Universitat Autònoma de Barcelona

Achieving sustainability transitions: Behavioral barriers, limits to green growth, and investments under uncertainty

Ardjan Gazheli

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Table of contents

Preface

I would like to express my appreciation and gratitude to my supervisor Jeroen van den Bergh. Without his help, supervision, knowledge and patience I wouldn't have been able to write this thesis. I thank him for encouraging my research and for allowing me to grow professionally in this field. His ideas, advice, guidance and feedback in this research have been priceless. A special thanks goes also to my second supervisor, Dr. Miklós Antal, especially for the help given during the first two years of my research. I would also like to thank the members of the evaluation committee for the time devoted to my thesis.

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Ardjan Gazheli Barcelona, 30 August 2016

Summary

It is widely agreed that a transition to sustainability is urgently needed. How to make such a transition is strongly debated. It is clear, though, that it will involve radical, large-scale socio-technical changes that go well beyond traditional policy approaches. This PhD thesis addresses this challenge through three distinct, complementary studies.

The first is motivated by the fact that the performance of transition policies – in terms of effectiveness, equity and efficiency – depend very much on the underlying model of individual behavior. Only an empirically founded model of individual action and motivation can guarantee the design of adequate transition policies. A potential obstacle to a sustainability transition can be behavioral barriers to change. The different stakeholders involved in a transition have their own interests and will try to maintain any power position. Insights about bounded rationality, social interaction and learning can contribute to making transition polices more effective in addressing barriers and opportunities to realize a sustainability transition. In order to arrive at policy recommendations I focus on behavioral features of both individual and organizational level, paying attention to issues like lock-in, surprises in innovation systems, and network interactions, while trying to connect these to policy design. The analysis combines insights from the literatures on sustainability transitions, "environmental-behavioral economics", and behavioral foundations of learning and innovation.

Next, I consider the potential conflict between economic growth and climate change mitigation. This is done by developing a sector-based approach to analyze the relation between on the one hand carbon dioxide emissions per dollar of output and on the other the growth in economic output and labor productivity. This allows us to investigate whether green growth – combining economic growth with environmental sustainability – is feasible. A main conclusion is that despite past climate policy, developed under the Kyoto protocol, relatively clean sectors do not seem to be more productive than dirtier ones, and neither show a higher productivity growth. In fact, sectors associated with high carbon intensity grew more in absolute terms than those with low carbon intensity. The share of the first type of sectors increased suggesting that green development requires an extremely rapid pace of decarbonization (to allow for green growth), or the economy as a whole to shrink (green decline). An important additional finding of this study is that longer-term sectoral growth, as expressed by a change in value added, does not seem to be positively correlated with carbon intensity.

In a final study I examine optimal investment by a community or firm considering to diversify its investment in two renewable energy technologies with distinct learning rates and initial costs, like solar PV and wind electricity. The results show the importance of the learning rate: it affects anticipation of the option to invest in, and it reduces the critical threshold for exercising it, or for higher initial production cost. The greater the amount of capital invested, the more learning stimulates earlier exercising of the option to invest, due to a cost reduction effect. More uncertainty in energy prices or technology costs postpones the option to invest. Through subsidies, governments implicitly protect investors against price fluctuations and uncertainty. A surprising message from this study is that although investing in both solar and wind may be profitable under particular conditions of price and cost uncertainty, the theoretically optimal strategy is generally investing in only one technology, that is, solar or wind, depending on their relative initial costs and learning rates. This suggests that the practice in most countries of diversifying renewable energy may be a wrong strategy. However, perhaps certain motivations for diversifying are not or insufficiently covered by our model, which suggests a need for further research employing more complex models.

Chapter 1

Introduction

1.1 Background and approach

Currently we are facing various problems connected to climate change, resource exhaustion and energy and oil dependency. In order find a solution to these problems a transition to a more sustainable system is widely accepted as a requirement. The need of a sustainability transition is essential to the economy in general, but especially to some key sectors such as agriculture, industry, transport and energy which can be the most important in terms of carbon dioxide (CO_2) emissions and resource demanding. Such a transition may give hope or expectations about solving environmental and resource problems which seem to be difficult to solve in current reality. As a result, there is a need for radical, large-scale and integrated socio-technical changes that goes well beyond traditional policy approaches.

A transition to sustainability is generally defined as "a gradual continuous process of societal changes in which society (or a complex subsystem of it) structurally changes its character" (Rotmans et al., 2000). It is intended then that such a systemic change besides requiring the implication of greener technologies requires also various gradual and radical changes, affecting not only technology as such but also sectoral composition, industrial networks, user practices and consumer behavior (Geels, 2002).

There have been developed different approaches to research on sustainability transitions, namely: (i) innovation systems (IS), (ii) multi-level perspective (MLP), (iii) complex systems, and (iv) evolutionary systems (van den Bergh et al., 2011). IS focuses on the system failures, its function, the operation of the supply chain and the different system networks such as social, political and learning (Jacobsson and Bergek, 2011). The MLP, which is widely accepted to be the most practical and used approach to research on sustainability transitions sees a transition as a complex system of multiple competing technologies pointing towards a structural change. It identifies different stages of transitions such as niche, regime and landscape (Geels, 2011). Complex systems develops the important element of transition management (TM) which tries to foster a transition to sustainability bo governing, facilitating and directing this process of societal change (Rothmans and Loorback, 2011). Evolutionary systems focus on population diversity, cumulative change, multiple selection factors, and important elements which may impede a sustainability transition such as path dependency and lock-in (Safarzynska et al., 2011).

