Other work indicates that each demonstration costs \$1b (Reiner, 2016) while others have designed strategies in which a similar amount is divided into 5 to 6 grants of \$200m each (IEA/UNIDO, 2011). The second is an even bigger open question (Reiner, 2015). Some have suggested that 5–10 projects are needed (Herzog, 2011), while others have modelled deployment based on 10 projects (Nemet et al., 2015). Clearly an empirically based pathway to commercialisation will help inform this decision-making.

A second direction is how to consider public acceptance (Krause et al., 2014, Geels et al., 2016). That these projects are industrial scale and typically unfamiliar make them unlikely candidates for favourable and consistent embrace by various publics. Given the need for governments to take risk and tolerate failures, public attitudes are important to understand. If publics are sceptical, interim problems can become high profile failures and create insurmountable setbacks. This is particularly important if taking risks and experimenting. The abrupt ending of CCS deployment in Germany is a cautionary tale, as are early adoption of even apparently benign technologies such as solar water heaters in California (Taylor et al., 2007).

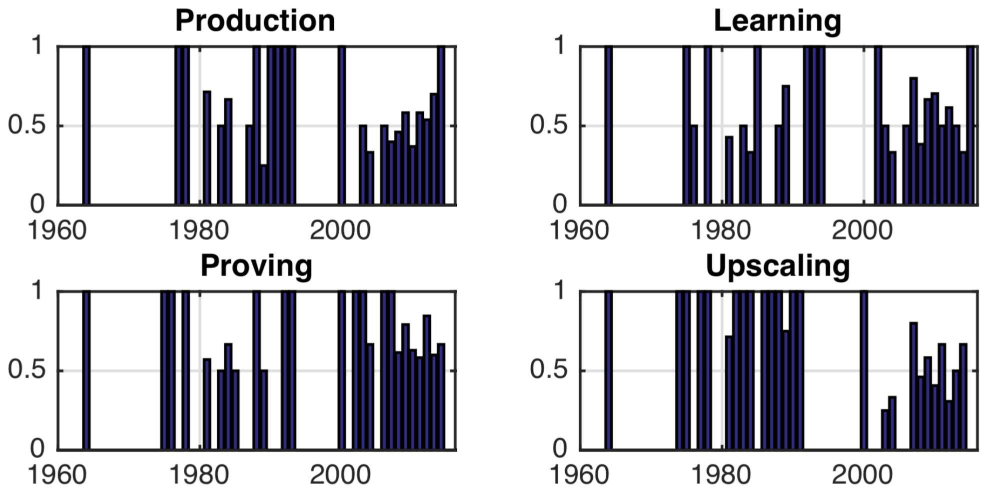
Coming back to the original technology pork barrel argument, a third direction is to account for the political economy dimensions of demonstration projects. But rather than an interpretation encapsulated in governments should avoid picking winners, here there is an opportunity to think more normatively about how to design programs within a setting of influential political actors (Klitkou et al., 2013). For example, "advocacy coalitions" are a promising dimension to understand and address specifically in demonstration program design (Dasgupta et al., 2016).

2.8 Appendix

2.8.1 Motivations for demonstration projects

Motivations over time are shown in Figure 2-11.

Figure 2-11: Motivations of demonstration projects



Note: Share of projects stating each motivation by year.

2.8.2 Timing of demonstration projects

Averages across projects for indicators of timing are shown in Table 2.2.

Table 2.2: Timing of demonstration projects.

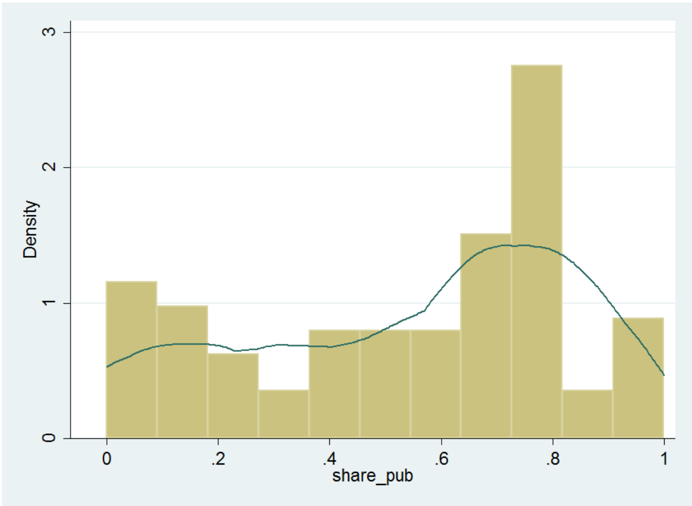
Technology	Start	Online	End	Start to online (in years)	Start to end (in years)	Online to end (in years)	% cancel
1) Sol. Th. Elec.	2010	2012	2017	2.7	6.8	4.1	1%
2) Nuclear Power	1974	1976	1991	2.5	17.6	15.1	56%
3) Wind Power	1981	1983	1990	1.8	8.8	6.9	13%
4) CCS Power	2010	2016	2013	6.0	3.5	-2.5	17%
5) CCS Industry	2009	2011	2013	2.2	4.0	1.8	6%
6) Steel	1999	2003	1996	4.0	-2.9	-6.9	0%
7) Cement	2011	2013	.	2.5	.	.	0%
8) Syn. Fuels	1979	1985	1989	5.6	9.7	4.2	3%
9) Cell. Biofuels	2009	2011	2012	1.8	2.7	0.9	3%
All sectors	1992	1994	1997	1.9	4.6	2.8	36%

2.8.3 Regression analysis of public funding share

The correlations of the share of public funding with the starting year of the projects, the market variable as well as the sequence variable, let us to investigate this relationship further in a regression framework. As the dependent variable is a percentage, which also takes values of zero and one, a fractional logit estimation is used. The fractional logit estimation was developed by Papke and Wooldridge (1996) to take account of the bounded nature of percentage values while at the same time allowing for values at the boundaries. A logit transformation of the data is not adequate as this is not defined for values at the boundaries. These are however present in our data, as Figure 2-12 shows.

Using the glm command in Stata (Baum, 2008), dummies for each technologies are specified and the budget in USD 2015 as our baseline explanatory variables. In subsequent estimations, the starting year of the project, the starting year lagged by one year, a dummy variable indicating whether the project was cancelled, the market variable, and the sequence variable are added one by one to the baseline specification. We abstain from a joint estimation of these explanatory variables, as they show significant and high correlations amongst each other. The estimation results are

Figure 2-12: Histogram with kernel density of public share



shown in Table 2.3, with the baseline specification in column 2. No significant results are found, albeit the budget variable is slightly significant at the ten percent level in two out of six estimations with a negative sign. The dummy for the cancellation of projects is also found to be significantly negative. However, given these vague results, we are not able to draw conclusions from these estimations.

Table 2.3: Fractional logit estimation for public funding share

Dep variable: Public share	(1)	(2)	(3)	(4)	(5)	(6)	(7)
D STE	-0.21	-0.32	-110.1	-101.1	-0.32	-1.12	-0.35
	(-0.77)	(-1.17)	(-86.22)	(-86.17)	(-1.17)	(-1.48)	(-1.17)
D Wind power	-0.11	0.64	-108.5	-108.4	1.004	-0.1	0.61
	(-0.56)	(-0.59)	(-85.67)	(-85.62)	(-0.7)	(-0.83)	(-0.6)
D CCS energy	-0.27	-0.15	-110.6	-110.5	0.15	-0.65	-0.26
	(-0.27)	(-0.28)	(-86.63)	(-86.59)	(-0.32)	(-0.57)	(-0.31)
D CCS industry	0.43***	0.46***	-109.9	-109.9	0.6***	0.12	0.22
	(-0.16)	(-0.17)	(-86.62)	(-86.57)	(-0.16)	(-0.5)	(-0.38)
D Steel	0.84	0.74	-109.2	-109.1	0.75	-0.066	0.69
	(-0.59)	(-0.66)	(-86.26)	(-86.21)	(-0.67)	(-1.02)	(-0.66)
D Cement	0.21	0.23	-110.3	-110.3	0.23	-0.72	0.21
	(-0.74)	(-0.75)	(-86.71)	(-86.67)	(-0.75)	(-1.22)	(-0.76)
D Synfuels	-0.47	-0.19	-108.8	-108.7	0.21	-0.91	-0.23
	(-0.71)	(-0.79)	(-85.15)	(-85.11)	(-0.74)	(-1.45)	(-0.78)
D Biofuels	0.14	0.19	-110.2	-110.2	0.29	-0.75	0.065
	(-0.2)	(-0.22)	(-86.7)	(-86.65)	(-0.24)	(-1.01)	(-0.28)
Budget		-0.000046	-0.000047	-0.000047	-0.000048*	-0.00005*	-0.00004
		(0)	(0)	(0)	(0)	(0)	(0)
Year begin			0.055				
			(-0.04)				
L1 Year begin				0.055			
				-0.04			
D Cancelled					-0.54**		
					(-0.27)		
Market						0.008	
						(-0.01)	
Sequence							0.01
							(-0.01)
N	126	107	107	107	107	103	107

Note: Standard errors in parentheses. Significance levels * p<0.10, ** p<0.05, *** p<0.01.

Chapter 3

Green public procurement and the innovation activities of firms*

3.1 Introduction

The public sector has a large potential as buyer to influence the production of more environmentally friendly products through public purchases. Public procurement accounted for 12% of GDP on average in the OECD countries in 2015 (OECD, 2017). Acknowledging that this demand could be directed towards the purchase of more environmentally friendly products opens a wide field of action for governments. However, little is known so far on the effects of using environmental criteria in public procurement, so-called green public procurement (GPP), on e.g. procurement practices of buyers, competition effects in the procurement auction, or effects on induced innovation at the firm-level.

*The paper is published as DIW Discussion Paper 1820 (2019), available under https://www.diw.de/documents/publikationen/73/diw_01.c.676416.de/dp1820.pdf. The author would like to thank Nils May, Karsten Neuhoff, Gregory Nemet, and the participants of the DIW Brown Bag seminar for their helpful comments, as well as the ZEW, especially Ms. Gottschalk, for her support in accessing and working with the MIP data.

Green public procurement falls into the category of strategic procurement, which aims at achieving additional, strategic policy goals through procurement.[1] In the case of green public procurement, the political goal is to achieve a more sustainable economy. This is done by explicitly including environmental criteria in the procurement process of works, services, and supplies. In practice, this might be done in form of technical requirements or, more flexibly, through additional selection criteria next to a price selection criteria.

Green public procurement can be considered as demand-side innovation policy tool. Demand-side innovation policies are considered to trigger innovations or spread the diffusion of new technologies through a demand-pull effect – in contrast to supply-side policies which work through technology-push effects (Edler and Georghiou, 2007). Public procurement might create this demand effect through the creation of lead markets or by overcoming market failures. One main argument for public procurement as innovation policy, which is especially relevant for the case of GPP, is that broader policy objectives such as sustainability might be achieved sooner with more innovation (Edler and Georghiou, 2007). The research question of this paper is thus whether green public procurement works as demand-pull factor for innovations.

This paper provides a first empirical analysis on the relationship between GPP and firms' innovation activities in Germany from 2006-2016 by using a new firm-level dataset. Building on the Tenders Electronic Daily (TED) database of the European Commission, green procurement awards[2] are identified and matched to the Mannheimer Innovation Panel, the German part of the European Community Innovation Survey (CIS). The combination of these two datasets allows to infer correlations

[1] Strategic procurement refers i.a. to innovative, green, and social procurement. These are forms of procurement which emphasise certain quality measures in the procurement process to achieve more innovation, sustainability or inclusiveness in the overall economy (European Commission, 2017b).

[2] The terminology of 'winning a GPP award' and 'winning a GPP contract' is used interchangeably in this paper.

between winning GPP contracts and firms' innovation activities. Firms' innovations are measured as indicator variable which measure whether a firm produced a general innovation or not. This indicator is further differentiated into general product and general process innovations. The dataset also offers a separate indicator for environmental innovations (env. product and env. process innovations) which is however only available for two out of ten survey waves.

The results show that winning a GPP contract is associated with a higher probability of producing product innovations while no significant correlation with the probability of process innovations can be confirmed. A more detailed look at the probability of having environmental innovations shows no significant relationship of winning a GPP contract – neither for environmental product nor for environmental process innovations.

The results on general product and process innovations differ across sectors. While the water supply and waste industry show a positive correlation between winning a GPP contract and the probability of product innovations, the electricity and gas sector shows a positive correlation between winning a GPP contract and process innovations. The manufacturing sectors only shows a positive relationship between a cumulative GPP measure and product innovations, potentially indicating a slower but sustained effect of GPP.

Related literature

The paper is related to three literature streams and adds to them in the following three ways. First, the paper adds to the research on economic effects of GPP by providing first empirical evidence on firm-side effects of GPP. Second, it adds an additional type of procurement to the empirical literature on procurement and innovations.

Furthermore, this paper uses a more direct way of measuring procurement as this analysis is based on actual contract data matched to firm-level data instead of relying on proxies of procurement, as e.g. Aschhoff and Sofka (2009) use. Third, the paper adds a missing piece to the literature around the drivers of environmental innovations by providing first empirical evidence on GPP as demand-side driver.

First of all, the paper relates to the literature around green public procurement. There is a growing field of literature around the implementation of GPP, but studies about the effect of GPP on firms' activities are still missing (see Cheng et al. (2018) for a review). The theoretical framework of GPP is related to preferential procurement (see Marion (2007) for the context of SMEs) and scoring auctions (Lundberg et al., 2011, Asker and Cantillon, 2008). Many quantitative studies investigate the implementation and potential barriers of GPP (Testa et al. (2012), Testa et al. (2014), see Cheng et al. (2018) for a more detailed review). Studies on the economic impacts of GPP are only a handful. Simcoe and Toffel (2014) show empirical evidence that GPP can enhance the diffusion of environmental technologies by affecting the private sector demand. Rietbergen and Blok (2013) use the case of the Netherlands to show that GPP reduced the CO_2-intensity of the supply chains of the public sector. Lundberg et al. (2015) find that GPP does not significantly influence the decision of firms to participate in a tender nor the overall number of bids submitted. However, the increased complexity of some GPP contracts is associated with a higher drop-out rate of bids at the qualification stage where bids are evaluated whether they meet all binding requirements.

Second, this paper relates to the literature which analyses procurement as demand-side innovation policy. There are some early and some more recent empirical studies investigating the link between public procurement and innovation (see Appelt and

Galindo-Rueda (2016) and Mowery and Rosenberg (1979) for reviews), often comparing public procurement to other innovation policy tools. Empirical studies often face the difficulty of data availability – either on the side of the procurement or on the link between firm-level data and procurement, which is why often innovation surveys are used. Aschhoff and Sofka (2009) for example made use of the 2003 German innovation survey. Comparing the effect of procurement to R&D subsidies and university research, they found that both public procurement and the public provision of R&D infrastructure in universities had a positive effect on firms' innovations. Slavtchev and Wiederhold (2016) find causal evidence of increasing technological content on R&D activities in high-tech sectors in the US. Czarnitzki et al. (2018) use the German CIS data and show a significant positive effect of innovative procurement on the sales share of new products of firms who won a procurement contract.

Third, this paper also relates to the literature on the drivers of environmental innovations. GPP seems a highly under-researched piece in this literature. While studies investigated the effect of technology-push factors such as R&D grants and tax credits (Dechezleprêtre et al., 2016), demonstration plant funding (Nemet et al., 2018), regulatory push factors such as environmental regulations (Dechezleprêtre et al., 2015), as well as demand-pull factors like standards (Montero, 2002; Holland et al, 2009) and the pricing of externalities (Borghesi et al., 2015, Calel and Dechezleprêtre, 2016), an analysis of GPP as driver of environmental innovations is still missing. A notable contribution in this field is Ghisetti (2017) who provides first empirical evidence of the effect of innovative procurement on environmental innovations using Innobarmenter data from the European Union. Horbach et al. (2012) analyse a range of potential drivers and show that i.a. customer requirements are an important driver of environmental innovations for firms, supporting the case for procurement as driver of environmental innovations.

The paper is structured as follows. Section 3.2 provides a rationale for GPP in the innovation context. Section 3.3 describes the data and methodology used for the empirical analysis. Section 3.4 presents the results, followed by section 3.5 providing some robustness checks. Section 3.6 concludes.

3.2 Framework

The framework for this paper is grounded on the innovation model developed by Crepon et al. (1998) as well as the taxonomy of the innovation and procurement policy space by Edler and Georghiou (2007). To analyse the research question of this paper, whether green public procurement works as demand-pull factor for innovations, the framework explained in this section is used to develop three hypotheses, which will be tested empirically later on in this paper.

Public procurement as demand-side innovation policy only recently attracted more attention – even though first empirical studies were conducted already in the early 1980s (see Mowery and Rosenberg (1979) for a review). As Edler and Georghiou (2007) review in their seminal paper, public procurement was mostly neglected in conceptual research[3] as well as on the policy agenda until the early 2000s when the European Union picked it up again.

There are three main rationale, according to Edler and Georghiou (2007), to implement public procurement as demand-side innovation policy tool, even if the effect on innovation through public procurement will only be indirect. While there are policies, such as R&D grants, which are solely targeted at increasing innovations and which rather directly impact the innovation process, there are still good reasons

[3] A notable exception and interesting read is Geroski (1990). Using a historic case study approach, he identifies conditions under which procurement as innovation policy might be effective and when it might not be.

to consider public procurement as useful demand-side innovation policy. First, the large share of public demand might create lead markets. Second, public procurement might be able to overcome existing market failures which lead to an under-supply of innovations. Third, public procurement might be used as innovation policy to achieve other normative policy objectives than innovation goals. The transition towards a low-carbon economy could be such a policy objective, which might be achieved faster through procurement-enhanced innovations than without procurement.

Looking at the innovation process within firms, a demand-pull effect of procurement might work through a direct channel affecting innovation output. In the innovation cycle framework developed by Crepon et al. (1998), firms' innovations are a function of their innovation budget, the size of the firm, sectoral effects, technological push and demand-pull effects. These demand-pull effects might work as direct effect on innovation output and/or as indirect effect through the firms' innovation input, e.g. R&D budget, on innovations. From their multistage innovation model, Crepon et al. (1998) conclude that the direct effect of demand-pull factors is by far larger than the indirect effect: Using a reduced form estimation, they proxy demand-pull factors with a categorical survey variable and find that the magnitude of the indirect effect on innovative sales as innovation output variable is five times the direct effect of demand-pull factors. Keeping this evidence in mind, the analysis of this paper focuses on the direct effect of the demand-pull factors only.

Green public procurement implemented as environmental selection criteria might be especially suitable for triggering innovations through a demand-pull effect. Certainly, so-called innovation procurement, which explicitly involves innovative components in the procurement object with subsequent acquisition of successful products, is the most obvious type of procurement to trigger innovation. However, when awarding a tender through selection of the most economically advantageous tender (MEAT) instead of the lowest price criterion, additional criteria are specified for awarding the tender – which leave room for innovations to the firm. These selection criteria might be related to quality, delivery time or – in the case of GPP – to environmental aspects. These environmental aspects are often defined in broad terms, such as 'energy efficiency', 'CO_2-reduction', 'lowest life-cycle cost'. The broadness of the criteria allows firms to be creative in the way of achieving the criteria and might thus spur innovation even if this is not an explicit innovation procurement.[4] Therefore the following hypothesis is tested:

> *H1: Winning a green public procurement contract works as direct demand-pull effect in triggering general innovations.*

Green public procurement allows governments to internalise the environmental externalities of production and consumption as well as to solve market failures regarding environmental innovations. Similar to the case of general procurement being used as innovation policy to overcome market failures[5] (Edler and Georghiou, 2007), green public procurement can be used as environmental policy to overcome the problem of environmental externalities as it can help taking into account environmental externalities from the production and consumption process . Moreover, green public procurement can help overcome market failures arising around environmental innovations: While environmental innovations are anticipated to have a double pay-off in terms of limiting environmental damage and increasing innovations at the same

[4]The broadness of environmental terms used in the selection criteria makes this selection criteria more likely to spur innovation than e.g. requirements on delivery time.

[5]Such market failures might be asymmetric information between the user and the producer of innovations where procurement can help facilitating this interaction (Edler and Georghiou, 2007), or it might be spill-overs of R&D where procurement can help to reduce the resulting under-supply of innovations

time[6], they also have a double externality problem (Katsoulacos and Xepapadeas, 1996, Rennings, 2000). Next to the usual externality of innovations in the research phase in terms of knowledge spill-overs, environmental innovations also face externalities in the diffusion stage where the innovating firm does not reap the benefits of environmental innovations (i.e. the reduced environmental harm which is a public good) but incurs the costs. This leads to an under-provision of environmental innovations. GPP might thus be a suitable policy tool to overcome these market failures for environmental innovations.[7] These environmental innovations could lie on the consumption side where the environmental performance of using a product is increased or they might lie on the production side where environmental impacts of the production process are reduced. Therefore the following hypothesis is tested:

> *H2: Winning a green public procurement contract increases the probability of producing 'environmental' product innovations (consumption side) as well as 'environmental' process innovations (production side).*

Green public procurement is considered a so-called strategic procurement (European Commission, 2017b). Edler and Georghiou (2007) define strategic procurement as procurement which encourages "the demand for certain technologies, products or services [...] to stimulate the market" (p. 953). This implies that strategic procurement is often targeted at specific sectors (Edler and Georghiou, 2007). In the case of green public procurement, these sectors might for example be sectors where the government could buy readily available environmentally friendly products or they

[6] See Porter and Linde (1995) and moreover Jaffe et al. (2002) for a critical and detailed discussion

[7] Another relevant point in overcoming market failures in the special case of green public procurement is that by buying new environmentally friendly products and services, the government can demonstrate the functioning of the novel products as well as drawing public attention to them. Especially in the case of environmentally friendly products, this seems important as these products are often met with scepticism. Unfortunately, an analysis of this factor lies outside of the scope of this paper.

might be sectors which do not perform well in terms of environmental measures such as CO_2 performance and might thus still need to innovate. The government might target these sectors with different ways of GPP implementation. While for sectors with readily available products, a specification in the technical requirements might work as technology diffusion, using GPP in the selection criteria of contracts might be a more suitable way of targeting sectors which lag behind. While the selection specification of GPP thus provides incentives for better environmental performance, the effectiveness of this demand-pull effect might considerable differ across industries. Not only might it be absent in some but it might differ in magnitude across sectors. Therefore the following hypothesis is tested:

> *H3: The demand-pull effect of green public procurement on general innovations differs across sectors.*

3.3 Empirical analysis

3.3.1 Data

The analysis in this paper uses a novel firm-level dataset for Germany which combines information on awarded green public procurement contracts with information on firm characteristics, especially firms' innovation activities. The datasets were matched at the firm-level, based on fuzzy string matching on the firms' name and address information.[8] The combined dataset is an unbalanced panel dataset, spanning the time period 2006 to 2016, covering 5374 individual firms of which 46% innovated at some point during the observation period. Table 3.1 shows descriptive statistics for the underlying dataset.