A transition to sustainability may face different problems. Lock-in of dominant technologies for example explains why it is so difficult to change the structure of a system and go to another direction. A solution to the lock-in of dominant technologies is recognized to be by maintaining diversity as this can enhance system adaptability and thus contribute to long-term stability. Other problems may be connected to the fact that technical innovations which can contribute to solve environmental problems are peculiar and cannot develop into a large market without parallel, fundamental changes in economic and social-cultural conditions. Another problem has to do with the effectiveness of current environmental policy or it may have to do with the fact that the correct, advised policies have not been well implemented.

Resistance to behavioral change is another problem that a transition to sustainability faces. Such a transition involves different actors such as consumers, producers, innovators, institutions, governments and the networks between these. These actors will play important roles in all stages of a transition, notably predevelopment, take-off, acceleration and stabilization (Rotmans et al., 2001). All these actors will influence the different stages of transition with their, goals, knowledge, interests, information, power and relations. Some actors having to go to a change during a transition may show resistance to change or inertia, while other actors may play an important role in fostering a transition, the so-called “change agents”. Identifying these economic and social actors, their behavioral aspects, the role they may have in a transition and their relations may help to draw, advice and implement more effective transition policies.

A further problem that a transition to sustainability may face has to do with the pollutive sectors of the economy and their size. Examining the linkage between economic growth and environmental pollutants, the so-called environmental Kuznets curve, one can test and draw conclusions for de-linking of per capita income and specific environmental pressure indicators. This can be done at an aggregate country level, but perhaps it is more interesting to make such analysis on a sector-level data and investigate on the different agriculture, industry, transport and energy sectors which may need to go to fundamental changes in a sustainability transition. A high intensity of technology is at the basis of both a combination of high and increasing labor productivity, which fuels growth, and high emission intensity, which fuels climate change. The reason for the latter might be that intense technology use is generally associated with high energy use. Making a historical analysis on the correlation between sectoral carbon intensity and sectoral growth we can test on the success of the effectiveness, advertisement and implementation of the last environmental and transition policies. Such analysis at a sectoral-level should perhaps consider the relations between the different economic sectors through an input-output (IO) analysis, but should also consider especially the pollutants deriving by outsourcing, or externalizing the production in some pollutive sectors.

A last problem that may face a transition to sustainability is connected to the uncertainty of the investments in this field. Traditional evaluation models such as cost-benefit analysis, notably using the net present value (NPV) criterion, fail to assess the strategic dimension of investments in renewable energy sources (RES) by leaving out important components, such as risk and uncertainty connected to future rewards (Brealey and Myers, 2003). More sophisticated evaluation techniques are needed to deal with these. One is real options theory which sees the firm as an investor holding a financial option. It gives it the flexibility to exercise the option now or wait (at a cost) in order to acquire more information on uncertain market (competition and prices) and technological conditions. In line with investments in RES, the initial investment cost is considered irreversible, that is, once the firm decides to invest, it kills the option and the investment cost is considered sunk. The aim here is to develop a decision-making model considering the factors affecting firms’ or community willingness to invest in different renewable energy projects. As a result of weather conditions which are related to the production of energy by renewable sources, the different initial costs that technologies may have and the different learning curves, one may see diversifying as a good strategy in order to reduce costs and avoid lock-in. However, learning in one technology is strongly connected to the capital invested in such technology. The more capital we invest, the more we learn, and as a result decrease future costs. This may result in contrary of a diversifying strategy since by dividing the capital invested we may not have a high cost reduction and as a result will require higher revenues to invest.

Transitions to sustainability are complex mechanisms involving different actors, relations power games and interests. For this reason, dealing with the problems mentioned above is not easy. However, the objective of this thesis is to shed light on these with the finality of deriving more effective and acceptable transition policies.

1.2 Research objectives and questions

This thesis aims to analyze various aspects of transitions to sustainability from the angle of particular theories, such as behavioral economics, green growth and investments under uncertainty. In order to investigate on such fields, this research is guided by different research objectives which are presented in the different chapters. The first objective is to examine and fill the gap between two disciplines, sustainability transitions and behavioral economics. Generally, writings on sustainability transitions pay slight attention to the specific behavioral characteristics of individuals, groups and organizations. To this end, the thesis identifies how bounded rationality, social interaction and learning can contribute to making transition polices more effective. In first play the behavior anomalies that are important in a transition context are identified and secondly conclusions for more effective and efficient sustainability transition policies are drawn.

Growth may be important in economic terms, however, in order to achieve a transition to sustainability we have to grow in a sustainable way. The second objective of this thesis is to investigate if the policies implemented in the last years did make green growth real or perhaps more radical policies are needed in order to achieve such objective. As a result of climate change, carbon emissions are important to see how pollutive an economic sector is. To achieve sustainability means that we have to go away from dirty/pollutive sectors which are associated to a high carbon intensity and focus more on clean sectors. By having carbon intensity and different indicators of economic growth or production correlated it can be seen if policies proliferating green growth were effective in the last years or not.

The third and final objective of this thesis is to investigate investments under uncertainty such as those in renewable energies, which are the case of investments related to sustainability transitions. These investment projects are surrounded by a high degree of uncertainty regarding electricity prices and technology costs. Because of this high degree of uncertainty, one can think that maybe diversifying the investment is a good strategy. The problem gets more complex when we consider different types of uncertainties and the different technological learning parameters which allow a future cost reduction. The more capital is invested in one technology, the more we learn from it and as a result reduce future costs. It is important to understand the trade-off between the diversification strategy and the cost reduction coming from the learning parameter of a specific technology. Testing the role that uncertainty, learning parameter, initial costs of technology and electricity prices has can help to draw better policies in order to reduce this high degree of uncertainty.

The studies presented explore and give answers to the following questions:

- Which are the most important behavioral features of stakeholders important to sustainability transitions in order to create a more realistic view of limits and opportunities for a transition?
- How can different literatures on behavior/learning, policies, innovation and transitions be combined to draw such conclusions?
- What is the relation between sectoral growth and carbon intensity?
- Is challenge of green growth is enormous and easily tangible or underestimated?
- Does green growth require much tougher policies than the ones we have seen so far?

- What is the role of a change in uncertainty, learning curves, initial cost, and electricity price in investments under uncertainty connected to sustainability transition?
- Is diversifying a good strategy in investments to renewable energies, which may carry a high degree of uncertainty?

1.3 Outline of the thesis

The thesis is structured in three chapters to elaborate the research questions mentioned above. *Chapter 2* examines how modern insights about bounded rationality, social interaction and learning can contribute to making transition polices more effective in addressing barriers and opportunities to realize a sustainability transition in the near future. We argue that the behavioral underpinnings of features like lock-in, surprises in innovation systems, and network interactions have been insufficiently elaborated and connected to policy design. We identify and illustrate the most important behavioral features of relevant stakeholders in transition processes. By focusing on behavioral features at both individual and organizational levels, we arrive at recommendations for policy makers regarding important barriers to change and how to overcome these. Specific policy insights are offered at multiple levels, for different stakeholders, and associated with both behavioral biases and social interactions. The analysis combines insights from the literatures on sustainability transitions, “environmental-behavioral economics”, and behavioral foundations of learning and innovation. Our framework may serve as a basis for coherent behavior studies of transitions that otherwise run the risk of being ad hoc. This will improve conditional forecasting of system responses to transition policies.

Chapter 3 considers the potential conflict between economic growth and climate change mitigation. Some believe green growth is an option, while others think climate goals are incompatible with growth. It does so by developing a sector-based approach to analyze the relation between on the one hand carbon dioxide emissions per dollar of output and on the other the growth in economic output and labor productivity. This allows us to investigate whether green growth – combining economic growth with environmental sustainability – is feasible. The analysis covers Denmark, Germany and Spain for the period 1995-2007. An important innovation of this study is that carbon intensity is calculated in two different ways: (1) as direct carbon dioxide emissions from each sector, which can be seen to immediately result from the processes in the respective sector; and (2) as total, direct plus indirect, emissions, by using environmentally-extended input-output tables and considering also indirect carbon emissions through imported goods. Another novelty of this study is that we calculate correlations over time between sectoral carbon intensity and a range of economic indicators: sectoral total and relative output, final demand, value added, and so-called output and valued-added productivity indicators, and their change. A main conclusion is that despite past climate policy, developed under the Kyoto protocol, relatively clean sectors do not seem to be more productive than dirtier ones, and neither show higher productivity growth. Sectors associated with high carbon intensity grew more in absolute terms than those with low carbon intensity. The share of these sectors increased suggesting that green development requires an extremely rapid pace of decarbonization (to allow for green growth), or the economy as a whole to shrink (green decline). An important additional finding of this study is that longer-term sectoral growth, as expressed by a change in value added, does not seem to be positively correlated with carbon intensity.

Chapter 4 investigates on the optimal investment by a community or firm who wants to diversify its investment in two distinct renewable energy technologies, like wind and solar PV electricity. We assume technological learning curves that describe reduction of electricity production costs due to experience, captured by cumulative capital investment. A real options approach is applied as it takes into account uncertainty about prices and learning, as well as irreversibility associated with investment decisions. Revenues are obtained by selling the electricity produced with either technology, which is not storable, at a uniform market price. We investigate three different cases dealing with particular combinations of uncertainty that affect optimal choices about investment in renewable energy, namely: uncertainty about future electricity prices, in great part caused by competition with fossil fuel electricity; and uncertainty about the speed with which learning drives the costs of wind and solar electricity down. We assess the minimum threshold for the stochastic price and the maximum cost that makes it optimal for the firm to invest in the two technologies, that is, to exercise the option to invest. The results show the importance of the learning rate in terms of anticipating the option to invest and exercising it at a lower critical threshold or for higher initial production cost. The greater the amount of capital invested the more learning stimulates earlier exercising of the option to invest, as a result of cost reduction. More uncertainty in energy prices or technology costs postpones the option to invest. In the case of more certain electricity price due to subsidies, governments implicitly protect investors against price fluctuations and uncertainty. A surprising message from this study is that although investing in both solar and wind may be profitable under particular conditions of price and cost uncertainty, the optimal strategy is investing in only one technology, solar or wind, depending on their initial costs and learning rates. This suggests that the practice in most countries of diversifying renewable energy may be a wrong strategy.

Finally, in *Chapter 5* I provide a summary of the thesis, present main insights and draw overall conclusions.

Chapter 2

The Behavioral Basis of Policies Fostering Long-Run Transitions: Stakeholders, Limited Rationality and Social Context[1][2]

2.1 Introduction

It is now widely accepted that a transition to a low carbon economy is needed in the near future. This represents a fundamental shift away from the current socio-economic system characterized by intensive use of fossil fuels and high pressure on the environment towards a more sustainable economy. Such a transition requires, besides greener technologies, various gradual and radical changes, which will affect social and regulatory institutions, sectoral composition, industrial networks, user practices and consumption (Rotmans et al., 2000; Geels, 2002). Transitions involve the scaling up of system innovations, which alter the structure of technological and socio-economic subsystems and their connections (Jacobsson and Bergek, 2011).

Current writings on transitions discuss the types of policies that manage, govern and facilitate transitions (Kemp et al., 1998; Kemp and Loorbach, 2003; van den Bergh, 2013a). Most studies, however, adopt a rather abstract and high-level view in which agents and their behavior receive little or just implicit attention. As a result, the literature on transitions is not very well connected with disciplines that have accumulated much knowledge about individual behavior and behavioral change on the basis of empirical evidence. A serious risk is then that transition studies suggest unrealistic, unfeasible or ineffective strategies, policies and scenarios. To address these concerns, this paper aims to offer a behaviorally explicit perspective on the role of the various stakeholders in transition processes, which allows for a detailed analysis of the feasibility and effectiveness of transition policies.