[8]The matched results underwent a manual scrutiny check to exclude false positive matches.

Table 3.1: Descriptive statistics

Variable	Mean	Std. dev.	Min	Max
Dependent variables				
Product innovations[1]	0.286	0.452	0	1
Process innovations[1]	0.224	0.417	0	1
Env. product innovation[1]	0.315	0.465	0	1
Env. process innovation[1]	0.494	0.500	0	1
Variable of interest				
GPP[1]	0.005	0.07	0	1
Control variables				
Innovation intensity (Mio. EUR per employee)	0.003	0.011	0	0.345
Number of employees	354.3	6,748	1	402,700
High-skilled employees (%)	20.12	24.65	0	100
Export intensity	0.137	0.241	0	1
Costs per employee (Mio. EUR)	0.158	1.131	0.001	89.81
Public R&D support[1]	0.186	0.389	0	1
Business group[1]	0.264	0.441	0	1
Foreign business group[1]	0.129	0.335	0	1
East Germany[1]	0.376	0.484	0	1

Note: [1]denotes dummy variables. The data is cleaned for implausible values such as an export intensity above one or a share of high-skilled employees above 100.

The public procurement data was taken from the Tenders Electronic Daily (TED) database of the European Commission (TED, 2019). This database contains information about all public procurement notices and awards published in the European Union above certain thresholds.[9] The data is collected by the European Commission and directly taken out of the standard procurement forms provided by the European Commission which are filled by the public authorities. Next to the date of the procurement award, the name of the contracting authority, and the name of the winning firm, the database also contains information about the selection criteria for awarding

[9]To ensure transparency and a competitive procurement process EU-wide, the European Commission defined thresholds in terms of the Euro value of procurement tenders above which call for tenders have to be published in the TED database. These thresholds vary over time, type of contract, and type of public authority. For example, as of 2017, supplies contracts by sub-central authorities above a value of 221.000 Euros were required to be published in TED (European Commission, 2017a). As it is considered good practice to publish public tenders in the TED, even tenders below the threshold are published in TED. For the analysis of this paper, it is however not necessary to constrain the analysis to above threshold contracts only, even if they may have a larger impact due to their sheer size, on innovation activities of firms.

the procurement awards. For the analysis in this paper, only the contracts which were won by German firms were considered. These were 319,862 procurement contracts in total from 2006 to 2016.

The data on innovation activities and firm characteristics is taken from the Mannheimer Innovation Panel (MIP) which is collected by the Leibniz Centre for European Economic Research (ZEW)[10] since 1993 and which builds the German part of the Community Innovation Survey (CIS) of the European Commission. In contrast to other CISs, the MIP is constructed as panel survey and gathered annually. Around 6000 firms answer the questionnaire each year, yielding a response rate around 20%. The ZEW conducts annual non-response surveys, which show that the share of innovators among the responding firms is lower than among the non-responding firms (Peters and Rammer, 2013). The results of the analysis in this paper should thus be understood as lower bound effects.

The MIP is constructed as representative sample of the German industrial and service sectors.[11] The main focus of the survey lies on gathering information about a variety of innovation activities of firms. Not only are R&D expenditures collected as measure of an innovation input, but also indicators on product as well as process innovations and the share of new product sales in overall sales as measure of innovation outputs. The MIP in general thus allows to analyse the whole innovation cycle, while other measures used in innovation research often only give information on either inputs (e.g. R&D expenditure) or outputs (e.g. patents) to the innovation process.[12] Next to detailed information about innovations at the firm-level, the dataset also

[10]The data was accessed within the premises of the ZEW's Research Data Centre.

[11]For more information on the German CIS and the survey methodology, see Peters and Rammer (2013).

[12]Nonetheless, the usual caveats of survey data should be kept in mind – even if the MIP questionnaire contains several plausibility questions to reduce the risk of inconsistent answers. For a more detailed discussion on the use of different innovation measures, see Gault (2013).

contains information about firm performance such as e.g. turnover, exports, number of employees. Moreover, each year there is a focus theme around which additional questions are asked, for example about environmental innovations. Unfortunately, these questions are often not repeated in subsequent surveys. Therefore, the information about environmental innovations used later in this analysis, is limited to two survey waves (survey waves 2009 and 2015).

3.3.2 Estimation framework

The estimation approach used in this paper goes back to the innovation model developed by Crepon et al. (1998). This paper focuses on the so-called innovation equation which tries to explain the drivers of innovation outputs. However, departing from the multi-stage model from Crepon et al. (1998) which uses predicted innovation, this paper estimates the following single-stage reduced form equation based on recorded innovation outputs, using a random effects probit model:[13]

$$Y_{it} = \beta_1 GPP_{it} + \beta X_{it} + \gamma_s + \tau_t + u_i + \epsilon_{it} \tag{3.1}$$

where Y_{it} is a dummy indicating whether the firm produced innovations in the last three years, GPP_{it} is a dummy indicating whether the firm won a GPP contract or not, X_{it} are firm-level control variables, γ_s are industry dummies, τ_t are year dummies, u_i is a random firm-specific effect, and ϵ_{it} is the remaining error term.

[13] The panel structure of the data yields itself to using panel estimation methods. The assumption of the random effects probit is that the explanatory factors are uncorrelated with the individual heterogeneity. This assumption is strong and will be relaxed later by using a the Mundlak approach (Mundlak, 1978).

Dependent variables

In order to answer the hypotheses laid out in section 3.2, equation 3.1 is estimated for four different dependent variables. All of these dependent variables are dummy variables which indicate whether the firm had process, product, environmental process, or environmental product innovations. Using these variables as innovation indicators follows other studies in this field which investigate the drivers of innovations (Griffith et al., 2006) or of environmental innovations (Borghesi et al., 2015). To investigate *H1*, two dummies are used as indicator of innovation outputs. Firms are asked in the MIP questionnaire whether they had product innovations in the last three years and whether they had process innovations in the last three years.[14] This differentiation allows to evaluate in more detail, where in the production process, the innovations took place. Using this variable instead of other output variables such as patents, allows to take into account all innovations, not only the patented or patentable ones, as well as it avoid accounting for patents which are never used in practice. To investigate *H2*, a dummy variable is taken from the MIP which indicates specifically environmental innovations. This dummy is again differentiated between environmental product and environmental process innovations. Environmental product innovations are defined as innovations which reduce environmental externalities arising from using the product, while environmental process innovations are defined as innovations which reduce environmental externalities during the production process on site. Given that the information about environmental innovations was only part of two survey waves (2008 and 2013), the estimations relying on environmental innovations as dependent variable are estimated using a pooled probit model.[15]

[14] The definition of product and process innovations follows the definition in the Oslo Manual (OECD/Eurostat, 2005).

[15] Running a random effects probit model shows a rho-coefficient similar to zero which indicates that the panel-dimension of the data does not add much to the explanation of the underlying data

Variable of interest

The main explanatory variable of interest to this paper indicates whether firms won a GPP contract or not. Using actual award-level data for procurement instead of having to rely on proxies of procurement as other studies had to (e.g. information about the customers of firms as in Aschhoff and Sofka (2009)), provides a major advancement in the analysis of the economic effects of procurement as this data is much more specific. The information provided by the TED database on the selection criteria of the procurement awards was used to create this variable of interest. The GPP-dummy indicates whether a firm won a green public procurement contract or not. The selection criteria of each procurement tender are specified as free text in the original database. This information is searched for keywords which indicate environmental criteria, e.g. recyclable, energy efficient, sustainable etc., to code the dummy variable.[16] Out of all 319.862 contracts won by German firms in 2006-2016, only 2.19% were classified as GPP. In addition to the simple dummy, a cumulative measure of having won a GPP contract is calculated as cumulative sum of the original GPP dummy variable.[17] This cumulative variable is used to analyse whether there is a longer lasting relationship between winning a GPP contract and innovation.

Control variables

A range of firm-level control variables, X_{it}, are included in the analysis. The initial innovation model from Crepon et al. (1998), including innovation intensity (R&D

generating process. Thus, the pooled probit estimation is preferred. Results of the random effects probit model are available from the author upon request.

[16]The language of the procurement tender documents is often equivalent to the language of the country where the procuring authority is based. However, to ensure that also GPP contracts are detected which were won by German firms but called for by non-German authorities, the keyword search was not only conducted in German but also in the languages of the biggest European economies, namely in English, French, Spanish, and Italian.

[17]Each time a firm won a GPP contract, the cumulative measure increases by one.

expenditure over employees), firm size (log of number of employees, lagged), sector dummies[18] is supplemented with established controls used in similar research (e.g. Czarnitzki et al. (2018), Borghesi et al. (2015), Aschhoff and Sofka (2009), Griffith et al. (2006)), namely human capital (share of high-skilled employees, lagged), export intensity (total exports over total turnover, lagged), a dummy for receiving public R&D support in the last three years, production costs per employee (lagged), a dummy for belonging to a business group, a dummy for belonging to a foreign business group and a dummy for being located in east Germany. In the estimation on the environmental innovations, an additional ETS-dummy is included as control variable, indicating whether the sector is subject to the European Emission Trading Scheme or not.[19]

3.4 Results

Hypothesis 1

The results of analysing hypothesis 1 show mixed supportive evidence for innovations (see Table 3.2). While winning a GPP contract increases the probability of having product innovations, no significant relation is found on the probability of having process innovations (Table 3.2). Looking at the cumulative GPP measure described above, which potentially is able to track longer term impacts of GPP on innovations, shows still a significant but smaller coefficient than in the previous estimation for product innovations.[20] While these aggregate results suggest a positive demand-pull

[18] Sector dummies are based on the 21 main categories of NACE Rev. 2 classification. See Appendix 3.7.1 Table 3.5 for more details.

[19] Nace2-sectors covered until 2013 under the Emission Trading Scheme include paper and paper products (sector 17), coke and refinery (sector 19), ceramics and cement (sector 23), metallurgy (sectors 24 and 25). After 2013, chemicals (sector 20) is added.

[20] Note that coefficients are displayed, not marginal effects.

effect of GPP on new products, there seems no effect on new production processes as a result of winning GPP contracts.

The control variables are mostly significant and have the expected signs.[21] Innovation intensity, firm size and public R&D support significantly increase the probability of having product and process innovations. Additionally, for product innovations, human capital, the export intensity, the production costs per employee contributes to a higher probability of innovation. Belonging to a business group is statistically relevant for the likelihood of process innovations while being located in the east of Germany is associated with a lower probability of process innovations.

The results also show that a random effects probit estimation is preferred to a pooled probit estimation, as the panel structure is statistically important to explain the underlying data generation process (see rho and Chi-squared statistic in Table 3.2). The underlying assumption that the regressors are uncorrelated with any unobserved heterogeneity will be relaxed later on in the robustness checks.

Hypothesis 2

Testing hypothesis 2 yields neither a clear rejection nor an acceptation of the hypothesis that winning a GPP contract is associated with an increased probability of having environmental innovations. The results in Table 3.3 show no significant correlations of winning a GPP contract and the probability of environmental product or process innovations, nor does a cumulative measure of GPP has statistical significance. Keeping in mind that these estimations are to be understood as lower bound of any possible effect, a clear conclusion that there is no relationship between GPP and

[21]The Akaike information criterion (AIC) and the Bayesian information criterion (BIC) were evaluated to test whether the inclusion of additional control variables actually contributes to the explanatory power of the estimation model instead of over identifying it. The specification shown in Table 3.2 showed the lowest values of AIC and BIC. Results of different specifications of control variables are available upon request.

Table 3.2: Hypothesis 1 – Estimation results (random effects probit)

	Product innovations		Process innovations	
	I	II	I	II
GPP[1]	0.918**		0.123	
	(0.025)		(0.755)	
GPP (cum.)		0.538**		0.0802
		(0.013)		(0.677)
Innovation intensity (t-1)	27.73**	27.78**	5.918**	5.923**
	(0.013)	(0.013)	(0.048)	(0.048)
Firm size (t-1)	0.134***	0.132***	0.229***	0.228***
	(0.000)	(0.000)	(0.000)	(0.000)
High-skilled employees (%) (t-1)	0.00693***	0.00692***	0.000108	0.000104
	(0.000)	(0.000)	(0.943)	(0.944)
Export intensity (t-1)	1.361***	1.352***	0.112	0.111
	(0.000)	(0.000)	(0.418)	(0.420)
Public R&D support[1]	2.864***	2.866***	1.919***	1.919***
	(0.000)	(0.000)	(0.000)	(0.000)
Costs p.c. (t-1)	0.00803***	0.00802***	0.0554	0.0552
	(0.000)	(0.000)	(0.169)	(0.170)
Business group[1]	0.0547	0.0581	0.226***	0.227***
	(0.592)	(0.569)	(0.008)	(0.007)
Foreign business group[1]	0.117	0.116	-0.132	-0.132
	(0.378)	(0.380)	(0.207)	(0.207)
East Germany[1]	-0.0527	-0.0570	-0.128**	-0.129**
	(0.481)	(0.447)	(0.047)	(0.045)
Constant	-3.230***	-3.215***	-4.489***	-4.486***
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	8651	8651	8637	8637
Pseudo R-squared	0.055	0.055	0.041	0.041
rho	0.660	0.660	0.560	0.560
Chi-squared (comparison test)	334.7	334.9	272.3	272.3

Note: p-values in parentheses * p<0.1, ** p<0.05, *** p<0.01. Robust std. errors used. Industry and year dummies not shown. [1]denotes dummy variables.

environmental innovations is not possible. In contrast to the estimation of hypothesis 1, this estimation is conducted using a pooled probit model for the two survey waves which include information about environmental innovations. Additional estimations of a panel probit model showed that the panel factor (rho) is not significant.[22] This is as expected considering that there are only two years of data available for this

[22]Results available upon request.

estimation.

Table 3.3: Hypothesis 2 – Estimation results (pooled probit)

	Env. product innovations		Env. process innovations	
	I	II	I	II
GPP[1]	0.118		0.295	
	(0.764)		(0.445)	
GPP (cum.)		0.133		0.182
		(0.554)		(0.361)
Innovation intensity (t-1)	2.053	2.076	0.864	0.870
	(0.627)	(0.627)	(0.568)	(0.566)
Firm size (t-1)	0.0842***	0.0832***	0.116***	0.115***
	(0.000)	(0.000)	(0.000)	(0.000)
High-skilled employees (%) (t-1)	0.0000765	0.0000575	-0.00313**	-0.00314**
	(0.963)	(0.973)	(0.047)	(0.045)
Export intensity (t-1)	-0.0457	-0.0449	-0.0420	-0.0411
	(0.767)	(0.770)	(0.817)	(0.820)
Public R&D support[1]	0.761***	0.762***	0.838***	0.838***
	(0.000)	(0.000)	(0.000)	(0.000)
Costs p.c. (t-1)	0.0131	0.0130	-0.0503	-0.0500
	(0.878)	(0.879)	(0.356)	(0.359)
Business group[1]	-0.000409	0.000211	0.0602	0.0615
	(0.991)	(0.996)	(0.170)	(0.161)
Foreign business group[1]	0.0470	0.0477	0.0328	0.0325
	(0.642)	(0.641)	(0.686)	(0.690)
East Germany[1]	-0.0615	-0.0619	-0.0747	-0.0754
	(0.562)	(0.561)	(0.309)	(0.302)
ETS[1]	-0.110***	-0.109***	0.0295***	0.0299***
	(0.000)	(0.000)	(0.000)	(0.000)
Constant	-1.437***	-1.432***	0.270***	0.271***
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	2525	2525	2555	2555
Pseudo R-squared	0.080	0.080	0.102	0.102

Note: p-values in parentheses * p<0.1, ** p<0.05, *** p<0.01. Std. errors are clustered at industry-level. Industry dummies not shown. [1]denotes dummy variables.

The ETS dummy, additionally included in the analysis of environmental innovations, is significantly negatively related to the probability of having environmental product innovations, while it is significantly positively related to the probability of having environmental process innovations. The negative effect on the probability of environmental product innovations might be a crowding-out effect of investments into process innovations: While firms regulated under the EU ETS are reliable for their own emissions on their production site, they are not reliable for environmental externalities which arise through the use of their products. It is thus reasonable for a firm to invest into environmental process innovations to reduce their externality costs. However, this might reduce investments into the development of new products and thus lead to a crowding-out effect on environmental product innovations. The positive correlation with the probability of environmental process innovations is also in line with previous literature (see Borghesi et al. (2015) for a more in-depth study of the effects of the EU ETS on environmental innovations).

The other control variables show slightly different results compared to the estimations on overall innovations before. The innovation intensity is not found to be a significant contributor for the probability of having environmental innovations (in line with previous research, e.g. Borghesi et al. (2015)). Firm size and public R&D support is positively significant as before. The human capital variable is negatively related to environmental process innovations, and the export intensity, costs per capita, belonging to a (foreign) business group, and the location in East Germany are not significantly related to the probability of environmental product or process innovations.

Hypothesis 3

To evaluate hypothesis 3, whether the demand-pull effect might be larger in different sectors, equation 3.1 is estimated with a pooled probit model for several sectors separately.[23] As GPP contracts are used in varying intensities in different sectors,

[23]A pooled probit model is used here as an estimation of a random effects probit model only confirms the significance of the panel structure for one of the sectors (manufacturing sector). For the sake of comparability, a pooled probit estimation is shown for all sectors. The random effects probit results for sector 3 confirm the results of the pooled estimation. Detailed results are available

the results are only shown for sectors where GPP contracts were identified at all. These sectors are: manufacturing; electricity, gas, steam and air conditioning supply; water supply, sewerage, waste management and remediation activities; professional, scientific and technical activities; administrative and support service activities.

The results shown in Table 3.4 indicate a positive relationship between winning a GPP contract and the probability of product innovations for the water supply and waste industry. The electricity and gas sector shows an increase in the probability of process innovations when a GPP contract is won. Using the cumulative measure of GPP, the effect in the water supply and waste industry is confirmed again. Additionally, the manufacturing industry shows a positive effect on the probability of product innovations from a cumulative measure of GPP. The cumulative measure of GPP shows a negative relation with the probability of process innovations in the water and sewerage sector.

The results show that the correlation between winning a GPP contract and the probability of product or process innovations differs across sectors. While the water and sewerage sector sees a correlation between GPP and product innovations, there seems to be a slight crowding-out effect for investments into process innovations. The electricity sector on the other hand sees a positive correlation between winning a GPP contract and process innovations. This might indicate that the product in this sector is a perfect substitute in terms of the usage - but that firms are able to differentiate themselves in terms of the production process used to generate electricity (e.g. conventional versus renewable energy). The positive association of the cumulative GPP measure and the probability of product innovations in the manufacturing sector might indicate a slow but sustained effect of GPP.

---

upon request.

3.5 Robustness checks

3.5.1 Unobserved heterogeneity

The random effects probit estimation relies on the assumption that the regressors are uncorrelated with the unobserved individual heterogeneity. This might be questionable in the case of this paper because there might be unobserved individual factors like managerial attitudes which are correlated with e.g. R&D spending. An alternative estimation technique, the Mundlak approach (Mundlak, 1978), allows for a correlation of explanatory variables and the individual heterogeneity by including individuals' mean value of time-varying variables. Results of this Mundlak estimation of Hypothesis 1 are shown in Appendix 3.7.2 Table 3.6 and partly confirm the results found earlier – depending on whether the mean value over time of the GPP variable is included (Table 3.6 columns .I) or not (Table 3.6 columns .II). As the results show a significant coefficient of the mean value of GPP, this indicates that the mean should be included – which renders the coefficient of the GPP dummy variable insignificant in the case of product innovations. Slightly different is the case of the cumulative GPP measure where the time average is not statistically significant and thus maybe a sign of no correlation between the cumulative GPP measure and unobserved heterogeneity.

Table 3.4: Hypothesis 3 – Sector specific results

Table continuous on next page

	Sector 3				Sector 4			
	Product innovations		Process innovations		Product innovations		Process innovations	
	I	II	I	II	I	II	I	II
GPP[1]	0		0.225		-0.152		0.935*	
	(.)		(0.663)		(0.801)		(0.087)	
GPP (cum.)		0.874**		0.312		0.0871		0.524
		(0.039)		(0.243)		(0.819)		(0.140)
Innovation intensity (t-1)	54.86***	54.61***	3.204	3.239	107.4	107.5	218.1	179.9
	(0.004)	(0.004)	(0.451)	(0.446)	(0.661)	(0.658)	(0.175)	(0.282)
Firm size (t-1)	0.123***	0.122***	0.176***	0.174***	0.227**	0.215*	0.00500	-0.00770
	(0.000)	(0.000)	(0.000)	(0.000)	(0.038)	(0.059)	(0.954)	(0.932)
High-skilled employees (%) (t-1)	0.00604***	0.00608***	0.000612	0.000579	-0.0266*	-0.0285*	-0.0169	-0.0152
	(0.005)	(0.004)	(0.703)	(0.717)	(0.080)	(0.063)	(0.256)	(0.294)
Export intensity (t-1)	0.690***	0.687***	0.00593	0.00641			-9.847	-7.763
	(0.000)	(0.000)	(0.955)	(0.951)			(0.139)	(0.214)
Public R&D support[1]	1.688***	1.690***	1.277***	1.279***	2.273***	2.275***	2.544***	2.524***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Cost p.c. (t-1)	-0.488***	-0.486***	0.0123	0.0123	0.159	0.153	0.194	0.168
	(0.009)	(0.008)	(0.885)	(0.884)	(0.306)	(0.336)	(0.142)	(0.189)
Business group[1]	-0.0787	-0.0736	0.0987	0.102	-0.304	-0.288	-0.209	-0.189
	(0.366)	(0.396)	(0.193)	(0.176)	(0.396)	(0.420)	(0.538)	(0.573)
Foreign business group[1]	0.136	0.135	-0.0566	-0.0577	0.0592	0.0587	-0.00143	-0.00645
	(0.186)	(0.190)	(0.511)	(0.503)	(0.905)	(0.905)	(0.998)	(0.990)
East Germany[1]	-0.0209	-0.0254	-0.106**	-0.108**	-0.342	-0.331	-0.175	-0.237
	(0.703)	(0.642)	(0.045)	(0.041)	(0.396)	(0.405)	(0.599)	(0.487)
Constant	-2.147***	-2.142***	-2.209***	-2.200***	-3.104***	-3.031***	-2.324***	-2.265***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	3973	3982	3979	3979	248	248	260	260
Pseudo R-squared	0.386	0.388	0.219	0.219	0.406	0.406	0.340	0.337

Note: p-values in parentheses * p<0.1, ** p<0.05, *** p<0.01. Robust std. errors used. Year dummies not shown. [1]denotes dummy variable.
These sector numbering follows the NACE Rev. 2 categorisation and denotes: (3) manufacturing; (4) electricity, gas, steam and air conditioning supply; (5) water supply, sewerage, waste management and remediation activities; (13) professional, scientific and technical activities; (14) administrative and support service activities.

Table 4 (cont.): Hypothesis 3 – Sector specific results

	Sector 5				Sector 13		Sector 14	
	Product innovations		Process innovations		Process innovations		Process innovations	
	I	II	I	II	I	II	I	II
GPP[1]	1.045**		0		1.047		0.357	
	(0.038)		(.)		(0.147)		(0.525)	
GPP (cum.)		0.757***		-0.418*		-0.333		0.131
		(0.001)		(0.078)		(0.562)		(0.711)
Innovation intensity (t-1)	128.3***	127.5***	120.7***	120.4***	4.279*	4.257*	137.5	136.0
	(0.007)	(0.008)	(0.001)	(0.001)	(0.071)	(0.072)	(0.300)	(0.307)
Firm size (t-1)	-0.0631	-0.0977	0.0505	0.0541	0.149***	0.152***	-0.0529	-0.0519
	(0.318)	(0.115)	(0.373)	(0.343)	(0.000)	(0.000)	(0.394)	(0.407)
High-skilled employees (%) (t-1)	-0.00932	-0.00966	-0.00268	-0.00259	0.000267	0.000326	0.00827*	0.00821*
	(0.163)	(0.151)	(0.642)	(0.655)	(0.870)	(0.841)	(0.053)	(0.056)
Export intensity (t-1)	1.358**	1.198**	1.075**	1.145**	0.290	0.297	0.422	0.429
	(0.011)	(0.022)	(0.041)	(0.030)	(0.257)	(0.247)	(0.558)	(0.554)
Public R&D support[1]	1.205***	1.228***	2.126***	2.142***	1.148***	1.137***	2.991***	2.995***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Costs p.c. (t-1)	0.269	0.262	-0.220	-0.219	-0.0793	-0.0797	-0.788	-0.812
	(0.319)	(0.326)	(0.577)	(0.578)	(0.521)	(0.521)	(0.291)	(0.278)
Business group[1]	0.153	0.110	0.215	0.216	-0.0269	-0.0332	0.927***	0.937***
	(0.472)	(0.613)	(0.252)	(0.250)	(0.872)	(0.842)	(0.000)	(0.000)
Foreign business group[1]	-0.419	-0.307	-0.0975	-0.117	-0.154	-0.156	-0.650	-0.681
	(0.414)	(0.544)	(0.769)	(0.727)	(0.504)	(0.496)	(0.145)	(0.127)
East Germany[1]	0.0577	0.0538	0.0130	0.00912	0.146	0.156	-0.423**	-0.429**
	(0.758)	(0.776)	(0.935)	(0.954)	(0.139)	(0.114)	(0.049)	(0.045)
Constant	-2.001***	-1.872***	-3.222***	-3.246***	-2.139***	-2.151***	-2.616***	-2.620***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	702	702	695	702	1149	1149	426	426
Pseudo R-squared	0.255	0.272	0.328	0.328	0.199	0.198	0.340	0.339

Note: p-values in parentheses * p<0.1, ** p<0.05, *** p<0.01. Robust std. errors used. Year dummies not shown. [1]denotes dummy variable.
These sector numbering follows the NACE Rev. 2 categorisation and denotes: (3) manufacturing; (4) electricity, gas, steam and air conditioning supply; (5) water supply, sewerage, waste management and remediation activities; (13) professional, scientific and technical activities; (14) administrative and support service activities.
Note that for sectors 13 and 14 only process innovations are shown as there were no observation pairs which received GPP and produced product innovations.

3.5.2 Intensity of GPP

As a robustness check, the cumulative GPP variable is also calculated as cumulative sum of all GPP contracts won – instead of simply accumulating the plain GPP variable.[24] Investigating Hypothesis 1 based on the cumulative sum of all GPP contracts won confirms the results found with the simple cumulative measure. This might indicate that there is no additional demand-pull effect on a single firm through winning multiple green contracts in one year but that the pull effect is already triggered through winning one contract.

3.6 Conclusion

The paper provides the first empirical analysis of green public procurement and the innovation activities of firms. The research question whether GPP can act as demand-side innovation policy is investigated using a novel firm-level dataset which combines procurement award-level data with firm-level economic and innovation data. By relying on actual procurement award data, the paper is able to identify a direct effect of winning a GPP contract instead of relying on proxy measures of procurement.

The results indicate indeed that the strategic use of green public procurement might be able to trigger new product innovations. These results however only hold for certain industries: a positive correlation between winning a GPP contract and the probability of general product innovations is found for the water supply and waste sector, while the electricity and gas sector shows a positive correlation for general process innovations. A slow but sustained demand-pull effect of GPP is identified in the manufacturing sector where a positive significant relation between a cumulative

[24] Example: If in one year, a firm wins two contracts, the cumulative sum increases by two.

measure of GPP and general product innovations is found. Regarding the relationship between GPP and environmental innovations, no significant correlation is found. The absence of a statistically significant correlation does however not necessarily imply that there is no demand-pull effect as the statistical insignificance might be related to the larger share of non-innovators in the sample as well as to the limited number of survey waves asking about environmental innovations.

While GPP is a major priority on the policy agenda of multilateral organisations, the current implementation rate can be considered as a homeopathic dose. The United Nations anchored sustainable production and consumption in their framework of the Sustainable Development Goals as target under SDG 12 (target 12.7, see UNEP (2017)), the European Commission prioritises the uptake of green public procurement as one of its six priority areas in their 2017 procurement strategy (European Commission, 2017b). Analysing the data from the European Tenders Electronic shows however, that only 2.19% of the contracts won by German firms in 2006-2016 were procurement contracts which included environmental aspects in the selection criteria. This discrepancy between political ambition and actual implementation might be overcome by providing more training opportunities for procurement officers, developing handbooks for the implementation of GPP, enhanced joint procurement, and financial support from the general government to local authorities to cover their potential increased procurement costs due to the implementation of GPP (Chiappinelli and Zipperer, 2017).

The analysis in this paper should not be understood as exhaustive but only as the starting point for future research in this field. While this paper is not able to provide any causal evidence on the link between GPP and innovation, conducing such an analysis is a promising research path. Collecting more information on environmental innovations to conduct a robust analysis on environmental innovations is certainly an important future step. Moreover, as described above, this paper only looks at the direct pull effect of GPP. An analysis of the indirect pull effect of GPP through an effect on R&D efforts would add to the understanding of the channels of GPP. Furthermore, it is important to gain a better understanding of the type of innovations triggered by GPP, whether these are rather incremental innovations or whether GPP is able to trigger breakthrough technology development. Related to this question, investigating whether GPP has an actual effect on the creation of lead markets (e.g. for environmental products) seem a promising research area. Unrelated to the effect of GPP on innovation, it is also important to conduct more research on the effectiveness of GPP in terms of CO_2 reductions and other environmental measures.

3.7 Appendix

3.7.1 Sectors covered

Table 3.5: Sectors covered

Number	Sector	Freq.	Percent
1	Agriculture, forestry and fishing	7	0.08
2	Mining and quarrying	173	1.98
3	Manufacturing	4,001	45.89
4	Electricity, gas, steam and air conditioning supply	260	2.98
5	Water supply; sewerage, waste management and remediation activities	705	8.09
6	Construction	179	2.05
7	Wholesale and retail trade; repair of motor vehicles and motorcycles	451	5.17
8	Transportation and storage	583	6.69
9	Accommodation and food service yctivities	10	0.11
10	Information and communication	466	5.35
11	Financial and insurance activities	199	2.28
12	Real estate activities	74	0.85
13	Professional, scientific and technical activities	1,163	13.34
14	Administrative and support service activities	430	4.93
15	Public administration and defence; compulsory social security	0	0.00
16	Education	3	0.03
17	Human health and social work activities	3	0.03
18	Arts, entertainment and recreation	4	0.05
19	Other service activities	7	0.08
Total		8,718	100.00

Note: This sample covers the number of observations in the sectors in the MIP from 2006-2016. The nomenclature follows the NACE Rev. 2 and is retrieved from https://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM_DTL&StrNom=NACE_REV2. None of the firms in section 15 (Public administration and defence; compulsory social security) have sufficient information to be included in our analysis. Section 20 (activities of households as employers; undifferentiated goods and services producing activities of households for own use) and section 21 (activities of extraterritorial organisations and bodies) are not covered by the MIP and therefore not included.

3.7.2 Mundlak approach

Table 3.6: Robustness check Hypothesis 1 – Mundlak approach

	Product innovations				Process innovations			
	I.I	I.II	II.I	II.II	I.I	I.II	II.I	II.II
GPP[1]	0.995**	0.282			0.151	-0.202		
	(0.018)	(0.587)			(0.705)	(0.687)		
GPP (cum.)			0.623***	0.296			0.102	-0.183
			(0.004)	(0.441)			(0.606)	(0.506)
Innovation intensity (t-1)	-0.649	-0.739	-0.747	-0.761	-0.264	-0.302	-0.277	-0.287
	(0.953)	(0.946)	(0.946)	(0.945)	(0.958)	(0.952)	(0.956)	(0.954)
Firm size (t-1)	-0.0423	-0.0380	-0.0469	-0.0414	0.0342	0.0368	0.0339	0.0383
	(0.721)	(0.748)	(0.693)	(0.727)	(0.734)	(0.714)	(0.736)	(0.704)
High-skilled employees (%) (t-1)	0.000317	0.000398	0.000367	0.000403	-0.00344	-0.00340	-0.00344	-0.00339
	(0.925)	(0.906)	(0.913)	(0.905)	(0.258)	(0.263)	(0.257)	(0.264)
Export intensity (t-1)	0.717**	0.693**	0.682**	0.683**	-0.326	-0.330	-0.328	-0.328
	(0.032)	(0.035)	(0.038)	(0.037)	(0.237)	(0.230)	(0.234)	(0.234)
Public R&D support[1]	1.950***	1.948***	1.950***	1.948***	1.480***	1.479***	1.480***	1.479***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Costs p.c. (t-1)	0.0713	0.0738	0.0738	0.0743	0.108**	0.108**	0.108**	0.108**
	(0.278)	(0.272)	(0.275)	(0.272)	(0.024)	(0.024)	(0.024)	(0.024)
Business group[1]	0.0487	0.0478	0.0520	0.0497	0.224***	0.224***	0.225***	0.222***
	(0.646)	(0.652)	(0.624)	(0.640)	(0.009)	(0.009)	(0.009)	(0.009)
Foreign business group[1]	0.105	0.103	0.105	0.104	-0.155	-0.156	-0.155	-0.156
	(0.435)	(0.443)	(0.437)	(0.442)	(0.144)	(0.142)	(0.144)	(0.142)
East Germany[1]	-0.110	-0.113	-0.115	-0.115	-0.145**	-0.147**	-0.146**	-0.146**
	(0.162)	(0.151)	(0.145)	(0.146)	(0.028)	(0.026)	(0.027)	(0.026)
Innovation intensity[2]	33.91**	34.23**	34.12**	34.25**	6.044	6.154	6.069	6.146
	(0.017)	(0.016)	(0.016)	(0.016)	(0.303)	(0.295)	(0.301)	(0.295)
Firm size[2]	0.170	0.161	0.171	0.164	0.199*	0.194*	0.199*	0.193*
	(0.171)	(0.195)	(0.170)	(0.188)	(0.055)	(0.062)	(0.056)	(0.064)
High-skilled employees[2]	0.00716*	0.00692*	0.00706*	0.00694*	0.00372	0.00362	0.00372	0.00360
	(0.067)	(0.077)	(0.071)	(0.076)	(0.279)	(0.293)	(0.280)	(0.296)
Export intensity[2]	0.676*	0.701*	0.708*	0.710*	0.468	0.473	0.470	0.472
	(0.091)	(0.077)	(0.074)	(0.073)	(0.139)	(0.134)	(0.137)	(0.135)
Public R&D support[2]	1.386***	1.391***	1.394***	1.394***	0.623***	0.624***	0.623***	0.624***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Cost p.c.[2]	-0.191	-0.198	-0.198	-0.200	-0.130*	-0.132*	-0.130*	-0.132*
	(0.333)	(0.325)	(0.328)	(0.325)	(0.085)	(0.082)	(0.085)	(0.081)
GPP[2]		1.825**		1.325		0.852		1.141
		(0.024)		(0.260)		(0.259)		(0.173)
Constant	-3.446***	-3.423***	-3.429***	-3.421***	-4.681***	-4.667***	-4.677***	-4.669***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	8651	8651	8651	8651	8637	8637	8637	8637
Pseudo R-squared	0.055	0.055	0.055	0.055	0.041	0.041	0.041	0.041
AIC	5705.6	5704.0	5702.6	5703.6	6432.7	6433.6	6432.6	6433.4
BIC	5960.0	5965.4	5957.0	5965.0	6680.0	6687.9	6679.8	6687.7
rho	0.677	0.676	0.677	0.677	0.570	0.569	0.570	0.569
Chi-squared (comparison test)	326.7	326.0	327.0	326.3	274.9	274.3	274.9	274.1

Note: p-values in parentheses * $p<0.1$, ** $p<0.05$, *** $p<0.01$. Robust std. errors used. Year dummies not shown. [1]denotes dummy variable. [2]denotes firm averages over time (Mundlak terms).

Chapter 4

Benchmark design for emissions trading schemes*

4.1 Introduction

Emissions trading has emerged as the most favoured way to price carbon, with a total of 21 schemes operating in 2018, covering 15% of global GHG emissions (ICAP, 2018). In theory, carbon pricing internalises the cost of carbon in choices made throughout

*This chapter is joint work with Misato Sato and Karsten Neuhoff. An earlier version of this paper was published as DIW Discussion Paper No. 1712 (2017), available under https://www.diw.de/documents/publikationen/73/diw_01.c.574078.de/dp1712.pdf, and GRI Working Paper No. 287 (2017), available under http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2017/12/Benchmarks_for_emissions_trading_general_principles_for_emissions_scope.pdf. The authors would like to thank Frank Venmans, Sebastian Schwenen, Tomas Wyns, Karl Buttiens, Ana Gonzalez Hernandez, Olga Chiappinelli and Nils May for their many helpful comments. The participants at the Grantham Workshop at the London School of Economics, the 33rd Annual Congress of the EEA, the 23rd Annual Conference of the EAERE, the 40th International Conference of the IAEE, the environmental economics seminar in VATT in Helsinki, the 6th International Symposium on Environment and Energy Finance Issues, the 5th Annual Conference of the IAERE, the Climate Friendly Materials Workshop at DIW in Berlin, the 2018 and 2016 FSR Climate Annual Conference, and the 2016 AUROE workshop have all improved this article. Vera Zipperer and Karsten Neuhoff thankfully acknowledge funding from German Federal Ministry for Economic Affairs and Energy contract N.03MAP316. Misato Sato gratefully acknowledges financial support from the Economic and Social Research Centre Future Research Leaders grant number ES/N016971/1, the Grantham Foundation, and the ESRC through the Centre for Climate Change Economics and Policy.

the value chain. This should incentivise improvements of carbon efficiency in production as well as the use of less carbon intensive intermediate and final goods, as carbon costs are, in theory, fully passed forward to the price of goods and services (Goulder and Parry, 2008). However, a key challenge facing carbon pricing in emissions trading schemes (ETS) is the need to address carbon leakage risk, especially for energy and trade intensive industries. Leakage occurs if emissions reductions in one region are directly offset by emissions increases in another region. To address this leakage concern, most emissions trading schemes grant partial free allocation to sectors considered to be at risk of carbon leakage to compensate firms for compliance costs, in cases where a similar carbon price burden is not borne by foreign competitors.

Two main principles of allocating free allowances in emissions trading schemes emerged over time: free allocation on the basis of historic emissions, so-called grandfathering, or on the basis of emissions benchmarks. In the European ETS (EU ETS), grandfathering was used in the two initial trading phases (2005-2012). Although this was politically popular, it resulted in large over-allocation and windfall profits (Sterner and Muller, 2008, Neuhoff et al., 2006, Sijm et al., 2006, Chen et al., 2008) which in turn suppressed the carbon price in the market, reduced mitigation incentives and credibility of the emissions trading scheme. While in the electricity sector, carbon costs were fully passed through, it was unclear if emissions prices were passed forward onto the prices of final goods and services in other sectors, thus undermining mitigation incentives downstream. Benchmarking was introduced in phase 3 (2012-2020) of the EU ETS to restore mitigation incentives and reward early action (Ellerman et al., 2010), and has been adopted in most emissions trading programs around the world, including those in California, China, Korea, and New Zealand (see Appendix 4.6.1 for an overview of characteristics of some international ETSs).

Under benchmarking, free allocation is distributed in proportion to output multiplied by the emissions benchmark[1], which is measured as carbon emissions relative to output produced. This implies that firms buy permits only for emissions exceeding the benchmark level, giving facilities the incentive to meet or even beat the benchmark level. The output with which the benchmark is multiplied, can be output from a historic period, so-called *ex-ante* allocation, or actual output, so-called output based allocation (OBA). Generally, OBA has a number of advantages over *ex-ante* allocation. It has been shown that carbon leakage is prevented more effectively (Demailly and Quirion, 2006, Fischer and Fox, 2012, Meunier et al., 2014) and that it avoids politically contentious surplus allocation with its associated windfall profits as well as threshold effects (Branger et al., 2015, Quirion, 2009). A disadvantage however is, that carbon prices are not necessarily passed forward to product prices anymore because there is no marginal cost to emitting – each unit of emission receives additional free allocation. Incentives to substitute demand towards low-carbon alternatives downstream are thus dampened (Skelton, 2017). Importantly, the level of benchmarks matters more under OBA than *ex-ante* allocation. This is because under OBA the plant's performance against the benchmark is felt at the margin, in contrast to *ex-ante* allocation where the impact of the benchmark is often not felt acutely if emissions fell short of the historic baseline level and firms had enough free allocation to cover their emissions.[2] The introduction of OBA in the Californian ETS as well

[1]In most ETSs, the majority of benchmarks is linked to products, so-called product benchmarks, and are set to reflect a "best in class" or a "best available technology" emissions performance. There are also e.g. fuel and heat benchmarks, which are often used as fall-back options when no product benchmarks could be specified. This article however focuses on the example of product benchmarks, the most widely used type of emissions benchmarks.

[2]As implied by Coase (1960) and Montgomery (1972), allowance allocation should not affect trading and emissions outcomes in an ideal world, as long as transfers are lump-sum (e.g. through grandfathering). However, emissions trading schemes are rarely operating under perfect conditions. The theoretical literature has shown that reasons like transaction costs (Stavins, 1995), imperfect competition (Hahn, 1984), or behavioural irrationality (Kahneman et al., 1991) might contribute to the independence property not to hold. The empirical evidence on this aspect is however mixed so-

as the EU ETS in phase 4, puts also the political spotlight on emission benchmarks.

The increasing importance of emissions benchmarks in ETSs through the use of OBA raises the need to examine benchmark design in more detail, in order to better understand and predict economic behaviour under different benchmark designs and evaluate their effectiveness. Currently, benchmark design predominantly reflects technical or political considerations. Developing benchmarks involves multiple choices, starting with which sectors to benchmark, over defining comparable economic activities within a sector supply chain to which benchmarks are applied to etc.[3] Comparing plants for benchmark calculations is straightforward if they are similar in configuration and environmental performance across sites due to factors which influence efficiency at the margin, such as fuel choice, plant vintage or capacity usage rate. However in many sectors, a plant set up can be fundamentally different, ranging from multi-product integrated plants with on-site input production to single-product plants sourcing inputs and power from off-site. The set up of plants determines however where emissions occur, may this be direct emissions on-site or indirect emissions off-site.[4] Comparing emissions intensity of plants with heterogeneous configuration and supply chain linkages with benchmarks is therefore not straightforward, and requires determining how to treat direct and indirect emissions attributable to inputs and outputs. It is thus crucial for the benchmark design to define the scope of emissions or activity to be considered.

This article investigates optimal emission benchmark design with a focus on the

far. Studies supporting the independence assumption include Reguant and Ellerman (2008), Fowlie and Perloff (2013), and Zaklan (2016). In contrast, studies underlining the irrational behavior of firms include De Vivo and Marin (2017) and Martin et al. (2014).

[3]Usually, economic activities are considered comparable if they have similar outputs such as the same product.