The methodological relevance of our approach is that the long-term issue of a transition to a sustainable, low-carbon economy needs a more coherent and complete treatment from the angle of policy-behavior links. The question here is how policies (can) affect stakeholders showing particular behaviors relevant to a large-scale socio-technical transition, taking into account behavioral features including bounded rationality, behavioral biases and social interactions driven by other-regarding preferences. Our framework is hoped to contribute to improving conditional forecasting of individual and system responses to transition policies. It is aimed to result in a general, systematic approach on which particular case studies, which often are ad hoc with regard to behavior-policy links, can build on. This will improve long-term decision-making that is needed for realizing a sustainability transition in the future. Such a

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[1] This chapter has been published as: Gazheli, A., Antal, M., van den Bergh, JCJM. 2015. The behavioral basis of policies fostering long-run transitions: Stakeholders, limited rationality and social context. *Futures*, 69: 14-30.

[2] Elisabeth Gsottbauer provided useful comments. Financial support was given by the EU through the WWWforEurope project (www.foreurope.eu).

transition should take into account the ultimate effect of the interaction of many complex behaviors that make up the global socioeconomic system (Lopolito et al, 2011; Vazquez-Brust et al, 2014; Neuvonen et al, 2014).

Agents with different behavioral characteristics play a role in the distinct stages of transitions, notably predevelopment, take-off, acceleration and stabilization (Rotmans et al., 2001). They influence the transition process through their goals, knowledge, information, power, interactions, relations and interests. They include economic agents, such as consumers, producers, and investors; institutions, such as governments and local authorities; and social agents, such as citizens, labor unions and NGOs (Geels, 2010). Agents that have to undergo behavioral change during a particular transition stage will sometimes show resistance to change or inertia. Other agents, however, may play crucial catalyzing roles in transition processes ("change agents"). In addition, new stakeholders may appear or changes in power structures or preferences may occur. Stakeholders may also join forces to cause future changes that otherwise would be impossible, such as in the case of labor unions and employers striking long term agreements. For all these reasons, policy makers do well to take seriously into account proven behavioral features when designing transition policies.

In existing writings, the notion of agency represents the principal behavioral view on transitions. According to theories of agency, individuals are agents proactively engaged in their own development who make things happen by their actions. It gives much attention to the role of power (Smith et al, 2005). Groups and organizations with different interests often try to alter the balance of power by increasing their political, economic or institutional influence. Since power can hinder or foster transitions, it is good to consider power relations in the analysis of transition policies, and to link these to behavioral features of relevant agents. This approach offers original policy lessons, but it also implies serious limitations in terms of understanding and guiding behavior.

This paper synthesizes insights about the role of agents in transitions. This will involve giving attention to the behavioral characteristics of agents, including of governments, and the behavioral basis of learning and innovation. Our main purpose is to identify the types of bounded rationality and other-regarding preferences of individuals and groups that have to be recognized by regulatory policies in order to improve the effectiveness of transition management. The following stakeholders are distinguished: consumers, producers, investors, and governments. They have distinct behavioral features, which may require the use of multiple, complementary policy instruments.

The paper is organized as follows. In section 2 we review how behavioral aspects are integrated into current writings on sustainability transitions. Section 3 examines relevant insights about consumer, firm and government behavior. In section 4 we provide a list of behavioral features, which can act as barriers for sustainability transitions. Section 5 underlines the importance of the behavioral roots of learning and innovation from a transition perspective. In Section 6 we translate the various behavioral insights obtained into general and specific policies overcoming barriers to, and fostering, a sustainability transition. This involves attention for multiple levels, different stakeholders, and behavioral biases as well as social interactions. Section 7 concludes.

2.2 Behavior in social science theories suitable for transition studies

The study of sustainability transitions applies theories from different research fields, such as history, political science, sociology, science and technology studies, innovation research and evolutionary economics (Markard et al., 2012; Kemp and Loorbach, 2006). Four main approaches have been used so far to integrate insights from these disciplines in order to describe and understand sustainability transitions: the innovation systems approach, the complex systems approach, the evolutionary systems approach and the multi-level perspective (MLP) (van den Bergh et al., 2011). The four approaches overlap to some extent but also relate to unique system elements and processes. Most attention has been devoted to the MLP (Geels, 2011).

These theories try to shed light on the understanding of sustainability transitions and the barriers that may hinder them. Barriers to sustainability transitions are numerous. Arthur (1989, 1994) identified technological lock-in caused by increasing returns as a general obstacle: widespread technologies can attract new users through network effects or scale economies in production leading to lower prices, instead of through mere better performance. This will delay or deter the entry of innovative new products or services to the market. As a consequence, substantial investments are often necessary for sustainability transitions to create a level playing field, including changing existing infrastructures or adding new ones. Apart from technological lock-in, psychological and political factors are essential. Psychological factors may be related to agents feeling a small incentive to contribute to global environmental problems (the well-known free riding problem associated with public goods), not seeing the indirect, rebound type of effects of their well-intended decisions (e.g., on energy saving), or being more myopic (high discounting) regarding environmentally relevant investments than purely monetary decisions. Important sources of political-behavioral resistance may include unsustainable mechanisms at the landscape level, such as the existence of tax havens that allow large companies to pay much lower taxes than small ones, or the lobbying power of regime actors to protect their interests at the disadvantage of environmental innovations. Changes in regulations, market conditions and behavioral motivations are necessary to circumvent these barriers and foster sustainability transitions (Unruh, 2000).