[4]A recent study finds energy productivity within narrowly defined sectors can be vastly different, with the 90th percentile producing 580 percent more output than the 10th percentile (Lyubich et al., 2018).

scope of emissions covered. A partial equilibrium model is used to analyse how the treatment of indirect emissions in the scope of benchmarks affect firms' mitigation incentives under free allocation. The model differentiates between indirect and direct emissions and whether the emissions are attributed to inputs or outputs. The holistic approach to emissions benchmarks based on total emissions ensures a fair comparison of plants of different configurations through a systematic adjustment of emissions scope. Based on the model insights, generalised principles for emission benchmark design are derived, which are universal for optimal emission benchmark setting across any policy setting. The model shows that in cases where the carbon price is not internalised in the price of inputs, indirect emissions attributable to such input should be incorporated in the benchmark emissions scope. On the output side, emissions attributable to by-products (e.g. heat) should be included in the scope of benchmarks if the by-product competes in the market with alternatives where carbon costs are not internalised in the product price. Crucially, the scope adjustment hinges on the carbon cost incidence of a plant's inputs and outputs. A back-of-the-envelop calculation based on actual plant-level data shows the significant magnitude of distortions arising from sub-optimal emissions scope coverage in benchmark design. This article also shows the implication of scope adjusted benchmarks when a complementary consumption tax on the carbon content of basic materials (Böhringer et al., 2017, Neuhoff et al., 2014) is introduced to restore the carbon price signal along the value chain under OBA. Overall, the results demonstrate the importance of systematically adjusting emissions scope in benchmarks to drive efficient input and output choice, which are aligned with technological progress and deep emission cuts in industrial production.

This article contributes to the nascent field of literature which looks at the economic effects of emissions benchmarks. Empirical studies find evidence that the introduction of benchmarking reduced free allocation volumes in the EU ETS. In an early assessment of the introduction of harmonised emissions benchmarks in the EU ETS, Sartor et al. (2014) look at the distributional effects of using benchmarks compared to grandfathering in the cement sector, showing that benchmarking reduced free allocation volumes and thus windfall profits.[5] In line, Stenqvist and Åhman (2016) also find support for benchmarks reducing free allocation in the cement sector but not in the pulp and paper sector. Stenqvist and Åhman (2016) point out that the over-allocation of allowances in the pulp and paper sector was due to benchmarks being based on non-integrated single-product mills instead of integrated mills, leading to substantive over-allocation because the emission scope of the benchmarks is not set appropriately.[6] Eichhammer et al. (2018) on the other hand, find no evidence that the introduction of benchmarks correlated with improvements in carbon efficiency in the cement, pig iron, ammonia and nitric acid sectors. The early theoretical literature in this field looks at incentive effects of benchmarks in emissions trading, highlighting the time inconsistency problem related to the adjustment of benchmarks over time - if firms anticipate that improving emissions intensity today will reduce free allocation in the future (Rosendahl and Storrøsten, 2015, Zetterberg, 2014). Other studies point out distortions in investment choices and the effects on the product substitutes, if different benchmarks are applied to two goods that are perfect or imperfect

[5] The authors stress however that the combination of emissions benchmarks with *ex-ante* output measures still gives rise to large distortion for plants operating below full capacity.

[6] Benchmarks can be based on integrated plants or stand-alone plants. Industrial production in an integrated plant is typically more CO_2 efficient than in stand-alone plants because of opportunities to recover and reuse energy including heat, and waste gases (EPA, 2009). For example, coke is a key, carbon intensive input into steel production. Coke production results from carbonising coking coal in airtight coke ovens, and is accompanied by a number of by-products including coke oven gas, which can be reused in integrated plants. A product benchmark based on an integrated production process would then reflect the most efficient technology, and support the use and reuse of heat, waste gases, and other energy recovery whenever efficient from a global perspective. Currently however, the EU ETS divides production units into sub-installations rather than setting product benchmarks based on integrated processes (European Commission, 2011).

substitutes (Neuhoff et al., 2006, Flues and Dender, 2017). Others investigate how incentives are affected by the choice of where benchmarks are applied in the supply chain (Quirion, 2009, Branger and Sato, 2017). The paper closest to this article is Branger and Sato (2017) who show that upstream benchmarks in the cement sector do not set any incentives to improve carbon efficiency in the cement production through input substitution. If instead, benchmarks are placed on the downstream product cement, perverse incentives are created to displace own input production with imported inputs, if the indirect emissions in the imported input are not taken into account in the cement benchmark (Branger and Sato, 2017). This hinges on the perverse incentives created when benchmarks do not consider indirect emissions in their design. This article is the first to explicitly address the difficulty of indirect emissions and unaccounted carbon costs in inputs as well as outputs when setting emissions benchmarks.

The article proceeds as follows. Section 4.2 provides background for the analytic model by illustrating different ways of defining emissions scopes. Section 4.3 develops a simple model for evaluating how benchmarks affect firms' production incentives, considering four distinct cases of emissions scope adjustment. General principles for benchmark scope adjustment are derived, based on model insights. Section 4.4 explores aspects of applying scope adjusted benchmarks in practice. First, the magnitude of distortions corrected is estimated, using actual data from a steel plant. Second, complementary policies to restore mitigation incentives in the value chain are explored. Section 4.5 concludes by considering some of the potential policy implications of the findings.

4.2 Scope of benchmarks: direct and indirect emissions

A production processes typically involves multiple activities and total emissions include both direct and indirect emissions. According to the GHG Protocol, *direct* emissions are “emissions from sources that are owned or controlled by the company” (also called ‘scope 1 emissions’) while *indirect* emissions are “emissions that are a consequence of the activities of the company but occur at sources owned or controlled by another company” (GHG Protocol, 2004a). The indirect emissions can be further differentiated as ‘scope 2 emissions’ which cover indirect emissions from the company’s purchased energy, ans ‘scope 3 emissions’ which cover “all other indirect emissions that occur in a company’s value chain” (GHG Protocol, 2004b). Figure 4-1 illustrates the different scopes using the example of steel production. In a steel production facility, there are direct emissions from the production process, which turns iron into hot metal, and often also from on-site electricity production.[7] Indirect emissions arise for example through purchased electricity or through purchased material inputs like coke.[8]

In many emissions trading systems, benchmarks account only for direct emissions, and they typically attribute all emissions to the main product output neglecting by-products (see Figure 4-1). However, all industrial processes give rise to by-products (Kronenberg and Winkler, 2009)[9], which are in the steel production process mainly

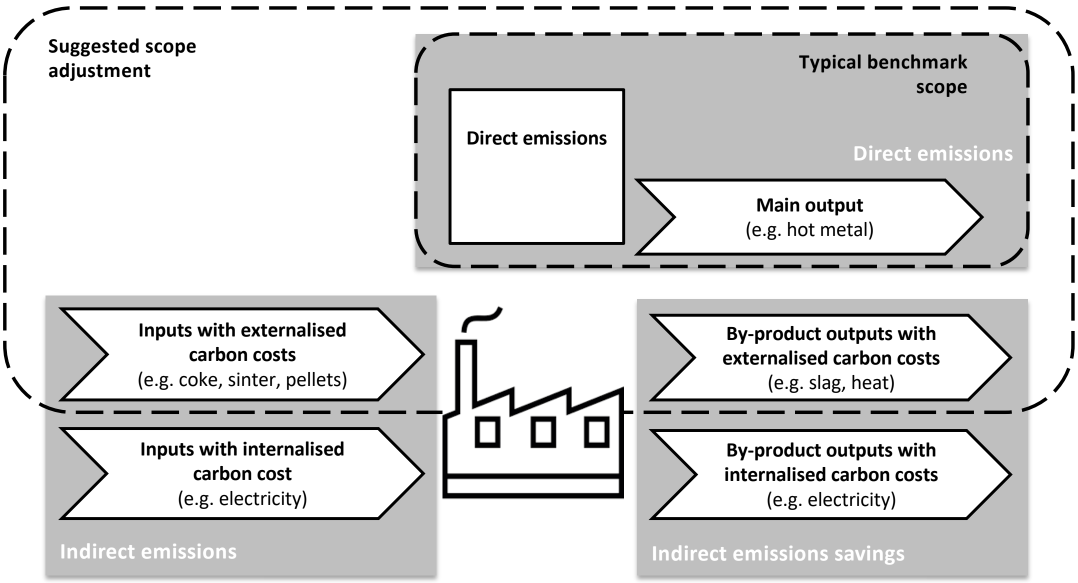
[7]The primary steel production process is typically based on iron-making in an integrated blast furnace (BF) where the iron in the sinter and pellets, is reduced to hot metal (pig iron) using coke as a reducing agent and energy source. An integrated BF plant typically also has its own electricity generation, coking and sintering plants, which contribute to the direct emissions.

[8]Integrated plants might have indirect emissions, for example if they purchase additional coke, sinter or electricity from off-site facilities. Pellets are also usually purchased from off-site plants (Siitonen et al., 2010).

[9]Kronenberg and Winkler (2009) argue, using an evolutionary perspective on production, that economies adapt to find useful purposes for joint outputs.

slag, heat and blast furnace gas.[10] Indirect emissions and savings from by-products are thus typically excluded from the scope of product benchmarks. Consequently, firms focus on reducing their direct emissions to maximise free allocation, rather than considering options to minimise overall emissions throughout the value chain.[11]

Figure 4-1: Direct and indirect emissions from a steel plant



Note: Simplified illustration of the direct and indirect emissions from an integrated production facilities using as an example an integrated blast furnace plant in steel making.

Furthermore, inputs and outputs can be distinguished by carbon cost incidence i.e. those where the carbon costs are internalised or externalised. Some input prices such as purchased electricity prices reflect the cost of carbon because there is full cost pass through in electricity. In contrast, coke or sinter prices may not reflect carbon

[10]The heat and BF gas can be recovered and reused on-site or off-site, either directly or as an input for electricity generation. Slag can be processed into granulated slag and used as a low-carbon substitute for clinker in cement production.

[11]Taking the steel sector as an example, from an overall sector perspective, emissions abatement is expected to come from a number of channels including the reduction of fuel use, reduction of material inputs, reduction of yield losses (Milford and Cullen, 2011), improvement of energy recovery, improved material by-product recovery, increased share of steel produced through recycling (Pauliuk and Allwood, 2013) and CCS.

costs, if coke plants receive free allocation based on OBA such that there is limited cost pass through.[12] On the output side, the prices of the competing product that the by-product displaces, may or may not reflect carbon costs. With slag, carbon prices are externalised in the price of the competing product clinker, because like coke, clinker production receives free allocation under OBA. The electricity output instead competes with grid electricity for which carbon costs are internalised in the product price. Thus, four indirect emissions categories can be distinguished as depicted in the bottom half of Figure 4-1.

Exceptions are sometimes made to account for indirect emissions in existing ETS benchmarks, but these are often in-transparent and ad hoc. For example, in the EU ETS, indirect emissions are accounted for in production processes which could either use primary energy inputs or run on electricity input generated off-site, to ensure a level playing field for these interchangeable installations (European Commission (2011), para 7). In California, indirect emissions are sometimes addressed by adjusting the free allocation amount by the ratio of direct to total emissions (California Air Resources Board (2011), p. 17). General principles for the treatment of indirect emissions could improve comparability of benchmarks across emissions trading schemes and facilitate harmonisation.

4.3 Scope adjusted benchmarks – a simple model

This section uses a simple model to analyse the effects of the suggested scope adjustment of emissions benchmarks on firms' incentives and compares situations of adjustment with non-adjusted benchmarks. Consider the following standard profit

[12] With OBA, even if a firm is less efficient than the benchmark, only the carbon costs exceeding the benchmark level is marginal and thus passed through.

maximisation problem of a firm:

$$\underset{q}{\text{Max}} \quad \Pi = p_q q + p_B B - p_I I - c(I, B) - p_e e(I, B) + p_e a \tag{4.1}$$

where q is the quantity produced of benchmarked product by a firm with price p_q, B is a vector of other outputs or by-products of the firm, with corresponding prices p_B, I is the input vector of the firm with prices p_I, c is the cost function of the firm, dependent on all inputs and outputs and assumed to be a long term cost function, allowing for investment costs and hence capacity expansion, e is the emission function of the firm, which depends, again, on all inputs and outputs and for which the allowance price p_e has to be paid, and a is the free allocation the firm receives. This article considers a firm to be a production site. However, this analysis can be transferred to any level of business activity e.g. plant, production site, or firm.

The article now considers adjustments to the scope of emissions in benchmarks. Free allocation to the firm, a, is defined as:

$$a = q_p BM_p - \gamma_m q_m BM_m + \gamma_b q_b BM_b \tag{4.2}$$

where BM_p is the product benchmark for q_p, which is the output quantity of the main product.[13] BM_p covers only direct emissions. Scope adjustment is made in two ways. First, a reduction is made through the term $q_m BM_m$ for indirect emissions attributable to purchased inputs. Second, a bonus is given by $q_b BM_b$ for the indirect emissions saving attributable to the production of by-products.[14] The parameter

[13]Throughout the analysis, the focus lies on product benchmarks, which are the most widely used type of benchmarks in current emissions trading schemes (see Appendix 4.6.1).

[14]The framework adopted here models the scope adjustment in the allocation formula. Alternatively, a model framework could be used where the adjustment is made directly in the benchmark formula. The equivalent to equation 4.2 in terms of a scope adjusted benchmark (SABM) would

$\gamma \in [0, 1]$, with $\gamma = 0$ equals no scope adjustment, and $\gamma = 1$ implies full adjustment. The next section studies how changes to the emission scope of benchmarks impact input and output decisions of an integrated steel plant and what appropriate values of the adjustment parameter are under different scenarios.

4.3.1 Analysing the model for various types of indirect emissions

Using the model described above and applying this to the steel production, the article tests how firms respond to adjustments to benchmark scope, examining each four categories of indirect emissions in turn.

Case 1: Emissions related to inputs with non-internalised carbon costs

This case can be exemplified by an integrated blast furnace plant with an on-site coking plant, which has an option to substitute between coke produced on- and off-site. The main product is hot metal (called steel here for simplicity).

The profit function of the steel plant is defined as follows:

$$\begin{aligned}\Pi_s = p_s q_s - p_k k_{off} - c_s(I, B, k_{tot}) - c_k(I, B, k_{on}) - p_e e_s(I, B, k_{tot}) - \\ p_e e_k(I, B, k_{on}) + p_e a\end{aligned} \tag{4.3}$$

Here, the cost and emission functions are split into that of steel making and the on-site coke-making. The cost function is defined as the sum of the two process' costs:

then be:

$$a = q_p SABM_p \quad where \quad SABM_p = BM_p - \gamma_m \frac{q_m}{q_p} BM_m + \gamma_b \frac{q_b}{q_p} BM_b$$

The underlying assumption here is that the main product benchmark, BM_p, is based on the most CO_2 efficient production process. This assures that plants do not receive an over-allocation of free allocation because of off-site inputs.

$c(I, B) = c_s(I, B, k_{tot}) + c_k(I, B, k_{on})$. The cost function of the steel making process, *inter alia* depends on the total amount of coke used, k_{tot}. The cost function of the coking process depends on the share of on-site coke, $(1 - \alpha)k_{tot}$, used in hot metal making, where α is defined as the share of off-site coke with respect to the total amount of coke used, $\alpha = \frac{k_{off}}{k_{tot}}$. The more coke is produced on-site, the higher the costs of the on-site coking process. It is assumed that all the coke produced on-site is consumed on-site. The price of purchased coke does not reflect carbon prices, because of output based allocation. A competitive market for coke is assumed.

The benchmark scope is extended to account for indirect emissions attributable to off-site coke production, by adjusting the free allocation according to Equation 4.2 (abstracting from the output side in this case):

$$a = q_s BM_s - \gamma \alpha k_{tot} BM_k \tag{4.4}$$

where q_s is the current output of steel. The steel benchmark, BM_s, assumes all coke is produced on-site.[15] The free allocation is thus reduced according to the share of off-site coke used in production. The scope adjustment parameter γ indicates whether scope adjustment is required or not.

The firm's choice of α, with and without the adjustment is of key interest. Substituting for k_{on} with $(1-\alpha)k_{tot}$ and replacing k_{off} with αk_{tot} in the profit maximisation problem (equation 4.3), differentiating with respect to the share α of off-site coke subject to the constraints that $\alpha \geq 0$ and $\alpha \leq 1$, the interior solution of the problem is determined by using the optimising condition $\frac{\partial \pi}{\partial \alpha} = 0$ (see Appendix 4.6.2 for details and a discussion of corner solutions of the Kuhn-Tucker maximisation). The equilib-

[15] Whether inputs are assumed to be produced on-site or off-site depend on the typical configuration of a plant. Either way, correct scope adjustments can neutralise the disincentives for less emissions efficient choices.

rium choice of the firm's share of off-site coke then depends on the marginal costs of producing coke on-site, $\frac{\partial c_k}{\partial k_{on}} + p_e \frac{\partial e_k}{\partial k_{on}}$, the costs of buying coke off-site, p_k, and the scope adjustment of the benchmark allocation, $p_e \gamma BM_k$:

$$p_k + p_e \gamma BM_k = \frac{\partial c_k}{\partial k_{on}} + p_e \frac{\partial e_k}{\partial k_{on}} \quad \text{iff } \gamma = 1 \tag{4.5}$$

Thus, a full scope adjustment ($\gamma = 1$) is needed to equalise marginal costs of on-site and off-site coke, assuming that the on-site emission intensity equals the benchmark emission intensity. The proposed scope adjustment re-installs a situation where carbon costs of inputs are fully internalised.[16] The adjustment thus neutralises the incentive to displace on-site emissions by off-siting coke.

The adjustment for inputs examined here allows making fair comparisons between plants of different configurations, with varying shares of inputs produced on-site or off-site. It is however applicable for any carbon intensive input for which the price does not internalise carbon costs, not only for coke inputs. For example, adjustment may be made for sinter and pellets in the case of steel, or for off-site clinker in the case of a cement benchmark, or for pulp in the case of a paper benchmark.

[16] Comparing the input choice of off-site coke (equation 4.5) with the input decision a firm faces when carbon costs are internalised in the price of the off-site input and no free allocation is given:

$$Max \quad \Pi_s = p_s q_s - p'_k k_{off} - c_s(I, B, k_{tot}) - c_k(I, B, k_{on}) - p_e e_s(I, B, k_{tot}) - p_e e_k(I, B, k_{on}) \tag{4.6}$$

where the price of the off-site coke now includes carbon costs, $p'_k = p_k + p_e EI_k$, where EI_k represents the emission intensity of the coke production process per ton of coke. If the coke plant produced at the benchmark level, the emission intensity would equal the coke benchmark, $EI_k = BM_k$. Rearranging the first order condition of the profit function (equation 4.6), differentiated with respect to the share of off-site coke, and assuming that the firm produced at the benchmark level, $EI_k = BM_k$, yields the same as equation 4.5.

Case 2: Emissions related to inputs with internalised carbon costs

Electricity input is used to illustrate this case. The price of the purchased electricity from the grid is assumed to fully reflect the marginal cost of carbon in electricity generation.[17] The profit maximisation problem of a steel plant that buys electricity from the grid is:

$$\underset{q_{si}}{\text{Max}} \quad \Pi_{s_i} = p_s q_{s_i} - (p_{el} + p_e EI_{el}) q_{el_i} - c_{s_i}(I,B) - p_e e_{s_i}(I,B) + p_e a_i \tag{4.7}$$

where EI_{el} is the emission intensity of the production process of electricity and with free allocation being scope adjusted and thus based on the steel output and the share of off-site electricity bought, $a_i = q_{s_i} BM_s - \gamma\alpha q_{el_i} BM_{el}$, with $\alpha = 1$.

Instead, a steel plant that generates all electricity on-site has the following profit maximisation problem:

$$\underset{q_{sk}}{\text{Max}} \quad \Pi_{s_k} = p_s q_{s_k} - c_{el_k}(I,B) - c_{s_k}(I,B) - p_e e_{s_k}(I,B) - p_e e_{el_k}(I,B) + p_e a_k \tag{4.8}$$

with free allocation being based on the steel output and the share of off-site electricity. As it is assumed that all electricity is generated on-site, $\alpha = 0$, and thus free allocation boils down to $a_k = q_{s_k} BM_s$.

First order conditions of the two plants are used ($\frac{\partial \Pi_{s_i}}{\partial q_{el}} = 0, \frac{\partial \Pi_{s_k}}{\partial q_{el}} = 0$) and it is assumed that electricity has the same marginal product for both plants ($\frac{\partial q_{s_i}}{\partial q_{el}} = \frac{\partial q_{s_k}}{\partial q_{el}}$) to compare the relation of the cost structures of the two plants.[18] Assuming the same emission intensity in the purchased and in the produced electricity, $EI_{el} = \frac{\partial e_{el}}{\partial q_{el}}$, and

[17] This assumption is generally supported by empirical studies in the EU ETS (Fabra and Reguant (2014); see Arlinghaus (2015) for an overview).

[18] The marginal costs of buying electricity off-site for plant i are $MC_i = p_{el} + p_e EI_{el} + \frac{\partial c_{s_i}}{\partial q_{el}} + p_e \frac{\partial e_{s_i}}{\partial q_{el}} + p_e \gamma BM_{el}$ and of producing electricity on-site for plant k are $MC_k = \frac{\partial c_{el_k}}{\partial q_{el}} + p_e \frac{\partial e_{el_k}}{\partial q_{el}} + \frac{\partial c_{s_k}}{\partial q_{el}} + p_e \frac{\partial e_{s_k}}{\partial q_{el}}$.

assuming that the price of off-site electricity equals the marginal costs of producing electricity on-site, $p_{el} = \frac{\partial c_{el}}{\partial q_{el}}$, reveals the following relation of the costs incurred by the two firms:

$$\frac{\partial c_{el}}{\partial q_{el}} + p_e \frac{\partial e_{el}}{\partial q_{el}} + \frac{\partial c_{s_i}}{\partial q_{el}} + p_e \frac{\partial e_{s_i}}{\partial q_{el}} + p_e \gamma BM_{el} = \frac{\partial c_{el_k}}{\partial q_{el}} + p_e \frac{\partial e_{el_k}}{\partial q_{el}} + \frac{\partial c_{s_k}}{\partial q_{el}} + p_e \frac{\partial e_{s_k}}{\partial q_{el}} \quad \text{iff } \gamma = 0 \tag{4.9}$$

The left hand side reflects the costs for the plant buying electricity from the grid, and the right hand side reflects the costs for a plant producing electricity on-site. As can be seen from equation 4.9, this equality only holds iff the adjustment parameter is zero, $\gamma = 0$.

A scope adjustment on the other hand, $0 < \gamma \leq 1$, would lead to an increase in the electricity costs for the firm buying electricity off-site by $p_e \gamma BM_{el}$. Such an adjustment would thus uneven the level playing field across firms purchasing the input versus firms producing the input on-site. In the case of inputs with internalised carbon costs, firms might thus end up paying twice for the carbon externality. This result holds for any other input with internalised carbon costs but these are few in practice.

Case 3: Emissions related to outputs competing with goods with non-internalised carbon costs

A major by-product of primary steel making is slag. Slag is a low-carbon substitute for clinker, which is a carbon intensive basic input factor to cement making (Benhelal et al., 2013). By displacing (or providing an equivalent service to) clinker, slag production generates indirect emissions savings and reduces overall emissions, thereby enhancing social welfare. However, for the blast furnace plant, producing a higher share of slag can increase marginal emissions and, hence, the marginal costs of steel

(Buttiens et al., 2016).

Slag competes directly with clinker producers. Clinker production volumes dominate the market and are thus assumed to be price setters for clinker (and hence also slag).[19] The clinker producer faces the following profit maximisation problem:

$$\underset{q_{cl}}{\text{Max}} \quad \Pi_{cl} = p_{cl}q_{cl} - c_{cl}(I, B) - p_e e_{cl}(I, B) + p_e a_{cl} \tag{4.10}$$

Clinker producers receive free allocation according to the clinker benchmark:

$$a_{cl} = q_{cl} BM_{cl} \tag{4.11}$$

From the first order condition, it follows that the clinker producer will sell clinker at the following price, assuming that they do not pass through carbon prices due to output based allocation:

$$p_{cl} = \frac{\partial c_{cl}}{\partial q_{cl}} + p_e \frac{\partial e_{cl}}{\partial q_{cl}} + p_e BM_{cl} \tag{4.12}$$

The steel plant's profit function, including the slag output (q_{sl}) is:

$$\Pi_s = q_s p_s + p_{sl}q_{sl} - p_I I - c_s(I, B) - p_e e_s(I, B) + p_e a_s \tag{4.13}$$

The benchmark scope is extended to account for indirect emission savings attributable to slag displacing clinker production, by adjusting free allocation to the

[19] In this example, market structures that might lead to temporary higher or lower revenues from e.g. slag sales dependent on product quality, location, and time are ignored. Steel producers often claim that the slag market is a "buyers market" in reality, meaning that the steel producers face a monopoly situation when selling to the cement producer who is essentially setting the price for slag. Such a monopolistic situation might imply that clinker and slag prices are not fully comparable nor interchangeable. It is also assumed that all slag produced is released to the market and sold for use in cement.

blast furnace plant according to Equation 4.2 (abstracting from the input side in this case):

$$a_s = q_s BM_s + \gamma\beta q_{sl} BM_{cl} \tag{4.14}$$

where γ is the scope adjustment parameter, β is a conversion factor for the quantity of slag needed to substitute one metric ton of clinker in cement production[20], and BM_{cl} is the benchmark for clinker. Here, slag receives an adjustment according to the clinker benchmark, rather than creating an additional slag benchmark, because it saves emissions in proportion to the clinker it displaces.[21]

Setting the first order condition equal to zero for the optimality condition, the steel producer will provide slag until marginal product equals marginal costs:

$$p_{sl} = \frac{\partial c_s}{\partial q_{sl}} + p_e \frac{\partial e_s}{\partial q_{sl}} - p_e \gamma\beta BM_{cl} \tag{4.15}$$

In an efficient economic market, prices and thus costs of clinker will equal the service equivalent of slag (comparing equation 4.12 and equation 4.15):

$$\frac{\partial c_{cl}}{\partial q_{cl}} + p_e \frac{\partial e_{cl}}{\partial q_{cl}} + p_e BM_{cl} = \frac{\partial c_s}{\partial q_{sl}} + p_e \frac{\partial e_s}{\partial q_{sl}} - p_e \gamma\beta BM_{cl} \quad \text{iff } \gamma = 1 \tag{4.16}$$

This equation only holds iff $\gamma = 1$, implying the need for full scope adjustment. The scope adjustment for the indirect emissions savings of slag production

[20] For simplicity, a linear relationship is assumed. Note however that a full, meaning 100%, substitution of clinker by slag is not possible.

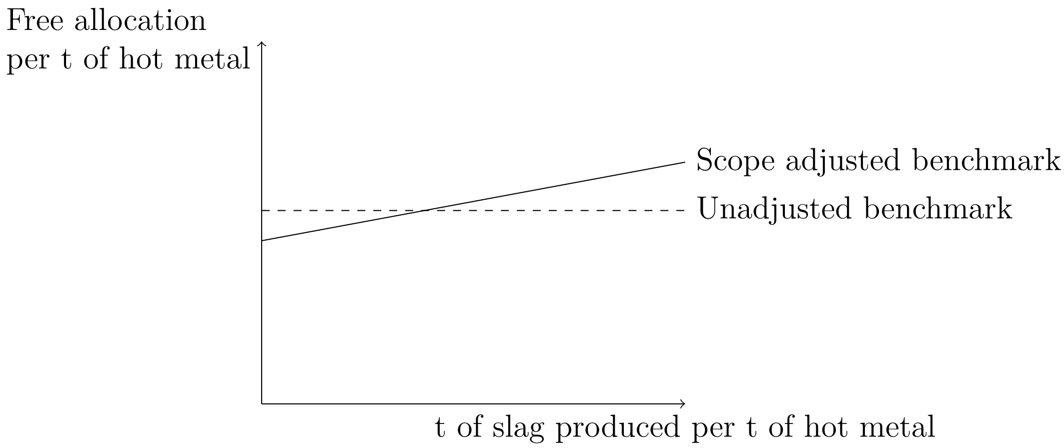
[21] The adjustment for the amount of slag only applies to slag which is sold in the market, not stored. Slag use needs to be feasible, e.g. artificial constraints on building codes that inhibit substitution need to be addressed. Policy support to induce demand for slag may be necessary, such as public procurement of low-carbon steel or eco-building standards. Otherwise the economic incentive cannot work and might have perverse results.

[21] Interior solutions are the main interest here. There is always some slag co-production such that q_{sl} is greater than 0. Similar to the coke case discussed before (see Appendix 4.6.2), cost functions are long term and the same adjustment is appropriate for additional slag capacity.

($-p_e\gamma\beta BM_{cl}$) thus reduces marginal cost of slag to make it competitive with clinker, which receives free allocation. This adjustment encourages the cement company to substitute more clinker with low-carbon slag, thus reducing overall emissions (see Appendix 4.6.2 on the cement plant's decision on slag and clinker).

Figure 4-2 illustrates the level of free allocation per metric ton of hot metal depending on the slag production. With an unadjusted benchmark (dotted line), free allocation stays constant, independent of slag output. Instead with scope adjustment, free allocation is increased according to slag output. The baseline hot metal benchmark is lower in the scope adjusted benchmark case, as the unadjusted benchmark assumes some amount of slag production.

Figure 4-2: Scope adjusted benchmark



Note: Free allocation per metric ton of hot metal with unadjusted benchmark, dashed line, and with scope adjusted benchmark, solid line. In the case of the unadjusted benchmark, no emissions are attributed to the by-product and thus the hot metal benchmark is independent of the amount of slag produced.

Allocating free emissions to by-products does not necessarily lead to a higher total allocation. Existing ETS benchmarks attribute total emissions to the main product and do not explicitly attribute emissions to by-products. However, they implicitly assume that some level of by-products is produced. If emissions are explicitly attributed for by-products with scope adjustment, a recalculation of the main product benchmark is necessary for every such by-product.

The scope adjustment studied here is also applicable to any industrial by-products that compete with goods receiving free allocations. For example, heat represents a by-product in the steel production process and if captured, can be sold for district heating, providing the equivalent service to conventional heat generation through gas or electricity. In the EU ETS, free allocation is given to heat plants on the ground of distributional concerns, such that carbon costs are not passed through to heat prices. To incentivise industrial plants to optimise heat recovery, reuse and supply, scope adjustment is necessary so that their by-product heat can compete with other heat producers.

Case 4: Emissions related to outputs competing with goods with internalised carbon costs

By-products with indirect emissions savings may also face competition from goods, where carbon costs are internalised in the prices already. For example, a steel plant producing electricity as a by-product creates indirect emissions savings but the competing producers (electricity utilities) face and pass forward carbon prices.

The steel plant generates and sells electricity and has the following profit function:

$$\Pi_s = p_s q_s + p_{el} q_{el} - c_s(I,B) - c_{el}(I,B) - p_e e_s(I,B) - p_e e_{el}(I,B) + p_e a \qquad (4.17)$$

with free allocation being scope adjusted for the additional electricity output, $a = q_s BM_s + \gamma q_{el} BM_{el}$.

The electricity generator faces the following profit maximisation problem:

$$\underset{q_{el}}{\text{Max}} \quad \Pi_{el} = p_{el}q_{el} - c_{el}(I,B) - p_e e_{el}(I,B) \tag{4.18}$$

where he is not eligible for free allocation.

Equation 4.19 shows on the left hand side, the marginal costs of the steel producer and on the right hand side the marginal costs faced by the electricity generator:

$$\frac{\partial c_{el}}{\partial q_{el}} + p_e \frac{\partial e_{el}}{\partial q_{el}} - \gamma q_{el} BM_{el} = \frac{\partial c_{el}}{\partial q_{el}} + p_e \frac{\partial e_{el}}{\partial q_{el}} \quad \text{iff } \gamma = 0 \tag{4.19}$$

This equality however only holds iff there is no scope adjustment, i.e. $\gamma = 0$. A zero scope adjustment thus provides a level-playing field for the output production of the two firms, assuming equal cost and emission functions. Therefore, no scope adjustment is necessary for the indirect emissions savings made by by-products if the price of the competing good internalises carbon costs. Such adjustment would lead to unfair competition among firms.

4.3.2 Emerging principles for benchmark design

Two general principles emerge from the four cases examined, for defining emissions scope in benchmarking. First, benchmarks need not to adjust for indirect emissions of inputs or indirect emissions savings of outputs, if carbon costs are internalised. Second, benchmarks should adjust for indirect emissions of inputs and outputs if instead carbon costs are not internalised in the price of an input or of an output's competing product. Such scope adjustment should be made in the following way: free allocation should be reduced for the indirect emissions attributable to purchased inputs from off-site facilities; and additional allocation should be given for indirect emissions savings from the production of desirable by-products, if the competing producers also receive free allocation. This implies that if explicit adjustments are made for by-products, the main product benchmark should be adjusted, to remove implicit attribution to these by-products.

Accounting correctly for indirect emissions in benchmarks not only enables fairer comparisons of plants of differing configurations, but also removes perverse incentives, and aligns incentives for mitigation along the supply chain. On the inputs side, it removes the incentive to artificially reduce plant emissions by purchasing inputs from off-site, and instead encourages on-site production of inputs in integrated facilities which are often more resource efficient. On the output side, it incites socially optimal levels of by-product production, by providing an option to cover incremental costs of producing by-products.

These principles hold not only for cases where there is full or zero carbon cost pass-through, but also when carbon costs are only partially passed forward. What changes is the weight which should be given to the adjustment, namely the value of the adjustment parameter γ. Depending on how much of the costs are passed on, the value of the adjustment parameter should lie somewhere between zero and one. One practical way of dealing with partial carbon cost pass through might be to set categories of low, medium, and high carbon cost pass through with respective threshold and adjustment parameter values. This will avoid excessive administrative and calculation burdens. However, similar to the assessment of carbon leakage risk, the categorisation of carbon cost pass through levels should be dealt with by policy makers and is outside of the scope of this article.

4.4 Scope adjusted benchmarks in practice

This section argues the economic importance of adjusting for indirect emissions in benchmarks, focusing on two aspects – the magnitude of the corrected distortionary effect and the role of scope adjusted benchmarks in mitigation in the value chain.

4.4.1 Quantifying the economic impact of scope adjusted benchmarks

Actual production data from an integrated blast furnace plant[22] and the example of the EU ETS to quantify the distortions corrected by shifting towards the scope adjusted approach to benchmarking, for both inputs and outputs. Table 4.1 shows the plant level emissions as well as the free allocation per ton of hot metal under the current EU ETS benchmarks (direct emissions only) and under scope adjusted benchmarks for inputs and outputs.[23]

In the input case, a plant that buys all coke input off-site is compared with a plant using only coke from on-site production, along the lines of the theoretical case discussed above. The on-site emissions are lower for a firm which outsources coke production. As EU ETS benchmarks are based on historic input shares, there is thus an incentive to outsource coke production after benchmark-based free allocation levels are determined. The scope adjusted benchmarks neutralise dis-/incentives for out-/in-sourcing input production. The calculation in Table 4.1 shows that whether a firm is choosing to buy coke off-site or to produce it on-site, the difference in free

[22]Production data for an actual integrated blast furnace plant is taken from Buttiens et al. (2016) is used to calculate adjusted benchmark values per metric ton of hot metal. Underlying values of production inputs are: 0.297t coke (in integrated blast furnace plant), 1.187GJ natural gas, 0.182t coking coal. Production outputs are: 1t hot metal, 1.433t CO2, 0.292kg slag.

[23]Note that the plant forming the basis of these calculations does not operate at the benchmark level in terms of CO_2-efficiency. Therefore the free allocation under current EU ETS benchmarks does not cover all firm's emissions.

allocation per tonne of output and the firm's emissions per tonne of output is the same.

Table 4.1: Free allocation with unadjusted and adjusted benchmarks

Case	Emissions	Allocation under EU ETS BM	Allocation under scope adj. BM	Allocation for cement producer	Total allocation (steel+ cement)
1: Input case					
Firm outsourcing coke	1.35	1.41	1.33		
Firm insourcing coke	1.43	1.41	1.41		
2: Output case					
Firm with BAU-amount of slag	1.43	1.41	1.41	0.69	2.10
Firm doubling amount of slag	1.60	1.41	1.64	0.46	2.10

Note: The numbers shown are normalised to one metric ton of hot metal output or one metric ton of cement, respectively. Underlying plant level data is taken from Buttiens et al. (2016). Benchmark values are taken from the EU ETS: BM hot iron 1.328t/t CO_2; BM clinker 0.766t/t CO_2; BM coke 0.286t/t CO_2. The last column shows the total allocation for one metric ton of hot metal and one metric ton of cement.

In the output case, a plant producing business-as-usual (BAU) level of slag is compared to a plant producing the double the amount of slag.[24] An increased amount of slag output, which might be influenced by the quality of iron ore used in the production process, is physically linked to an increased level of emissions. Under the current EU ETS scheme, both firms receive the same amount of free allocation. The scope adjusted benchmark grants additional emission certificates to the firm which produces more slag, based on the amount of slag being produced. The additional free allocation certificates are shifted away from the cement producer to the steel producer: As the cement producer, in the second step, uses an input with internalised carbon prices, his free allocation is reduced. Total free allocation is thus constant (see last

[24]The production capacity of slag of different BF plants is taken from Buttiens et al. (2016), where an average BF plant produces 0.3 metric tons of slag/metric ton of hot metal and the maximum amount of slag production of a BF plant is considered to be 0.6 metric tons of slag/metric ton of hot metal.

column of Table 4.1). In the case of an increased slag production, it is assumed that this slag is fully used in cement production, substituting clinker. In the extreme case of a doubling of slag production, the results in Table 4.1 for the scope adjusted benchmarks show that the firm would receive more free allocation than its actual emissions which is a result from the fact that slag production is more carbon efficient than clinker production. Whether firms will increase their slag production up to such a point where free allocation exceeds their actual emissions is however uncertain as additional costs, such as energy costs, will be incurred. The introduction of a consumption tax (as discussed in section 4.4.2) can however help to reduce any adverse incentives.

For each case, the resulting changes to contribution margins, i.e. selling price per unit minus variable costs per unit, are then estimated and compared to the change to profit margins (last column of Table 4.2). In the input case, purchasing coke from off-site plants reduces the contribution margin, primarily due to the high coke prices underlying our model (second column). The financial incentive to buy off-site coke is even lower under scope adjusted benchmarks (third column). In the output case, the contribution margins are higher for producing additional slag. This incentive is reinforced under scope adjusted benchmarks. The magnitude of these effects is economically important as shown in the last column – the double-differences in contribution margins (i.e. difference from switching under EU ETS benchmarks compared to difference under scope adjusted benchmarks) account for up to one third of the profit margin of one tonne of hot metal.[25] The adjustment for indirect emissions savings from producing extra slag contributes to recovering the incremental and fixed costs of adjusting output.

[25]For the calculation, a 5% profit margin, a 20 EUR/t CO_2 price, and take hot metal, clinker and coke benchmarks from the EU ETS are assumed.

Table 4.2: Changes in contribution margin in case of scope adjusted benchmarks

Case	Change in contr. margin under EU ETS BM	Change in contr. margin under scope adj. BM	Difference of change in margins relative to profit of one ton of hot metal
1: Firm switching from on-site to off-site coke	-22.73 EUR/t	-24.43 EUR/t	-10.59 %
2: Firm doubling amount of slag	3.04 EUR/t	7.63 EUR/t	28.69 %

Note: Contribution margin is defined as selling price minus variable costs. The calculations are normalised to Euros per one metric ton of hot metal output. Underlying plant level data is taken from Buttiens et al. (2016). The underlying benchmark values are taken from the EU ETS: BM hot iron 1.328t/t CO_2; BM clinker 0.766t/t CO_2; BM coke 0.286t/t CO_2. A CO_2 price of 20 EUR/t is used. The calculations of the contribution margin are based on variable costs/savings only, without considering new capital investments (e.g. for a granulator) and assuming a linear production process. Price data is taken from Eurostat, the online database Steelonthenet, and the US Government. A 5%-profit margin is assumed per metric ton of hot metal.

4.4.2 The role of scope adjusted benchmarks when combining OBA with a consumption tax

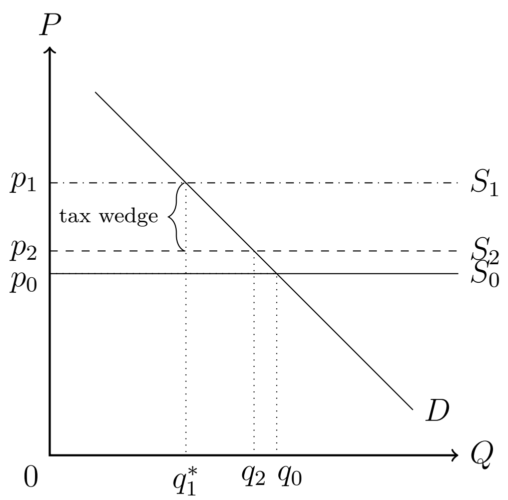
The literature on output based allocation highlights a key main challenge: it leads to excess production of carbon intensive goods by acting as an output subsidy – additional production garners additional free allowances, (Fischer, 2001, Fischer and Fox, 2007, Sterner and Muller, 2008). This mitigates the increase in marginal costs and product prices, such that the market signal for producers to develop cleaner processes and new, alternative low-carbon goods is hampered and mitigation from demand-side substitution is largely forgone (Munnings et al., 2016). Recent research argues that the combination of output-based allocation with a consumption tax[26] (based on the benchmarks underlying the free allowance allocation) represents a robust policy option

[26]The consumption tax works similarly to excise on fuels, alcohol and tobacco and is considered to be of low administrative cost (see Ismer et al. (2016) for details on the administrative implementation). Adhering to the example of the steel sector, the steel producer, receiving free allocation based on a benchmark, would pass on the tax liability along the value chain. At the point of final consumption, e.g. a car sale, the vendor is liable for the tax, which should be equivalent to the weight of the steel in the car sold, multiplied by the steel benchmark and the carbon price. The carbon price is thus restored at the final consumption end, and internalised in the price of the final good. The liability is waved on steel or cars that are exported, and firms that import carbon-intensive products have to report the weight of for example steel, and take the corresponding liability.

to avoid carbon leakage (e.g. Neuhoff et al. (2016)), equivalent to the implementation of carbon tax with border tax adjustments (Böhringer et al., 2017). This section investigates this combination and the role of scope adjusted benchmarks.

Figure 4-3 illustrates how the consumption tax corrects perverse incentives for excess output created by OBA. The introduction of emission pricing increases the marginal costs of production by the marginal cost of emission certificates, shifting the initial supply, S_0, up to S_1. Free allocation reduces the effective marginal costs for producers and thus shifts the marginal cost curve downwards to S_2. As the carbon costs are not fully internalised, the equilibrium supply quantity, q_2, is larger than under full cost internalisation, q_1^*, signifying an excess demand. Introducing a consumption tax creates a tax wedge, re-installing the socially optimal output, q_1^*.

Figure 4-3: Partial equilibrium output in emissions trading schemes



Note: Production outcomes in emissions trading scheme with output based allocation (line S_2) and consumption tax (line S_1).