Transition management helps to overcome these barriers by trying to govern, facilitate and direct the process of societal change (Elzen et al., 2004; Loorbach, 2010; Loorbach and Rotmans, 2006). In accordance with the focus on power, governance approaches (Rotmans et al., 2001) – and the literature on technological transitions with insights from complex systems theory (e.g., Kauffman and Macready, 1995) – had the largest influence on transition management strategies. The process of transition is not controlled directly; instead, transition management influences and adjusts each step of it. After structuring the problem, a transition agenda is developed, transition experiments are set up and carried out, and ultimately the lessons of these experiments are evaluated.

While economic theory and policy have long been dominated by the rational agent theory, slowly but irreversibly behavioral economics is becoming more important. It focuses on two broad topics: bounded rationality and limited self-interest (Rabin, 1993; Camerer, 1999). The first addresses a wide range of behavioral anomalies, including the analysis of choice under uncertainty and intertemporal decision-making, while the second considers all types of other-regarding preferences, such as fairness, comparison, status-seeking, reciprocity, spite, imitation and altruism. Different insights from behavioral economics can shed light on particular features of stakeholders in sustainability transitions. This then can provide relevant information about effective transition policies. Behavioral economics is expected to generate new insights for policies in several fields (Gsottbauer and van den Bergh, 2011): market-based instruments, framing of policy issues to create social-political support, and the role of information provision in general (e.g., the use of defaults) (Kahneman, 2011; Lindbeck, 1997; Cheema and Soman, 2006; Meier and Stutzer, 2008). In addition, habits, routines and factors underlying their change constitute an important area for transitional change.

Other authors, however, criticize behavioral economics for focusing too much on the individual level. For example, Urry (2010) emphasizes the role of economic, technological and social practices. And according to Shove (2010) “the dominant paradigm of ´ABC´- attitude, behavior, and choice” explain very little about climate policy. Instead, she gives more credit to other approaches: transition management (Elzen et al., 2004), which, as explained above, stresses change of markets, user practices, cultural values and infrastructure; theories of sociotechnical configurations (Berkhout et al., 2004), which see transition as a change in emergent qualities and characteristics of different types of sociotechnical constellations; theories of system provision and availability, which focus on the role of the design of infrastructures and buildings (including homes); and theories stressing that radical innovations redefine the rules of the game by reconfiguring interpretation of value and significance. The problem with this list is that, although it contains valid aspects, these are not inconsistent with recognizing and accepting the importance of individual behavior. Shove (2010) merely stresses the point that a number of contextual factors are relevant. Behavior of individuals and contextual factors are complementary elements of a complete explanation of behavioral regularities underlying transitions (or their absence). Behavioral theories are not meant to deny the relevance of contextual factors. Behavioral policy studies well recognize that individuals are constrained by existing technologies, infrastructure, buildings, and habits or routines (really a synonym of “user practices”). So it is not very convincing to say that behavior is not so important and therefore does need explicit attention in the analysis of transitions. What is true though is that many behavioral approaches in the past have not captured relevant aspects of transitions or barriers to it. This is exactly the motivation for writing this paper. Rational, representative agent theories cannot deal with habits or practices as they neglect bounded rationality and social context. Table 2.1 summarizes the main issues identified here and connects them to the goal of fostering sustainability transitions.

Table 2.1 Main behavioral features identified as relevant to foster sustainability transitions

Behavioral feature	*Connection to sustainability transition*
Altruism	Important for public goods dilemmas
Fairness	Increases the social-political feasibility of radical policies needed for institutional changes in a transition
Status seeking	Can stimulate the consumption of goods that are very pollutive
Norms	Can sometimes block behavioral change needed for a sustainability transition
Imitation	Can lead to lock-in and path dependency, but also to a critical mass of "green consumption" and a change of norms in a sustainability transition
Habits and routines	Can prolong environmentally damaging practices and block pro-environmental changes
Affect and the endowment effect	Can serve as a motivation for consumers to not give up on harmful consumption, and for vested interest groups to stick to their positions
Framing	Influences the acceptability of, and responses to, environmental policies
Discounting	Affects the weight given to environmental problems in the future, like long term damages associated with biodiversity loss and climate change
Loss aversion	Influences opportunities and interests to move away from the status quo, and tends to contribute to continuation of unsustainable practices
Satisfactory strategies	May explain resistance to change to greener practices by firms
Over-optimism	May lead to an underestimation of the difficulties of planning and environmental problem solving, especially relevant for decision-makers in firms (CEOs)
Organizational biases	Are relevant to understand opportunities for and barriers to a transition. E.g., career aspirations can create a conflict between personal and organizational goals; or anchoring can distort the perception of new, innovative projects and ideas
"Anomalies" of government behavior	Considering government behavior as boundedly rational is useful in analyzing sustainability transitions, because it aids the understanding of complex processes like political myopia, lobbying, lack of direct accountability and regulatory capture.[3] This may result in inefficient and ineffective management of transitions

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[3] A form of political corruption in which public agencies, created for the public interest, operate instead in the interest of particular groups.

2.3 Crucial behavioral features of stakeholders in sustainability transitions

In order to go one step further in pointing out the relevance of these behavioral features for transitions, we can link them to the different groups of stakeholders. For example, habits, affect, fairness and framing are important for consumer behavior. Routines, investment and innovation strategies, and over-optimism are relevant to the behavior of companies, while power games, lobbying and accountability to voters are particularly important for governments and policy makers.

2.3.1 Behavioral aspects of consumers/households

The fact that some people behave in a very pro-environmental way in relation to waste recycling while being very environmentally harmful in terms of their transportation decisions suggests that a consistent set of consumer preferences is rare (Steg and Vlek, 2008). Identifying these inconsistencies and considering them in sustainability transition policy design may increase policy effectiveness.