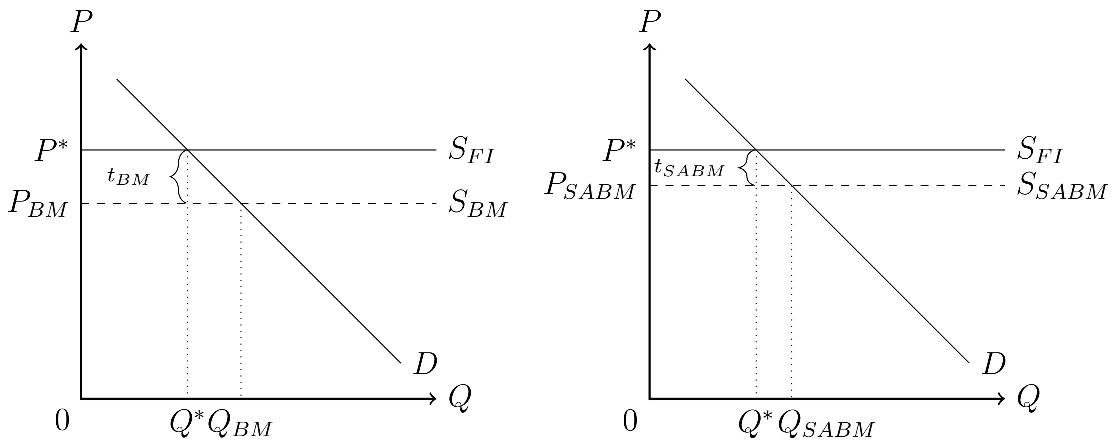
As Böhringer et al. (2017) show in an open economy model, the optimal consumption tax depends *inter alia* on the output subsidy. Thus, the underlying benchmarks used for the initial free allocation also determine the consumption tax. Assuming the consumption tax is set equal to a Pigouvian tax to re-install a situation of full carbon cost internalisation in the market, the effect of the output subsidy vanishes and the equilibrium quantity q_1^* is reached. Abstracting from any terms of trade effects of the consumption tax (see Böhringer et al. (2017) for an indepth analysis) for simplicity, the marginal consumption tax, t, is determined through the following equation:

$$t = p_e \frac{\partial a}{\partial q_x} \tag{4.20}$$

where q_x is the product benchmarked, and p_e the emission price and a the free allocation.

The design of benchmarks, whether they are scope adjusted or not, thus influences the tax level, thereby determining the shares paid for the externality by different producers and consumers. Figure 4-4 shows the case of a reduction of free allocation for example in the case of off-site coke production. The left hand panel shows the business-as-usual case of an unadjusted benchmark (BAU-BM), the right hand panel shows the case of scope adjusted benchmarks (SABM). The introduction of scope adjusted benchmarks reduces the initial deadweight loss of the externality (the small triangle in the right hand panel above the dashed line S_SABM) because the negative effects of the output subsidy is reduced. Consequently, the consumption tax, t_{SABM} needed will be smaller than in a BAU-case. Thus the scope adjusted benchmarks do not influence the efficiency outcome (the social optimal equilibrium of Q^* can be reached by both adjusted and non adjusted benchmark) but it impacts the distributional effects of who is paying for the externality (producers vs. consumers). Combining output based free allocation with scope adjusted benchmarks and a consumption tax can thus restore incentives for efficient material production and consumption by providing an appropriate measurement framework.

Figure 4-4: Consumption tax in emissions trading schemes



Note: Consumption tax in case of unadjusted benchmarks (BM), left panel, and scope adjusted benchmarks (SABM), right panel.

4.5 Conclusion

Benchmarks play an important role in policies to regulate industrial emissions, which constitute a major source of global emissions. This article investigated how firms respond to different benchmark design, and argues the importance of defining emissions scope for efficiency outcomes. It highlighted a prevalent problem with existing emissions trading scheme benchmarks that do not adequately account for indirect emissions, by demonstrating the economic importance of distortionary effects caused. The article derived general principles for the inclusion or exclusion of indirect emissions in benchmark scope which hinges on carbon costs incidence. Specifically, indirect emissions attributable to inputs should be included in the benchmark scope only if their price does not already reflect carbon costs. Indirect emissions attributable to by-products should be included, only if the price of the competing good's price does not reflect carbon costs. These principles can be adopted to any emissions benchmark design. Such adjustment can create incentives that are aligned with mitigation options along the supply chain.

Our results suggest that even in the absence of a global carbon price, unilateral carbon pricing can still be effective, with well designed and targeted anti-leakage measures, including benchmarking based free allocation. Suggested amendments to existing policies can help install a robust carbon price signal that is incorporated into the strategic choice of companies.

The general principles for benchmarking put forward in this article can also serve as a common basis and foster greater international harmonisation and comparability, and act as a focal point for global cooperation across emissions trading systems. As low-carbon technologies evolve, all emissions trading schemes face the same challenge to develop principles for updating benchmarks to incorporate new technologies. Updating is necessary to keep benchmarks ambitious and reflect the improvements in technology, but it can create early action problems, by linking mitigation actions today with allocation in the next period (Bøhringer and Lange, 2005, Rosendahl, 2008). This is particularly problematic for incentivising investment in radical or breakthrough innovations like carbon capture and storage (CCS), as implementing such technologies could punish early technology adopters by reducing future free allowances sharply. As previous research shows, anticipating this, firms may collude against adopting such innovations (Zetterberg, 2014). International cooperation on benchmarks can expand the pool of installations for the calculation of benchmarks, and reduce the early action problem, thus ensuring innovation incentives are retained in energy intensive sectors.

4.6 Appendix

4.6.1 International comparison of ETSs

Table 4.3: Design aspects of emissions benchmarks across international ETSs

	Type of benchmark	Corresponding activity level	Benchmark setting	Scope of emissions covered
EU (Phase 3)	52 product benchmarks, heat benchmark and fuel benchmark as fallback	Historic activity level in baseline year	Average emissions intensity for the top 10% most efficient installations within each sector	Direct emissions only. Share of indirect electricity emissions subtracted in some cases.
California	28 product benchmarks, fuel use benchmark	Recent output level updated annually, or historic baseline level for fuel benchmarks	Allocates 90% sector average emission intensity	Direct and indirect
New Zealand	42 product benchmarks, electricity usage benchmark	Recent output level updated annually	Industry average	Direct; indirect associated with electricity consumption
South Korea	3 sectors product benchmark, heat/fuel benchmark	Historic activity level in baseline year	Weighted average emissions intensity of eligible entities (not installations)	Direct; indirect emissions from large electricity consumers
China (pilots)	42 industry benchmarks, 79 benchmarks for sub-categories	Actual output level with frequent updating	Tightest of seven benchmarks considered (including EU benchmark, energy efficiency benchmark)	Direct; indirect emissions from electricity (and heat) consumption

Sources: European Commission (2011), California Air Resources Board (2011), Environmental Protection Agency (2010), Ministry for the Environment (2002), ICAP (2016a), ICAP (2016b), Qing (2015).

4.6.2 Calculus

Kuhn-Tucker conditions

The Kuhn-Tucker maximisation problem is:

$$Max\ \Pi_s = p_s q_s - p_k \alpha k_{tot} - c_s(I, B, k_{tot}) - c_k(I, B, (1 - \alpha k_{tot}) - p_e e_s(I, B, k_{tot})$$
$$-p_e e_k(I, B, (1 - \alpha k_{tot}) + p_e(q_s BM_s - \gamma \alpha k_{tot} BM_k) \quad s.t.\ 1 - \alpha \geq 0,\ \alpha \geq 0 \tag{4.21}$$

Corresponding Lagrangian:

$$\mathcal{L}(\alpha, \lambda, \cdot) = \Pi_s + \lambda(1 - \alpha) \tag{4.22}$$

The set of first order conditions:

$$\frac{\partial \mathcal{L}}{\partial \alpha} = -p_k k_{tot} + k_{tot} \frac{c_k}{k_{on}} + k_{tot} p_e \frac{\partial e_k}{\partial k_{on}} - p_e \gamma k_{tot} BM_k - \lambda \leq 0\ ,\ \frac{\partial \mathcal{L}}{\partial \alpha} \alpha^* = 0 \tag{4.23}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = 1 - \alpha \geq 0\ ,\ (1 - \alpha)\lambda^* = 0 \tag{4.24}$$

Breaking these conditions down, leads to three cases:

1. Strict interior solution: $\alpha^* > 0$ and $1 - \alpha^* > 0$. As $1 - \alpha^* > 0$, it must be $\lambda^* = 0$, otherwise $\frac{\partial \mathcal{L}}{\partial \alpha} \alpha^* = 0$ could not hold. As $\alpha^* > 0$, the first first order condition must hold with equality, otherwise $\frac{\partial \mathcal{L}}{\partial \alpha} \alpha^* = 0$ could not hold. This simplifies to the case of an unconstrained optimisation. Dividing by k_{tot} and rearranging yields the following solution: $p_k + p_e \gamma BM_k = \frac{\partial c_k}{\partial k_{on}} + p_e \frac{\partial e_k}{\partial k_{on}}$.

2. Left boundary: $\alpha^* = 0$. This implies that $1 - \alpha > 0$ and thus it must be $\lambda^* = 0$ and the first first order condition becomes $\frac{\partial \Pi_s}{\partial \alpha^*} \leq 0$, $\alpha^* = 0$. That is the case as long as $\frac{\partial c_k}{\partial k^*_{on}} + p_e \frac{\partial e_k}{\partial k^*_{on}} \leq p_k + p_e \gamma BM_k$.

3. Right boundary: $1 - \alpha^* = 0$. This obviously implies that $\alpha^* > 0$. Thus it must be $\frac{\partial \Pi_s}{\partial \alpha^*} = \lambda^* \geq 0$. Thus, at $\alpha^* = 1$, it needs to have the slope of the objective function be non-negative which yields: $\frac{\partial c_k}{\partial k^*_{on}} + p_e \frac{\partial e_k}{\partial k^*_{on}} \geq p_k + p_e \gamma BM_k$.

Corner solutions are not ruled out but the focus lies on internal solutions in the analysis where $\alpha^* > 0$ and $1-\alpha^* > 0$. As shown here in the Appendix, even if initially the share of off-site coke was zero or one, the same adjustment of the benchmark is appropriate.

Slag production

The cement producers chose the quantity of clinker and slag inputs to maximize their profit function:

$$Max \quad \Pi_{ce} = p_{ce}q_{ce} - p_{cl}q_{cl} - p_{sl}q_{sl} - c_{ce}(I, B) - p_e e_{ce}(I, B) \tag{4.25}$$

Partially differentiating this with respect to the clinker input q_{cl} and the slag input q_{sl}, and using the optimising conditions of $\frac{\partial \Pi_{ce}}{\partial q_{cl}} = 0$ and $\frac{\partial \Pi_{ce}}{\partial q_{sl}} = 0$ gives the following conditions by which the cement producer bases input decisions, namely equalising marginal revenue of each input to its marginal costs:

$$\frac{\partial q_{ce}}{\partial q_{cl}} p_{ce} = p_{cl} + \frac{\partial c_{ce}}{\partial q_{cl}} + p_e \frac{\partial e_{ce}}{\partial q_{cl}} \quad and \quad \frac{\partial q_{ce}}{\partial q_{sl}} p_{ce} = p_{sl} + \frac{\partial c_{ce}}{\partial q_{sl}} + p_e \frac{\partial e_{ce}}{\partial q_{sl}} \tag{4.26}$$

Keeping in mind that $q_{cl} = \beta q_{sl}$, the marginal product of slag can be expressed in terms of the marginal product of clinker: $\frac{\partial q_{ce}}{\partial q_{sl}} = \frac{1}{\beta} \frac{\partial q_{ce}}{\partial q_{cl}}$. Plugging this into the second equation of equation 4.26, solving for the marginal revenue of clinker and plugging this into the first equation of Equation 4.26, yields the following equality:

$$p_{cl} + \frac{\partial c_{ce}}{\partial q_{cl}} + p_e \frac{\partial e_{ce}}{\partial q_{cl}} = \beta(p_{sl} + \frac{\partial c_{ce}}{\partial q_{sl}} + p_e \frac{\partial e_{ce}}{\partial q_{sl}}) \tag{4.27}$$

Equation 4.27 depicts the marginal costs of clinker on the left side and the marginal costs of slag on the right side, multiplied by the conversion factor of slag to clinker. The equations show that the cement producer will thus only be willing to pay the service equivalent price for slag. Without the scope adjustment to the free allocation to the slag producing steel plant (Equation 4.14), for a given price, the steel producer is less willing to produce slag, thus slag is under-supplied.

General Conclusion

This dissertation addresses the capability of environmental policies to create innovation incentives for firms. Looking at various environmental policy tools through the lens of an innovation policy framework, the thesis evaluates the potential of these policies to function as technology-push or demand-pull triggers on the innovation activities of firms.

Chapter 1 shows that more stringent environmental policies have the potential to lead to short-term productivity gains. These gains are however only found for the most productive firms, while less productive firms might experience a productivity slow-down. The positive effect found on the industry-level is most likely simply a composition effect as the least productive firms might exit the market. More stringent environmental policies might thus drive some firms out of the market and thereby create losers. The analysis also shows that market based policy instruments are better suited to reap positive effects from tightening environmental policies: by pricing the environmental externalities, firms are free to develop their own solutions in terms of processes or products to comply with the new policies. They will choose the most suitable option for them which will be most productivity friendly. Even though firms might develop new technologies in this context, this chapter is not able to answer the question whether the productivity gains actually work through induced innovation.

Chapter 2 identifies five aspects of public innovation funding which help enhancing the effectiveness of the funding in terms of supporting demonstration projects until the commercial scale. An emphasis on learnings of the demonstration projects is crucial. This might be enforced through connecting milestone payments to monitoring and reporting targets. The diffusion of the knowledge created through projects is another essential part. Sequencing based on iterative learning is also important as successful scaling up needs time. This implies however, that there is a need for rapid action for low-carbon projects: the faster they are supported, the faster these technologies will be available to the market. Lastly, the creation of a robust demand-pull is critical to provide enough certainty for firms about future market developments so that firms will actually engage in the research and innovation of new projects.

Chapter 3 shows that such an effective demand-pull effect might be created by including additional environmental criteria in the selection process of public procurement tenders: the probability of general product innovations increases for firms which won a green public procurement contract. However, there is no significant correlation found between GPP and environmental innovations. This might be related to data limitations, the sample composition, or the fact that not all environmental innovations are declared as such. The results on general innovations differ across sectors while the intensity of GPP in terms of the number of contracts won by a single firm does not seem to play a significant role. The low number of GPP awards relative to classic procurement awards, paired with the potential of GPP to trigger innovations, underlines the need to support a wider implementation of GPP. This might be achieved through more training for procurement officers, joint procurement through e.g. a central office, and next to political commitment, more financial commitment to cover potential additional costs of GPP.

Chapter 4 shows the importance of covering all emissions, i.e. also indirect emissions, in the design of emission allowance allocation mechanisms. Indirect emissions from production inputs should be taken into account in the scope of emission benchmarks as long as there are no carbon costs reflected in the inputs yet. Indirect emissions attributable to by-products should also be taken into account as long as the competing products have no carbon costs reflected yet. Properly accounting for indirect emissions in the benchmark design can thus offer mitigation incentives along the whole value chain. A level-playing field for different technologies and business models is thus provided by ensuring incentives for emissions abatement. Benchmark-based free allocation being constructed on best available technology emission intensities offers firms the freedom of choosing the production technology which is most suitable for them while keeping abatement incentives active along the whole value chain. Updating emissions benchmarks is however problematic without a properly designed updating mechanism: as long as the benchmark calculation today is linked to the allocation tomorrow, an early-action problem arises where firms might collude against developing new low-carbon technologies to keep benchmark values artificially high. Developing updating mechanisms is thus crucial to keep innovation incentives active.

The analyses provided by this thesis underline the importance of policies being well-designed in order to be effective in terms of creating innovation incentives. Especially Chapter 2 and Chapter 4 stress the design aspects of policies, arguing for learning from innovation failures, creating a robust market demand for innovations, and providing a level-playing field among businesses by comprehensively covering all relevant emissions along the value chain when implementing an emissions trading scheme.

Moreover, the analyses show the need for complementary policies. While a demand-pull policy will not pull any innovations when there are no inventions in the first place, a technology-push policy will end up seeing innovations drowning in the valley of death when there is no strong market pull mechanism. Public innovation funding, even when well designed (Chapter 2), will not be judged effective in terms of providing market scale low-carbon innovations without complementary demand-pull measures – for example pricing emissions in a credible way (Chapter 4) or creating market demand through public procurement (Chapter 3).

While well-designed and complementary environmental policies are the proposed strategy for a successful transformation towards a low-carbon economy, one crucial aspect has to be kept in mind when implementing any of the suggested environmental policies is the political economy of environmental policies. It is far from trivial to implement suggested policies in practice as often political considerations play a role. The chapters of this thesis highlight some of these political barriers: First, politicians might avoid implementing stricter environmental policies because they fear a productivity slowdown with subsequent effects on the competitiveness of the industry and eventually on employment (Chapter 1 and 4). Second, governments might not have enough technological expertise to decide which innovation projects to support with public funding and therefore should not pick winners (technology pork barrel argument of Chapter 2). Third, the political commitment to a low-carbon future of the economy might be strong on paper but not in practice when it comes to covering additional costs of green public procurement (Chapter 3). Fourth, political systems might agree on second-best policies because they require a simple majority vote while other policies might require unanimous decisions - which are often hard to reach. The European Union is an example of such a system where e.g. a carbon tax requires more commitment of political actors than changes to the European Emissions Trading Scheme. All these examples of political obstacles show how difficult it is in practice to implement first best environmental policies. A growing public interest in low-carbon policies might thus be a chance to overcome some of these barriers as politicians need the support from their voter basis.

How political economy dynamics could be used to make even more progress in the implementation of environmental policies is only one open research question at the nexus of environmental and innovation policies. More research is needed in the field of public innovation funding regarding guidelines for governments for choosing projects which need financial support. Investigating incentive design concerning the documentation of learnings is another important topic for future research. The field of green public procurement is another under-researched topic where more research is needed around the costs, the optimal design and the economic effects of accounting for environmental quality in public tenders. It is crucial to gain more understanding of which types of innovations might be induced by GPP as well as whether and to what extent GPP is able to create lead markets for new products, processes, and services. More research is also needed regarding updating mechanisms for benchmarks in emissions trading schemes to ensure long-term innovation and technology diffusion incentives.

Bibliography

Acemoglu, D., P. Aghion, and F. Zilibotti. 2006. "Distance to frontier, selection and economic growth." *Journal of the European Economic Association*, 4(1): 37–74.

Ackerberg, D., K. Caves, and G. Frazer. 2006. "Structural identification of production functions." *Mimeo*.

Aghion, P., and P. Howitt. 2006. "Joseph Schumpeter lecture: appropriate policy growth: a unifying framework." *Journal of the European Economic Association*, 4(2-3): 269–314.

Ahman, M., L. J. Nilsson, and B. Johansson., "Global climate policy and deep decarbonization of energy-intensive industries." *Climate Policy*, 17(5): 1–16.

Albrizio, S. 2016. "Does internationalization pay off when envrionmental policy tightens?" In *PhD Thesis*. ed. by S. Albrizio, Florence: European University Institute.

Albrizio, S., T. Kozluk, and V. Zipperer. 2014. "Empirical evidence on the effects of environmental policy stringency on productivity growth." *OECD Economics Department Working Papers*, 1179, OECD Publishing, Paris.

Alpay, E., S. Buccola, and J. Kerkvliet. 2002. "Productivity growth and environmental regulation in Mexian and U.S. food manufacturing." *American Journal of Agricultural Economics*, 84(4): 887–901.

Ambec, S., M. Cohen, S. Elgie, and P. Lanoie. 2013. "The Porter Hypothesis at 20: can environmental regulation enhance innovation and competitiveness?" *Review of Environmental Economic Policy*, 7(1): 2–22.

Anadon, L. D., E. Baker, V. Bosetti, and L. A. Reis., "Too Early to Pick Winners: Disagreement across Experts Implies the Need to Diversify R&D Investment." *FEEM Working Paper*, 22.

Anadon, L. D., and G. F. Nemet. 2014. "The U.S. Synthetic Fuels Corporation: Policy Consistency, Flexibility, and the Long-Term Consequences of Perceived Failures." In *Energy Technology Innovation: Learning from Historical Successes and Failures*. eds. by A. Grubler, and C. Wilson, Cambridge: Cambridge University Press, 257–273.

Andrews, D., C. Criscuolo, and C. Menon. 2014. "Do resources flow to patenting firms? Cross-country evidence from firm level data." *OECD Economics Department Working Papers*, 1127, OECD Publishing, Paris.

Appelt, S., and F. Galindo-Rueda. 2016. "Measuring the Link between Public Procurement and Innovation." *OECD Science, Technology and Industry Working Papers*, 3, OECD Publishing, Paris.

Arens, M., and M. Meister. 2016. "R&D strategies of CO2 intensive industries in an uncertain world – The case of the European iron and steel industry." *Conference Paper, International Association for Energy Economics International Conference 2016.*

Arlinghaus, J. 2015. "Impacts of Carbon Prices on Indicators of Competitiveness: A Review of Empirical Findings." *OECD Environment Working Papers*, 87, OECD Publishing, Paris.

Arthur, W. B. 2007. "The structure of invention." *Research Policy*, 36(2): 274–287.

Aschhoff, B., and W. Sofka. 2009. "Innovation on demand – Can public procurement drive market success of innovations?" *Research Policy*, 38(8): 1235–1247.

Asker, J., and E. Cantillon. 2008. "Properties of Scoring Auctions." *RAND Journal of Economics*, 39(1): 69–85.

Averch, H., and L. L. Johnson. 1962. "Behavior of the firm under regulatory constraint." *The American Economic Review*, 52(5): 1052–1069.

Baer, W. S., L. Johnson, and E. Merrow. 1976. "Analysis of Federally Funded Demonstration Projects: Final Report." The Rand Corporation, Santa Monica.

Barbera, A. J., and V. D. McConnell. 1990. "The impact of environmental regulations on industry productivity: Direct and indirect effects." *Journal of Environmental Economics and Management*, 18(1): 50–65.

Bas, M., A. Johansson, F. Murtin, and G. Nicoletti. 2016. "The effects of input tariffs on productivity: panel data evidence for OECD countries." *Review of World Economics*, 152(2): 401–424.

Bassanini, A., and R. Duval. 2009. "Unemployment, institutions, and reform complementarities: Re-assessing the aggregate evidence for OECD countries." *Oxford Review of Economic Policy*, 25(1): 40–59.

Baum, C. F. 2008. "Stata tip 63: Modeling proportions." *Stata Journal*, 8(2): 299–303.

Becker, R. 2011. "Local environmental regulation and plant-level productivity." *Ecological Economics*, 70(12): 2513–2522.