A first group of behavioral features attributed to consumers includes altruism and reputational concerns (Bénabou and Tirole, 2006). Altruism is concern for the welfare of others. Helping others by making personal sacrifices can have important consequences for economic behavior (Simon, 1992). The supply of public goods, for example, strongly depends on the level of altruism. It is affected by several factors, including gender, identity and intrinsic rewards in the form of personal gratification. Altruism and reputational concerns may stem from intrinsic motivations that can be discouraged by extrinsic motivations like rewards or punishments – known as crowding-out. A famous example is the introduction of a fine for parents arriving late to pick up their children at school that only aggravated the problem which it was intended to solve: parents arrived even later, because they no longer felt guilty after paying the fine (Gneezy and Rustichini, 2000). Carpenter and Mayers (2007) also found that altruism and reputational concerns which are positively associated with socially beneficial behavior (volunteering, in this case) can be crowded out by monetary incentives. The reduction of positive feelings after doing something good ("warm glow") is partly responsible for this (Andreoni, 1989, 1990). Thus, rewards and punishments can be counterproductive if they crowd out community-oriented aspirations and can thus restrain bottom-up initiatives. The latter are seen in transitions theory as niches worthy for protection.

Studies further find that individuals do not use their full bargaining power in bilateral transactions (as opposed to competitive markets). Moreover, participants of group-level public goods dilemmas are willing to invest in costly punishments to maintain cooperation (Ostrom et al., 1992). Aspiring for fairness or reciprocity are deviations from the rational actor model that seem to be rooted in the evolutionary history of our species and influence decision-making already in non-humans (Santos and Hughes, 2009; deWaal and Luttrell, 1988). Such behaviors can be explained by a mix of selfish and equality-oriented (or inequality-averse) players that evaluate psychological costs and benefits of social comparison and prefer avoiding losses to acquiring gains (Fehr and Schmidt, 1999).

An unconscious desire for fairness (and power) can also be in the background of the quest for social status. In his "Theory of the Leisure Class", Thorstein Veblen (1899) draws attention to differences in social status and how life is determined by the social vestiges of society rather than just utility. More recently, Johansson-Stenman and Martinsson (2006) showed that when choosing a car brand, most people (even though many would not admit this) are more concerned about status and image than environmental issues. The importance of status is further indicated by the fact that in biology some types of altruistic acts are explained as a costly signal of status. Similarly, it has been observed that consumers increase the consumption of costly green products when they are shopping in public (Griskevicius et al., 2010).

Environmental and social behavior is strongly affected by moral and normative concerns too. Norms and rules often emerge in families, groups of friends or social organizations. As people like to feel part of these groups, they are influenced by other members and the norms of the group. Various experimental studies show that people often act to favor members of the same group over out-group members (Tajfel et al., 1971; Tajfel and Turner, 1986). As leaders of "virtual groups", role models can have a similar influence on behavior. Thus, creating opportunities for environmentally beneficial behaviors to spread through social networks is important to facilitate transitions.

The powerful role of norms is, to a large extent, rooted in the human desire for conformity which also drives imitation and behavioral copying. People usually imitate the behavior of peers, especially when they are overwhelmed by information or uncertainty (Cialdini, 1993). In addition, according to Witt (1977) a transition through imitation becomes easier when a critical mass of people imitating and diffusing the same innovation is reached.

Apart from the role of social interactions and other-regarding preferences, the limited rationality of individuals is the other main issue which has to be considered when devising strategies for transitions. To begin with, individual agents often show habitual behavior (Verplanken and Aarts, 1999). The more frequently an action is repeated and the more closely it is associated with a reward, the stronger the mental habit will be. Individual habits are learned, stored and retrieved from the memory when the particular situation with which the habit is associated is perceived by the agent (Aarts et al, 1998; Aarts and Dijksterhuis, 2000). In accordance with Lewin's 3-step theory (1947), the process of changing unsustainable consumer practices can start with the "unfreezing" of environmentally detrimental habits, followed by learning in a transitional period of adaptation, and finally the new, sustainable behavior can be "frozen".

To develop more sustainable habits, the emotional appraisal of consumer activities likely has to change. Gatersleben (2007) points out the role of affect to explain environmental behavior. She uses the example of car use, which is largely driven by affective and symbolic motives. Generally, people attribute a high affective value to objects they own. Furthermore, the subjective value of an object increases as it becomes property (Kahneman et al., 1990). This effect – known as the endowment effect in behavioral economics – is a significant motivation to stick to existing consumption behaviors and, more generally, to prefer the status quo (Thaler, 1980).

A related cognitive bias results from the effect of framing, which – in contrast with the prediction of rational actor theory – has a non-negligible influence on choices (Tversky and Kahneman, 1981). In other words, the same contents presented differently result in different decisions. This is equally true for communication (Lakoff, 2010) and consumption decisions (Thaler and Sunstein, 2008).

In intertemporal decision-making, which affects environmentally relevant choices, individuals' rationality is limited. The standard assumption of exponential discounting, like in cost-benefit analyses, does not capture the variety of intertemporal decision-making observed in the real-world (Frederick et al., 2002).

Recognizing and understanding gender differences regarding behavioral features of consumers and households can contribute to better policy design as well as policy acceptance. Andreoni and Vesterlund (2001) find that when altruism is expensive women tend to show more altruistic behavior than men, while the reverse is the case when altruism is cheaper. In a review of trust and reciprocity on gift exchange games, Eckel and Grossman (1996) on a study on gender issues and the impact of fairness on the outcome of economic transactions find men more likely to make decisions on principle while women more responsive to changes in the parameters of the decision-making environment. Rau (2014) finds that in many experimental studies men tend to show more trust than women by sending higher amounts to second movers in trust and gift-exchange games. However, this behavior can be related to risk attitudes since men are usually risk seeking while women tend to be risk averse (Croson and Gneezy, 2009).