Beers, C. V., and J. V. D. Bergh. 1997. "An Empirical Multi-Country Analysis of the Impact of Environmental Regulations on Foreign Trade Flows." *Kyklos*, 50(1): 29–46.

Benhelal, E., G. Zahedi, E. Shamsaei, and A. Bahadori. 2013. "Global strategies and potentials to curb CO2 emissions in cement industry." *Journal of Cleaner Production*, 51 142–161.

Berman, E., and L. T. M. Bui. 2014. "Environmental Regulation and Productivity: Evidence From Oil Refineries." *The Review of Economics and Statistic*, 83(3): 498–510.

Bøhringer, C., and A. Lange. 2005. "On the design of optimal grandfathering schemes for emission allowances." *European Economic Review*, 49(8): 2041–2055.

Böhringer, C., K. E. Rosendahl, and H. B. Storrøsten. 2017. "Robust policies to mitigate carbon leakage." *Journal of Public Economics*, 149 35–46.

Borghesi, S., G. Cainelli, and M. Mazzanti. 2015. "Linking emission trading to environmental innovation: Evidence from the Italian manufacturing industry." *Research Policy*, 44(3): 669–683.

Borghesi, S., M. Montini, and A. Barreca. 2016. "The EU ETS: The Pioneer – Main Purpose, Structure and Features." In *The European Emission Trading System and Its Followers: Comparative Analysis and Linking Perspectives.*: Springer International Publishing.

Bossink, B. G. 2015. "Demonstration projects for diffusion of clean technological innovation: a review." *Clean Technologies and Environmental Policy*, 17(6): 1409–1427.

Botta, E., and T. Kozluk. 2014. "Measuring environmental policy stringency in OECD countries: A composite index approach." *OECD Economics Department Working Papers*, 1177, OECD Publishing, Paris.

Bourlès, R., G. Cette, J. Lopez, J. Mairesse, and G. Nicoletti. 2013. "Do product market regulations in upstream sectors curb productivity growth? Panel data evidence for OECD countries." *Review of Economics and Statistics*, 95(5): 1750–1768.

Branger, F., J.-P. Ponssard, O. Sartor, and M. Sato. 2015. "EU ETS, Free Allocations and Activity Level Thresholds: The devil lies in the detail." *Journal of the Association of Environmental and Resource Economists*, 2(3): 401–437.

Branger, F., and M. Sato. 2017. "Solving the clinker dilemma with hybrid output-based allocation." *Climatic Change*, 140(3-4): 483–501.

Brunel, C., and A. Levinson. 2016. "Measuring the Stringency of Environmental Regulations." *Review of Environmental Economics and Policy*, 10(1): 47–67.

Brunnermeier, S. B., and M. A. Cohen. 2003. "Determinants of environmental innovation in US manufacturing industries." *Journal of Environmental Economics and Management*, 45(2): 278–293.

Bush, V. 1945. "Summary of the Report to the President on a Program for Postwar Scientific Research." *Science*, 102(2639): 79–81.

Buttiens, K., J. Leroy, P. Negro, J.-S. Thomas, K. Edwards, and Y. De Lassat. 2016. “The Carbon Cost of Slag Production in the Blast Furnace: A Scientific Approach.” *Journal of Sustainable Metallurgy*, 2(1): 62–72.

Calel, R., and A. Dechezleprêtre. 2016. “Environmental policy and directed technological change: Evidence from the European carbon market.” *The Review of Economics and Statistics*, 98(1): 173–191.

California Air Resources Board. 2011. “*Appendix B*: Development of Product Benchmarks for Allowance Allocation.” Document for Public Workshop to discuss draft changes to the Greenhouse Gas Cap-and-Trade and Mandatory Greenhouse Gas Reporting Regulations. Retrieved on 2016-05-01 under http://www.arb.ca.gov/cc/capandtrade/meetings/meetings.htm.

Chen, Y., J. Sijm, B. Hobbs, and W. Lise. 2008. “Implications of CO2 emissions trading for short-run electricity market outcomes in northwest Europe.” *Journal of Regulatory Economics*, 34(3): 251–281.

Cheng, W., A. Appolloni, A. D’Amato, and Q. Zhu. 2018. “Green Public Procurement, missing concepts and future trends – A critical review.” *Journal of Cleaner Production*, 176 770–784.

Chiappinelli, O., and V. Zipperer. 2017. “Using public procurement as decarbonisation policy: a look at Germany.” *DIW Weekly Report*, 49 523–532, DIW Berlin.

Coase, R. H. 1960. “The Problem of Social Cost.” *Journal of Law and Economics*, 3 1–44.

Cohen, L. R., and R. G. Noll. 1991. *The Technology Pork Barrel.* Washington: Brookings Institutional Press.

Cohen, M., and A. Tubb. 2015. “The impact of environmental regulation on firm and country competitiveness: A meta-analysis of the Porter Hypothesis.” *Vanderbilt Owen Graduate School of Management Research Paper*, 2692919.

Cohen, W. M., A. Goto, A. Nagata, R. R. Nelson, and J. R. Walsh. 2002. “R&D spillovers, patents and the incentives to innovate in Japan and the United States.” *Research Policy*, 31(8-9): 1349–1367.

Cole, M. A., and R. J. R. Elliott. 2003. “Do Environmental Regulations Influence Trade Patterns? Testing Old and New Trade Theories.” *The World Economy*, 26(8): 1163–1186.

Crepon, B., E. Duguet, and J. Mairessec. 1998. “Research, Innovation And Productivity: An Econometric Analysis At The Firm Level.” *Economics of Innovation and New Technology*, 7(2): 115–158.

Czarnitzki, D., P. Hünermund, and N. Moshgbar. 2018. “Public Procurement as Policy Instrument for Innovation.” *ZEW Discussion Paper*, 18-001.

Dasgupta, S., E. De Cian, and E. Verdolini. 2016. "The political economy of energy innovation." *UNU-WIDER Working Paper.*

Dasgupta, S., A. Mody, S. Roy, and D. Wheeler. 1995. "Environmental regulation and development: a cross-country empirical analysis." *Policy Research Working Paper*, 1448, The World Bank.

David, P., and G. Wright. 2003. "General purpose technologies and surges in productivity: Historical reflections on the future of the ICT revolution." In *The Economic Future in Historical Perspective.* eds. by P. David, and M. Thomas: Oxford University Press for the British Academy.

De Serres, A., F. Murtin, and G. Nicoletti. 2010. "A framework for assessing green growth policies." *OECD Economics Department Working Papers*, 774, OECD Publishing.

De Vivo, N., and G. Marin. 2017. "How neutral is the choice of the allocation mechanism in cap-and-trade schemes? Evidence from the EU-ETS." *SEEDS Working Paper Series*, 04/2017.

Dechezleprêtre, A., E. Einiö, R. Martin, K.-T. Nguyen, and J. Van Reenen. 2016. "Do tax incentives for research increase firm innovation? An RD Design for R&D." *NBER Working Paper Series*, 22405.

Dechezleprêtre, A., E. Neumayer, and R. Perkins. 2015. "Environmental regulation and the cross-border diffusion of new technology: Evidence from automobile patents." *Research Policy*, 44(1): 244–257.

Demailly, D., and P. Quirion. 2006. "CO2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: grandfathering versus output-based allocation." *Climate Policy*, 6(1): 93–113.

Denis-Ryan, A., C. Bataille, and F. Jotzo. 2016. "Managing carbon-intensive materials in a decarbonizing world without a global price on carbon." *Climate Policy*, 16 1–19.

Di Stefano, G., A. Gambardella, and G. Verona. 2012. "Technology push and demand pull perspectives in innovation studies: Current findings and future research directions." *Research Policy*, 41(8): 1283–1295.

Dosi, G., L. Marengo, and C. Pasquali. 2006. "How much should society fuel the greed of innovators?: On the relations between appropriability, opportunities and rates of innovation." *Research Policy*, 35(8): 1110–1121.

Dufour, C., P. Lanoie, and M. Patry. 1998. "Regulation and productivity." *Journal of Productivity Analysis*, 9 233–247.

EBRD. 2011. "Political economy of climate change policy in the transition region." In *Special Report on Climate Change: The Low Carbon Transition.* EBRD Publishing.

Edler, J., and L. Georghiou. 2007. “Public procurement and innovation - Resurrecting the demand side.” *Research Policy*, 36(7): 949–963.

Eichhammer, W., N. Friedrichsen, S. Healy, and K. Schumacher. 2018. “Impacts of the Allocation Mechanism Under the Third Phase of the European Emission Trading Scheme.” *Energies*, 11(6): 1–23.

Ellerman, A., F. Convery, and C. De Perthuis. 2010. *Pricing carbon: The European Union Emissions Trading Scheme.* Cambridge: Cambridge University Press.

Environmental Protection Agency, C. 2010. “Appendix J: Notice of public hearing to consider the adoption of a proposed California cap on greenhouse gas emissions and market-based compliance mechanisms regulation, including compliance offset protocols.” Retrieved on 2017-07-17 under: https://www.arb.ca.gov/regact/2010/capandtrade10/capv4appj.pdf.

EPA. 2009. *Technical support document for the iron and steel sector: Proposed rule for mandatory reporting of greenhouse gases.* U.S. Environmental Protection Agency, Office of Air and Radiation.

European Commission. 2011. “Commission Decision of 27 April 2011 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council.” *Official Journal of the European Union*, 2011/278/EU(L-130): 1–45.

European Commission. 2017a. “Commission delegated regulation (EU) 2017/2365 of 18 December 2017.” *Official Journal of the European Union*, L 337/19.

European Commission. 2017b. “Communication from the Commission to the European parliament, the council, the European economic and social committee and the committee of the regions. Making Public Procurement work in and for Europe.” COM(2017)5 1–14, European Commission.

Fabra, N., and M. Reguant. 2014. “Pass-Through of Emissions Costs in Electricity Markets.” *American Economic Review*, 104(9): 2872–2899.

Finon, D. 2012. “Efficiency of policy instruments for CCS deployment.” *Climate Policy*, 12(2): 237–254.

Fischer, C. 2001. “Rebating environmental policy revenues: output based allocations and tradable performance standards.” *RFF Discussion paper*, 1–22, Resources for the Future, Washington.

Fischer, C., and A. K. Fox. 2012. “Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates.” *Journal of Environmental Economics and Management*, 64(2): 199–216.

Fischer, C., and A. Fox. 2007. “Output based allocation of emissions permits for mitigation tax and trade interactions.” *Land Economics*, 83 575–599.

Flues, F., and K. v. Dender. 2017. "Permit allocation rules and investment incentives in emissions trading systems." *OECD Taxation Working Papers*, 33, OECD Publishing, Paris.

Fowlie, M., and J. M. Perloff. 2013. "Distributing Pollution Rights in Cap-and-Trade Programs: Are Outcomes Independent of Allocation?" *Review of Economics and Statistics*, 95 1640–1652.

Foxon, T. J. 2010. "Stimulating investment in energy materials and technologies to combat climate change: an overview of learning curve analysis and niche market support." *Philosophical Transactions of the Royal Society A*, 368(1923): 3469–3483.

Franco, C., and G. Marin. 2017. "The Effect of Within-Sector, Upstream and Downstream Environmental Taxes on Innovation and Productivity." *Environmental and Resource Economics*, 66(2): 261–291.

Freeman, C. 1974. *The economics of industrial innovation.* Cambridge, MA: The MIT Press.

Frishammar, J., P. Söderholm, K. Bäckström, H. Hellsmark, and H. Ylinenpää. 2015. "The role of pilot and demonstration plants in technological development: synthesis and directions for future research." *Technology Analysis & Strategic Management*, 27(1): 1–18.

Funk, J. L. 2013. "What Drives Exponential Improvements?" *California Management Review*, 55(3): 134–152.

Gal, P. N. 2013. "Measuring total factor productivity at the firm level using OECD-ORBIS." *OECD Economics Department Working Papers*, 1049, OECD Publishing.

Gal, P., and A. Theising. 2015. "The macroeconomic impact of structural policies on labour market outcomes in OECD countries: A re-assessment." *OECD Economics Department Working Papers*, 1271, OECD Publishing.

Gallagher, K. S., J. P. Holdren, and A. D. Sagar. 2006. "Energy-Technology Innovation." *Annual Review of Environment and Resources*, 31(1): 193–237.

Garud, R., and P. Karnoe. 2003. "Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship." *Research Policy*, 32(2): 277–300.

Gault, F. 2013. *Handbook of innovation indicators and measurement.* Cheltenham: Edward Elgar Publishing.

Geels, F., F. Berkhout, and D. v. Vuuren. 2016. "Bridging analytical approaches for low-carbon transitions." *Nature Climate Change*, 6 576–583.

Geroski, P. A. 1990. "Procurement policy as a tool of industrial policy." *International Review of Applied Economics*, 4(2): 182–198.

GHG Protocol. 2004a. "A Corporate Accounting and Reporting Standard." The Greenhouse Gas Protocol. Retrieved on 2018-11-21 under: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf.

GHG Protocol. 2004b. "Corporate Value Chain (Scope 3) Accounting and Reporting Standard." The Greenhouse Gas Protocol. Retrieved on 2018-11-21 under http://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard-EReader_041613_0.pdf.

Ghisetti, C. 2017. "Demand-pull and environmental innovations: Estimating the effects of innovative public procurement." *Technological Forecasting and Social Change*, 125(July): 178–187.

Gipe, P. 1995. *Wind energy comes of age.* New York: Wiley.

Godin, B., and J. P. Lane. 2013. "Pushes and Pulls: Hi(S)tory of the Demand Pull Model of Innovation." *Science, Technology & Human Values*, 38(5): 621–654.

Gollop, F., and M. Roberts. 1983. "Environmental regulation and productivity growth: the case of fossil-fueled electric power generation." *Journal of Political Economy*, 91(4): 654–674.

Gordon, R. J. 2012. "Is U.S. economic growth over? Faltering innovaiton confronts the six headwinds." *NBER Working Paper Series*, 18315.

Goulder, L., and I. Parry. 2008. "Instrument Choice in Environmental Policy." *Review of Environmental Economics and Policy*, 2(2): 152–174.

Gray, W. B. 1987. "The cost of regulation: OSHA, EPA and the productivity slowdown." *The American Economic Review*, 77(5): 998–1006.

Gray, W. B. 1997. "Manufacturing plant location: Does state pollution regulation matter?" *NBER Working Paper Series*, 5880.

Gray, W. B., and R. J. Shadbegian. 2003. "Plant vintage, technology, and environmental regulation." *Journal of Environmental Economics and Management*, 46(3): 384–402.

Greenstone, M., J. A. List, and C. Syverson. 2012. "The effects of environmental regulation on th ecompetitiveness of U.S. manufacturing." *NBER Working Paper Series*, 18392.

Griffith, R., E. Huergo, J. Mairesse, and B. Peters. 2006. "Innovation and productivity across four European countries." *Oxford Review of Economic Policy*, 22(4): 483–498.

Grubler, A., and G. F. Nemet. 2014. "Sources and Consequences of Knowledge Depreciation." In *Energy Technology Innovation: Learning from Historical Successes and Failures.* eds. by A. Grubler, and C. Wilson, Cambridge: Cambridge University Press, 133–145.

Grubler, A., and C. Wilson. 2014. *Energy Technology Innovation: Learning from Historical Successes and Failures.* Cambridge: Cambridge University Press.

Hahn, R. W. 1984. "Market Power and Transferable Property Rights." *Quarterly Journal of Economics*, 99 753–765.

Hall, B. H., J. Mairesse, and P. Mohnen. 2009. "Measuring the Returns to R&D." *NBER Working Paper Series*, 15622.

Hamamoto, M. 2006. "Environmental regulation and the productivity of Japanese manufacturing industries." *Resource and Energy Economics*, 28(4): 299–312.

Harborne, P., and C. Hendry. 2009. "Pathways to commercial wind power in the US, Europe and Japan: The role of demonstration projects and field trials in the innovation process." *Energy Policy*, 37(9): 3580–3595.

Harris, M. N., L. Kónya, and L. Mátyás. 2002. "Modelling the impact of environmental regulations on bilateral trade flows: OECD, 1990-1996." *World Economy*, 25(3): 387–405.

Hellsmark, H., "Unfolding the formative phase of gasified biomass in the European Union." In *PhD Thesis*. ed. by H. Hellsmark: Chalmers University of Technology.

Hendry, C., and P. Harborne. 2011. "Changing the view of wind power development: More than "bricolage"." *Research Policy*, 40(5): 778–789.

Hendry, C., P. Harborne, and J. Brown. 2010. "So what do innovating companies really get from publicly funded demonstration projects and trials? Innovation lessons from solar photovoltaics and wind." *Energy Policy*, 38(8): 4507–4519.

Herzog, H. 2016. "Lessons Learned from CCS Demonstration and Large Pilot Projects." *MIT Energy Initiative Working Paper*, Massachusetts Institute of Technology.

Herzog, H. J. 2011. "Scaling up carbon dioxide capture and storage: From megatons to gigatons." *Energy Economics*, 33(4): 597–604.

Horbach, J., C. Rammer, and K. Rennings. 2012. "Determinants of eco-innovations by type of environmental impact – The role of regulatory push/pull, technology push and market pull." *Ecological Economics*, 78 112–122.

Hotelling, H. 1931. "The Economics of Exhaustible Resources." *Journal of Political Economy*, 39.

Hurmelinna-Laukkanen, P., L. M. Sainio, and T. Jauhiainen. 2008. "Appropriability regime for radical and incremental innovations." *R&D Management*, 38(3): 278–289.

ICAP. 2016a. "Emissions Trading Worldwide – ICAP Status Report." International Carbon Action Partnership.

ICAP. 2016b. "Korea Emissions Trading Scheme, Factsheet." International Carbon Action Partnership. Retrieved on 2016-02-01 under: http://icapcarbonaction.com/en/ets-map.

ICAP. 2018. “Emissions Trading Worldwide – ICAP Status Report.” International Carbon Action Partnership.

IEA. 2014. “Energy Technology Perspectives 2014: Harnessing Electricity’s Potential.” International Energy Agency.

IEA/UNIDO. 2011. “Technology Roadmap Carbon Capture and Storage in Industrial Applications.” *International Energy Agency, and United Nations Industrial Development Organizations.*

IPCC. 2018. “Summary for Policymakers.” In *Global Warming of 1.5 C. An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* eds. by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. Matthews, Y. Chen, X. Zhou, M. Gomis, E. Lonnoy, M. T. Maycock, and T. Waterfield: World Meteorological Organization, Geneva, Switzerland.

Ismer, R., M. Haussner, K. Neuhoff, and W. Acworth. 2016. “Inclusion of Consumption into Emissions Trading Systems: Legal Design and Practical Administration.” *DIW Discussion Paper*, 1579, DIW Berlin.

Iyer, G., N. Hultman, J. Eom, H. McJeon, P. Patel, and L. Clarke. 2015. “Diffusion of low-carbon technologies and the feasibility of long-term climate targets.” *Technological Forecasting and Social Change*, 90(Part A): 103–118.

Jaffe, A. B., R. Newell, and R. N. Stavins. 2002. “Environmental Policy and Technological Change.” *Environmental and Resource Economics*, 22(1-2): 41–70.

Jaffe, A. B., and K. Palmer. 1997. “Environmental regulation and innovation: A panel data study.” *Review of Economics and Statistics*, 79(4): 610–619.

Javorcik, B. S., and Shang-Jin Wei. 2004. “Pollution Havens and Foreign Direct Investment: Dirty Secret or Popular Myth?” *The B.E. Journal of Economic Analysis & Policy*, 3.

Johansson, A., Y. Guillemette, F. Murtin, D. Turner, G. Nicoletti, C. De la Maisonneuve, P. Bagnoli, G. Bousquet, and F. Spinelli. 2012. “Long-term growth scenarios.” *OECD Economic Department Working Papers*, 1000, OECD Publishing, Paris.

Johnstone, N., I. Hascic, and M. Kalamova. 2010. “Environmental policy design characteristics and technological innovation: Evidence from patent data.” *OECD Environment Working Papers*, 16, OECD Publishing, Paris.

Johnstone, N., and J. Labonne. 2006. “Environmental policy, management and R&D.” *OECD Economic Studies*, 42(1): 169–203.

Kahneman, D., J. Knetsch, and R. Thaler. 1991. "Anomalies: The Endowment Effect, Loss Aversion, and Status Quo Bias." *Journal of Economic Perspectives*, 5 193–206.

Kalamova, M., and N. Johnstone. 2011. "Environmental policy stringency and foreign direct investment." *OECD Environment Working Papers*, 33, OECD Publishing, Paris.

Karlsson, R. 2016. "Apres Paris: Breakthrough innovation as the primary moral obligation of rich countries." *Environmental Science and Policy*, 63 170–176.

Katsoulacos, Y., and A. Xepapadeas. 1996. "Environmental Innovation, Spillovers and Optimal Policy Rules." In *Environmental Policy and Market Structure*. eds. by C. Carraro, Y. Katsoulacos, and A. Xepapadeas, Dordrecht: Kluwer Academic Publishers, 143–150.

Kemp, R., J. Schot, and R. Hoogma. 1998. "Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management." *Technology analysis & strategic management*, 10(2): 175–198.

Kingsley, G., B. Bozeman, and K. Coker. 1996. "Technology transfer and absorption: an 'R&D value-mapping' approach to evaluation." *Research Policy*, 25(6): 967–995.

Klitkou, A., L. Coenen, P. Dannemand Andersen, A. Fevolden, T. Hansen, A. Nikoleris, and D. S. Olsen. 2013. "Role of demonstration projects in innovation: transition to sustainable energy and transport." In *4th International Conference on Sustainability Transitions, Zurich.*

Koch, N., G. Grosjean, S. Fuss, and O. Edenhofer. 2016. "Politics Matters: Regulatory Events as Catalysts for Price Formation Under Cap-and-Trade." *Journal of Environmental Economics and Management*, 78 121–139.

Kozluk, T., and V. Zipperer. 2014. "Environmental policies and productivity growth." *OECD Journal: Economic Studies*, 2014(1): 155–185.

Krause, R. M., S. R. Carley, D. C. Warren, J. A. Rupp, and J. D. Graham. 2014. ""Not in (or Under) My Backyard": Geographic Proximity and Public Acceptance of Carbon Capture and Storage Facilities." *Risk Analysis*, 3 529–40.

Krautkraemer, J. A. 1998. "Non-renewable resource scarcity." *Journal of Economic Literature*, 36(4): 2065–2107.

Kronenberg, J., and R. Winkler. 2009. "Wasted Waste: An Evolutionary Perspective on Industrial By-Products." *Ecological Economics*, 68(12): 3026–3033.

Lanoie, P., J. Laurent-Lucchetti, N. Johnstone, and S. Ambec. 2011. "Environmental policy, innovation and performance: New insights on the Porter Hypothesis." *Journal of Economics and Management Strategy*, 20(3): 803–842.

Lanoie, P., M. Patry, and R. Lajeunesse. 2008. "Environmental regulation and productivity: Testing the Porter hypothesis." *Journal of Productivity Analysis*, 30(2): 121–128.

Lefevre, S. R. 1984. "Using demonstration projects to advance innovation in energy." *Public Administration Review*, 44(6): 483–490.

Lehne, J., and F. Preston. 2018. *Making Concrete Change Innovation in Low carbon Cement and Concrete.* Chatham House Report.

Levinsohn, J., and A. Petrin. 2003. "Estimating Production Functions Using Inputs to Control for Unobservables." *Review of Economic Studies*, 70(2): 317–341.

Levinson, A., and S. Taylor. 2008. "Unmasking the pollution haven effect." *International Economic Review*, 49(1): 223–254.

Lotker, M. 1991. "Barriers to Commercialization of Large-Scale Solar Electricity: Lessons Learned from the LUZ Experience." Contractor Report SAND91-7014, Sandia National Laboratories.

Lundberg, S., P.-O. Marklund, and R. Brännlund. 2011. "Assessment of Green Public Procurement as a Policy Tool: Cost-Efficiency and Competition Considerations." *SSRN Electronic Journal.*

Lundberg, S., P. O. Marklund, E. Strömbäck, and D. Sundström. 2015. "Using public procurement to implement environmental policy: an empirical analysis." *Environmental Economics and Policy Studies*, 17(4): 487–520.

Lupion, M., and H. J. Herzog. 2013. "NER300: Lessons learnt in attempting to secure CCS projects in Europe." *International Journal of Greenhouse Gas Control*, 19 19–25.

Lyubich, E., J. S. Shapiro, and R. Walker. 2018. "Regulating Mismeasured Pollution: Implications of Firm Heterogeneity for Environmental Policy." *NBER Working Paper*, 24228.

Macey, S. M., and M. A. Brown. 1990. "Demonstrations as a Policy Instrument With Energy Technology Examples." *Science Communication*, 11(3): 219–236.

Marion, J. 2007. "Are bid preferences benign? The effect of small business subsidies in highway procurement auctions." *Journal of Public Economics*, 91(7-8): 1591–1624.

Markusson, N., A. Ishii, and J. C. Stephens. 2011. "The social and political complexities of learning in carbon capture and storage demonstration projects." *Global Environmental Change*, 21(2): 293–302.

Markusson, N., F. Kern, J. Watson, S. Arapostathis, H. Chalmers, N. Ghaleigh, P. Heptonstall, P. Pearson, D. Rossati, and S. Russell. 2012. "A socio-technical framework for assessing the viability of carbon capture and storage technology." *Technological Forecasting and Social Change*, 79(5): 903–918.

Martin, R., M. Muuls, and U. Wagner. 2014. "Trading Behavior in the EU Emissions Trading Scheme." *SSRN Electronic Journal*, Available at SSRN: https://ssrn.com/abstract=2362810.

Mcconnell, V. D., and R. M. Schwab. 1990. "The impact of environmental regulation on industry location decisions: The motor vehicle industry." *Land Economics*, 66(1): 67–81.

Mertens, K., and M. O. Ravn. 2012. "Empirical evidence on the aggregate effects of anticipated and unanticipated US tax policy shocsk." *American Economic Journal: Economic Policy*, 4.

Meunier, G., J.-P. Ponssard, and P. Quirion. 2014. "Carbon Leakage and Capacity-Based Allocations. Is the EU right?" *Journal of Environmental Economics and Management*, 68(2): 262–279.

Milford, J. A., R.L., and J. Cullen. 2011. "Assessing the potential of yield improvements, through process scrap reduction, for energy and CO2 abatement in the steel and aluminium sectors." *Resources, Conservation and Recycling*, 55(12): 1185–1195.

Ministry for the Environment, N. Z. 2002. "Climate Change Response Act 2002." Retrieved on 2017-07-17 under http://www.legislation.govt.nz/act/public/2002/0040/latest/whole.html?search=qs_act%40bill%40regulation%40deemedreg_climate+change+response_resel_25_h&p=1#DLM1662644.

Montgomery, W. 1972. "Markets in licenses and efficient pollution control programs." *Journal of Economic Theory*, 5(3): 395–418.

Morgenstern, R. D., W. A. Pizer, and J. S. Shih. 2002. "Jobs versus the environment: An industry-level perspective." *Journal of Environmental Economics and Management*, 43(3): 412–436.

Mowery, D. C. 1998. "The changing structure of the US national innovation system: implications for international conflict and cooperation in R&D policy." *Research Policy*, 27(6): 639–654.

Mowery, D. C., and N. Rosenberg. 1979. "The influence of market demand upon innovation: a critical review of some recent empirical studies." *Research Policy*, 8(2): 102–153.

Mundlak, Y. 1978. "On the Pooling of Time Series and Cross Section Data." *Econometrica*, 46(1): 69–85.

Munnings, C., W. Acworth, O. Sartor, Y.-G. Kim, and K. Neuhoff. 2016. "Pricing Carbon Consumption." *RFF Discussion Papers*, 16–49, Resources for the Future.

Murphy, L. M., and P. L. Edwards. 2003. "Bridging the Valley of Death: Transitioning from Public to Private Sector Financing." Report NREL/MP-720-34036, National Renewable Energy Laboratory.

Nemet, G. F. 2009. "Demand-pull, technology-push, and government-led incentives for non-incremental technical change." *Research Policy*, 38(5): 700–709.

Nemet, G. F. 2010. "Robust incentives and the design of a climate change governance regime." *Energy Policy*, 38(11): 7216–7225.

Nemet, G. F. 2014. "Technological Improvements in Solar Thermal Electricity in the United States and the Role of Public Policy." In *Energy Technology Innovation: Learning from Historical Successes and Failures*. eds. by A. Grubler, and C. Wilson, Cambridge: Cambridge University Press, 165–177.

Nemet, G. F., E. Baker, B. Barron, and S. Harms. 2015. "Characterizing uncertainty in the effects of policy instruments on the future costs of carbon capture." *Climatic Change*, 133(2): 155–168.

Nemet, G. F., E. Baker, and K. E. Jenni. 2013. "Modeling the future costs of carbon capture using experts' elicited probabilities under policy scenarios." *Energy*, 56 218–228.

Nemet, G. F., P. Braden, E. Cubero, and B. Rimal. 2014. "Four decades of multiyear targets in energy policy: aspirations or credible commitments?" *Wiley Interdisciplinary Reviews: Energy and Environment*, 3(5): 522–533.

Nemet, G. F., M. Jakob, J. C. Steckel, and O. Edenhofer. 2017. "Addressing policy credibility problems for low-carbon investment." *Global Environmental Change*, 42 47–57.

Nemet, G. F., V. Zipperer, and M. Kraus. 2018. "The valley of death, the technology pork barrel, and public support for large demonstration projects." *Energy Policy*, 119 154–167.

Neuhoff, K., R. Ismer, W. Acworth, A. Ancygier, C. Fischer, M. Haussner, H.-L. Kangas, Y.-G. Kim, C. Munnings, A. Owen, S. Pauliuk, O. Sartor, M. Sato, J. Stede, T. Sterner, M. Tervooren, R. Tusveld, R. Wood, Z. Xiliang, L. Zetterberg, and V. Zipperer. 2016. "Inclusion of Consumption of carbon intensive materials in emissions trading – An option for carbon pricing post-2020." *Climate Strategies Report*, May 2016.

Neuhoff, K., K. Martinez, and M. Sato. 2006. "Allocation, incentives and distortions: the impact of EU ETS emissions allowance allocations to the electricity sector." *Climate Policy*, 6(1): 73–91.

Neuhoff, K., B. Vanderborght, A. Ancygier, A. T. Atasoy, M. Haussner, R. Ismer, B. Mack, J.-P. Ponssard, P. Quirion, A. Van Rooij, N. Sabio, O. Sartor, M. Sato, and A. Schopp. 2014. "Carbon Control and Competitiveness Post 2020: The Cement Report." *Climate Strategies Report*, February 2014.

Neuhoff, K., A. Ancygier, J.-P. Ponssard, P. Quirion, N. Sabio, O. Sartor, M. Sato, and A. Schopp. 2015. "Modernization and Innovation in the Materials Sector: Lessons from Steel and Cement." *DIW Berlin Report*.

Nicoletti, G., and S. Scarpetta. 2003. "Regulation, productivity and growth: OECD evidence." *Policy Research Working Paper*, 2944, The World Bank.

OECD. 2015. *Greening Steel: Innovation for Climate Change Mitigation in the Steel Sector*. Paris: OECD Publishing.

OECD. 2017. *Government at a Glance 2017*. Paris: OECD Publishing.

OECD/Eurostat. 2005. *Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data, 3rd Edition: The Measurement of Scientific and Technological Activities*. Paris: OECD Publishing.

Papke, L. E., and J. Wooldridge. 1996. "Econometric methods for fractional response variables with an application to 401(k) plan participation rates." *Journal of Applied Econometrics*, 11(6): 619–632.

Pauliuk, R. M. D. M., S., and J. Allwood. 2013. "The Steel Scrap Age." *Environmental Science and Technology*, 47(7): 3448–3454.

Pavitt, K. 1984. "Sectoral Patterns of Technical Change – Towards a Taxonomy and a Theory." *Research Policy*, 13(6): 343–373.

Peters, B., and C. Rammer. 2013. "Innovation panel surveys in Germany." In *Handbook of Innovation Indicators and Measurement*. ed. by F. Gault: Edward Elgar Publishing, 135–177.

Peters, M., M. Schneider, T. Griesshaber, and V. H. Hoffmann. 2012. "The impact of technology-push and demand-pull policies on technical change – Does the locus of policies matter?" *Research Policy*, 41(8): 1296–1308.

Popp, D. 2015. "Using scientific publications to evaluate government R&D spending: The case of energy." *NBER Working Paper Series*, 21415.

Porter, M. E. 1991. "America's green strategy." *Scientific American*, 264.

Porter, M. E., and C. V. D. Linde. 1995. "Toward a New Conception of the Environment-Competitiveness Relationship." *The Journal of Economic Perspectives*, 9(4): 97–118.

Qing, T. 2015. "Beijing Pilot ETS: Allowance Allocations, Benchmarks and Incorporation of Consumption." Presentation given at International Workshop on Benchmarking, hosted by KEI and DIW Berlin, Seoul, 1.-2. October 2015. Retrieved on 2017-07-17 under http://www.diw.de/sixcms/detail.php?id=diw_01.c.517429.en.

Quirion, P. 2009. "Historic versus output-based allocation of GHG tradable allowances: a comparison." *Climate Policy*, 9(6): 575–592.

Rai, V., D. G. Victor, and M. C. Thurber. 2010. "Carbon capture and storage at scale: Lessons from the growth of analogous energy technologies." *Energy Policy*, 38(8): 4089–4098.

Rajan, R. G., and L. Zingales. 1998. “Financial dependence and growth.” *The American Economic Review*, 88(3): 559–586.

Reguant, M., and D. Ellerman. 2008. “Grandfathering and the Endowment Effect: An Assessment in the Context of the Spanish National Allocation Plan.” *MIT CEEPR Working Paper*, 08-018, Massachusetts Institute of Technology.

Reiner, D. M. 2015. “Where can I go to see one? Risk communications for an ‘imaginary technology’.” *Journal of Risk Research*, 18(6): 710–713.

Reiner, D. M. 2016. “Learning through a portfolio of carbon capture and storage demonstration projects.” *Nature Energy*, 1.

Rennings, K. 2000. “Redefining innovation - Eco-innovation research and the contribution from ecological economics.” *Ecological Economics*, 32(2): 319–332.

Rietbergen, M., and K. Blok. 2013. “Assessing the potential impact of the CO2 Performance Ladder on the reduction of carbon dioxide emissions in the Netherlands.” *Journal of Cleaner Production*, 52 33–45.

Rogelj, J., M. Schaeffer, M. Meinshausen, R. Knutti, J. Alcamo, K. Riahi, and W. Hare. 2015. “Zero emission targets as long-term global goals for climate protection.” *Environmental Research Letters*, 10.

Rosenberg, N., and W. E. Steinmueller. 2013. “Engineering knowledge.” *Industrial and Corporate Change*, 22(5): 1129–1158.

Rosendahl, K. 2008. “Incentives and prices in an emissions trading scheme with updating.” *Journal of Environmental Economics and Management*, 56(1): 69–82.

Rosendahl, K., and H. Storrøsten. 2015. “Allocation of emission allowances: impacts on technology investments.” *Climate Change Economics*, 6.

Rubashkina, Y., M. Galeotti, and E. Verdolini. 2015. “Environmental regulation and competitiveness: Empirical evidence on the Porter Hypothesis from European manufacturing sectors.” *Energy Policy*, 83 288–300.

Russell, S., N. Markusson, and V. Scott. 2012. “What will CCS demonstrations demonstrate?” *Mitigation and Adaptation Strategies for Global Change*, 17(6): 651–668.

Sahal, D. 1985. “Technological guideposts and innovation avenues.” *Research Policy*, 14(2): 61–82.

Sanchez, D. L., and D. M. Kammen. 2016. “A commercialization strategy for carbon-negative energy.” *Nature Energy*, 1.

Sartor, O., C. Pallière, and S. Lecourt. 2014. “Benchmark-based allocations in EU ETS Phase 3: an early assessment.” *Climate Policy*, 14(4): 507–524.

Scarpellini, S., A. Aranda, J. Aranda, E. Llera, and M. Marco. 2012. "R&D and eco-innovation: opportunities for closer collaboration between universities and companies through technology centers." *Clean Technologies and Environmental Policy*, 14(6): 1047–1058.

Schmookler, J. 1962. "Economic Sources of Inventive Activity." *Journal of Economic History*, 22(1): 1–20.

Schreuer, A., M. Ornetzeder, and H. Rohracher. 2010. "Negotiating the local embedding of socio-technical experiments: a case study in fuel cell technology." *Technology Analysis & Strategic Management*, 22(6): 729–743.

Schumpeter, J. A. 1947. *Capitalism, socialism, and democracy.* New York, London: Harper.

Shackley, S., and M. Thompson. 2012. "Lost in the mix: will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables?" *Climatic Change*, 110(1): 101–121.

Sheshinski, E. 1967. "Tests of the Learning by Doing Hypothesis." *Review of Economics and Statistics*, 49(4): 568–578.

Siitonen, S., M. Tuomaala, and P. Ahtila. 2010. "Variables affecting energy efficiency and CO2 emissions in the steel industry." *Energy Policy*, 38(5): 2477–2485.

Sijm, J. P. M., K. Neuhoff, and Y. Chen. 2006. "CO2 cost pass-through and windfall profits in the power sector." *Climate Policy*, 6(1): 49–72.

Simcoe, T., and M. W. Toffel. 2014. "Government green procurement spillovers: Evidence from municipal building policies in California." *Journal of Environmental Economics and Management*, 68(3): 411–434.

Sivaram, V., and T. Norris. 2016. "The Clean Energy Revolution." *Foreign Affairs*, 95.

Skelton, J. A., A.C.H. 2017. "The carbon price: a toothless tool for material efficiency?" *Philosophical Transactions of the Royal Society A*, 375.

Slavtchev, V., and S. Wiederhold. 2016. "Does the Technological Content of Government Purchases Matter for Private-Sector R&D? Theory and Evidence from US States." *American Economic Journal: Macroeconomics*, 8(2): 45–84.

Smith, J., and W. Sims. 1985. "The Impact of Pollution Charges on Productivity Growth in Canadian Brewing." *RAND Journal of Economics*, 16(3): 410–423.

Spath, P., and H. Rohracher. 2010. "'Energy regions': The transformative power of regional discourses on socio-technical futures." *Research Policy*, 39(4): 449–458.

Stavins, R. N. 1995. "Transaction Costs and Tradeable Permits." *Journal of Environmental Economics and Management*, 29 133–148.

Stenqvist, C., and M. Åhman. 2016. "Free allocation in the 3rd EU ETS period: assessing two manufacturing sectors." *Climate Policy*, 16(2): 125–144.

Sterner, T., and A. Muller. 2008. "Output and abatement effects of allocation readjustment in permit trade." *Climate Change*, 86(1): 33–49.

Sun, H., Q. Zhi, Y. Wang, Q. Yao, and J. Su. 2014. "China's solar photovoltaic industry development: The status quo, problems and approaches." *Applied Energy*, 118 221–230.

Taylor, M., G. Nemet, M. Colvin, L. Begley, C. Wadia, and T. Dillavou. 2007. "Government Actions and Innovation in Clean Energy Technologies: The Cases of Photovoltaic Cells, Solar Thermal Electric Power, and Solar Water Heating, CEC-500-2007-012." PIER project report, California Energy Commission.

Taylor, M. R., E. S. Rubin, and D. A. Hounshell. 2003. "Effect of Government Actions on Technological Innovation for SO_2 Control." *Environmental Science & Technology*, 37(20): 4527–4534.

TED. 2019. "Tenders Electronic Daily csv dataset 2006-2017." *Supplement to the Official Journal of the European Union*, European Commission.

Teece, D. J. 1986. "Profiting from Technological Innovation – Implications for Integration, Collaboration, Licensing and Public-Policy." *Research Policy*, 15(6): 285–305.

Testa, F., E. Annunziata, F. Iraldo, and M. Frey. 2014. "Drawbacks and opportunities of green public procurement: An effective tool for sustainable production." *Journal of Cleaner Production*, 112 1893–1900.

Testa, F., F. Iraldo, and M. Frey. 2011. "The effect of environmental regulation on firms' competitive performance: The case of the building & construction sector in some EU regions." *Journal of Environmental Management*, 92(9): 2136–2144.

Testa, F., F. Iraldo, M. Frey, and T. Daddi. 2012. "What factors influence the uptake of GPP (green public procurement) practices? New evidence from an Italian survey." *Ecological Economics*, 82 88–96.

UNEP. 2017. *Global Review of Sustainable Public Procurement: 2017.* United Nations Environment Programme, Nairobi.

UNEP. 2018. *The Emissions Gap Report 2018.* United Nations Environment Programme, Nairobi.

Usher, A. P. 1954. *A History of Mechanical Inventions.* Cambridge, MA: Harvard University Press.

Usher, W., and N. Strachan. 2013. "An expert elicitation of climate, energy and economic uncertainties." *Energy Policy*, 61 811–821.

Vargo, D. 1974. "Wind Energy Development in the 20th Century." NASA Technical Memorandum TM X-71634, NASA, Lewis Research Center.

Verhoeven, D., J. Bakker, and R. Veugelers. 2016. "Measuring technological novelty with patent-based indicators." *Research Policy*, 45(3): 707–723.

Veugelers, R. 2012. "Which policy instruments to induce clean innovating?" *Research Policy*, 41(10): 1770–1778.

Watson, J. 2008. "Setting Priorities in Energy Innovation Policy: Lessons for the UK." *Harvard University, Belfer Center.*

Weimer, D. L., and A. Vining. 2015. "Chapter 8: Limits to Government Intervention: Government Failures." In *Policy analysis: Concepts and practice.* Routledge.

Weyant, J. P. 2011. "Accelerating the development and diffusion of new energy technologies: Beyond the "valley of death"." *Energy Economics*, 33(4): 674–682.

Wilson, C. 2012. "Up-scaling, formative phases, and learning in the historical diffusion of energy technologies." *Energy Policy*, 50 81–94.

Woertler, M., F. Schuler, N. Voigt, T. Schmidt, P. Dahlmann, H. B. Lüngen, and J.-T. Ghenda. 2013. *Steel's Contribution to a Low-carbon Europe 2050: Technical and Economic Analysis of the Sector's CO2 Abatement Potential.*: Boston Consulting Group.

Wooldridge, J. M. 2009. "On estimating firm-level production functions using proxy variables to control for unobservables." *Economics Letters*, 104(3): 112–114.

Wright, T. P. 1936. "Factors affecting the costs of airplanes." *Journal of the Aeronautical Sciences*, 3 122–128.

Wu, Y., and B. Wand. 2008. "Environmental regulation and total factor productivity growth: an empirical study of the APEC economies." *Economic Resources*, 43(5): 19–33.

Yang, C. H., Y. H. Tseng, and C. P. Chen. 2012. "Environmental regulations, induced R&D, and productivity: Evidence from Taiwan's manufacturing industries." *Resource and Energy Economics*, 34(4): 514–532.

Yörük, B., and O. Zaim. 2005. "Productivity growth in OECD countries: A comparison with Malmquist indices." *Journal of Comparative Economics*, 33(2): 401–420.

Zaklan, A. 2016. "Free allocation and the endowment effect in cap-and-trade systems: Evidence from the European electricity sector." *Conference paper: Beitraege zur VfS-Jahrestagung 2016.*

Zaklan, A., J. Abrell, and A. Neumann. 2016. "Stationarity Changes in Long-Run Fossil Resource Prices: Evidence from Persistence Break Testing." *Energy Economics*, 59 96–103.

Zetterberg, L. 2014. "Benchmarking in the European Union Emissions Trading System: Abatement incentives." *Energy Economics*, 43 218–224.

Zhou, Y., G. N. Xu, T. Minshall, and P. Liu. 2015. "How do Public Demonstration Projects Promote Green-Manufacturing Technologies? A Case Study from China." *Sustainable Development*, 23(4): 217–231.

List of Figures

List of Tables