2.3.2 Behavioral aspects of producers and other organizations

Traditionally, firms in competitive markets are assumed to be profit-maximizing entities. Alchian (1950) argued that although not all firms are profit-seeking, the selection pressure of competitive markets will increase the proportion of such firms in the total population of firms. Friedman (1953) tried to generalize this argument for profit-maximizing behavior. Winter (1964) and Hodgson (1999) criticize their views for reflecting an incorrect understanding of evolutionary mechanisms, notably selection processes. They instead argue that evolutionary selection does not mean that profit-maximizing strategies are perfectly replicated, because many firms simply do not know why they were successful, and even if they do, others cannot perfectly observe and copy the relevant details of successful strategies. As the operational environment of firms and technologies becomes more complex, it turns out to be more difficult to access and process information in order to maximize profits (Foxon, 2006). A similar conclusion appears already in Cyert and March (1956).[4]

Nevertheless, firms have been argued to make more (often) rational decisions than consumers (Armstrong and Huck, 2010). Reasons for this include the rationalization of organization and management processes, the reduction of economically disadvantageous behavioral biases due to professional, educated decision-making, and the repeated execution of actions that enables learning and performance improvement. In addition, pressure to adapt decisions in the face of competition can make firms more rational. On the other hand, several factors hamper perfect rationality. For example, a sense of fairness can motivate monopolists to set prices below the ones predicted by neoclassical theory (Kahneman et al., 1986), individuals' career aspirations can overrule firms' interests in decision-making (Kamoche, 2000), firms' routines and internal political processes can hamper rational and rapid adaptation to external changes (Nelson and Winter, 1982), and firms can imitate the strategies of their competitors instead of acting as isolated optimizers (Bentley et al., 2011).

Routines have received much attention in the literature. A routine denotes a complex set of simultaneous and sequential interactions of skilled individuals. The interactions depend on earlier contacts (learning, adaptation) and organization-specific “language”. Altered demand or product prices, ambitions to acquire new markets, or goals to increase the company's market share are reasons to periodically revise routines. However, these revisions are not as predictable in reality as rationality would dictate: they depend on random changes in the collection of interactive firm employees and their unique, often irreplaceable, capabilities (Nelson and Winter, 1982).

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[4] Morgan (2006) distinguishes between eight different views on organizations, such as machines, organisms, brains, cultures, political systems, psychic prisons, flux and transformation, and instruments of domination. Mintsberg et al. (1998) indentify ten different schools of strategic management (focused on design, planning, positioning, entrepreneurial, cognitive, learning, power, cultural, environmental and configuration).

Just as in the case of routines, the periodic revision and optimization of whole business strategies is imperfect from a purely rational perspective. Firms generally seek a satisfactory rather than maximum profit and do not change strategies if the realized profits are within the targeted range. Dixon (2000) reaches this result considering a duopoly market, while Oechssler (2002) simplifies and generalizes the results reached by Dixon using techniques from stochastic evolutionary game theory. Empirical data from the manufacturing sector indicate that firms shift to more aggressive strategies only if their profits fall below the industrial average (Cyert and March, 1956). Profits realized by competitors are often used as benchmarks in strategic planning.

A further argument pointing to the non-rational nature of firms pertains to the over-optimism of business decision makers. The illusion that everything is under control and will work out fine has three main reasons: organizational pressure and two cognitive biases known as anchoring and competitor neglect (Lovallo and Kahneman, 2003). Organizational pressure refers to the fact that firms undertake only those projects that look most promising on paper, so executives have to accentuate the positive aspects of their proposals. Anchoring means that managers stick to initial information as described in preliminary proposals that are overly optimistic, even after detailed financial analysis reveals imperfections later on. In addition, companies focus on their own capabilities and often neglect those of competitors, especially when they enter new, growing markets and increase capacities without considering that others may follow the same strategy.

Not all organizations are focused on profit. Many NGOs are in fact non-profit seeking organizations, such as environmental organizations, local community based movements and consumer associations. Since the objective of such organizations is not profitability, they may deviate from the behavioral features typical of profit seeking firms. Non-profit organizations may be society-, environment-, cultural-, humanitarian- and right-based, and thus may play an important role in promoting new cultural values that can help fostering a transition to sustainability. It is important, though, to underline that – like firms – these organizations show routines and satisficing strategies. Other behavioral features likely to be found in these organizations are over-optimism, organizational pressure, and anchoring.

Finally, behavioral differences between men and women may affect the behavior of firms through gender composition of management teams. Equal opportunity policies so far have not resulted in an equal representation of men and women in high-ranking positions. According to Gneezy et al. (2003), this is explained by the fact that women can be less effective than men in competitive as opposed to noncompetitive contexts. Male leaders are generally more competitive and more likely to take large risks than women (Niederle et al., 2009; Hogarth et al., 2012). While risk-taking of men can boost risky investments needed for a sustainability transition, women's ability to act efficiently in non-competitive environments may foster cooperation in communities necessary for local transition experiments.

2.3.3 Behavior of governments

One could exclude the government from the behavioral analysis of transitions and – in line with many policy theories – assume governments to be exogenous to the economy and society. However, transitions thinking can gain explanatory power by regarding governments as players in the system who are, like other players, characterized by limited means, bounded rationality, internal organizational complexity and conflicting aims between different governmental agencies or levels. We do not offer here a very deep and complete analysis as this would require a separate paper. Instead, we offer some food for thought.

Governments are boundedly rational in the sense that they do not realize outcomes that are best from a social welfare perspective. Deviations from the rational goal of welfare maximization can be attributed to the bounded rationality of individuals in the government or the structure of governments that creates conflicts between collective and individual goals (Sterner, 2003). Furthermore, social welfare is not a clear and unique goal. Different representatives or parties in the political spectrum adhere to different implicit social welfare functions, which motivate particular choices regarding solidarity, fairness, efficiency and the separation of private and public spheres. Objectively aggregating individual preferences into social preferences is impossible (Arrow, 1950). Next to bounded rationality, recognizing diversity of stakeholders and their opinions and behaviors is important to explain the political process and ultimately governmental behavior.

Decisions of policy makers, supposedly serving governmental or social purposes, are not necessarily more rational than decisions of consumers or private companies (Glaser, 2006). In fact, whereas market conditions provide incentives for consumers and especially for producers to act as rational agents, the government often operates outside markets, which means it is not affected by such incentives. Structural reasons for bounded rationality at the collective level include political myopia (election cycles, party interests and personal interests of politicians and public officers), stakeholder involvement and power games (e.g., lobbying), the lack of direct accountability to voters, and regulatory capture. These biases are particularly important for transition policies which have to balance long-term societal goals with short-term concerns (Kemp and Loorbach, 2003).

To better understand the bounded rationality of the government, the public choice model might serve as a starting point. It sees the political process as consisting of multiple actors (politicians, civil servants, voters, and NGOs, labor unions and business representatives) who act in a self-interested manner. Furthermore, public choice theory allows one to analyze the distribution of costs and benefits among the stakeholders involved in the political process (Hahn, 1990). This could be complemented by information about how power is distributed (Avelino and Rotmans, 2009; Safarzynska and van den Bergh, 2010) in order to arrive at a more complete behavioral model.

2.4 Overcoming behavioral barriers in sustainability transitions

Different barriers to sustainability transitions such as lock-in mechanisms, increasing returns to scale and inertia, or resistance to change, can be attributed to some extent to individual and group behavioral features. These behavioral features are possibly more important for some phases of sustainability transitions than others. In Table 2.2 we list such features and link them to the transition phases for which they are most relevant.

Table 2.2 Behavioral features important to transition phases

Stakeholder group	*Behavioral feature*	*Predevelopment*	*Take-off*	*Acceleration*	*Stabilization*
Consumers/households	Altruism	X			
	Fairness		X		
	Status	X	X		
	Norms		X	X	
	Imitation		X	X	
	Habits and routines		X	X	
	Affect	X			
	Endowment effect	X			
	Framing	X	X	X	X
	Discounting	X	X		
Producers/investors	Status quo bias	X			
	Loss aversion	X			
	Satisfactory strategies	X			
	Overoptimism	X	X		
	Career aspirations	X			
	Anchoring		X		
Governments	Political myopia	X	X		
	Lobbying		X	X	
	Regulatory capture	X			X

Altruism is especially important in the predevelopment phase since certain altruistic behaviors that precede transitions may become a norm (or even mandatory) in later stages. Fairness strongly influences the social-political feasibility of environmental policies, so it is particularly important in transitions where radical policies and large institutional changes – with potentially serious distributional consequences – are required. More specifically, inequity aversion suggests that fairness is crucial for gaining public support for policy. As policies supporting transitions and preventing a "backlash" (an attempt of regime actors to stop change) are often made in the take-off phase, this is where fairness has most immediate relevance. Status considerations are probably most important in the first two stages of transitions because this is where it is most difficult for new environmentally friendly products to compete with status goods.

Sustainability transitions do not include only technological but also societal changes. For this reason it is important to consider societal norms, especially in the take-off and acceleration phases of a transition when most actors have to change their norms. Several authors have investigated such changes in an environmental context. In the case of energy saving, for example, norms can sometimes be very powerful in motivating behavioral change (Goldstein et al., 2008). Cialdini (2003; 2007) highlights the difference between descriptive norms (dominant behaviors) and injunctive norms (approved or disapproved behaviors in a society). If the aim is to change behavior, focusing on injunctive norms is an appropriate strategy. If, on the other hand, the goal is to prevent negative behavior, both injunctive and descriptive norms can be used in persuasive messages.

Imitation is a behavioral feature of humans that is crucial for sustainability transitions since it can both hinder and foster a transition. Marketing efforts of companies stimulate the imitation of dirty technologies and habits. This can be a significant barrier to transitions by contributing to lock-in. If, on the other hand, imitation is used to adapt to changes (Bandura, 1977), it can substantially contribute to the take-off and acceleration phase of transitions. In fact, a window of opportunity can exist for the take-off of sustainability transitions because people are more likely to copy others' behavior in a crisis or when they are overwhelmed by uncertainty (Cialdini, 1993; Roe, 1996). When a critical mass of people imitating and diffusing the same innovation in the acceleration phase is reached, imitation becomes a force that helps the transition instead of hindering it (Witt, 1997). The current trend of increasing interconnectedness in social networks underlines the role of these mechanisms in fostering behavioral changes for sustainability (Bentley et al., 2011; Rogers, 1995).

Other two crucial behavioral features which make us stick to our established behavior and constitute barriers to change are consumer habits and firm routines. Without awareness and self-reflection, managers and consumers often stick to their traditional ways of doing things (Carrus et al., 2008). These behavioral features are blocking elements especially in the predevelopment and take-off phases of transitions where consumers and firms have to change their existing habits and routines and adopt new ones.

Other behavioral features we regard as important are the endowment effect and the affect attributed to things we own (Thaler, 1980; Steg, 2005). These often result in a reluctance to change unsustainable consumption behaviors.

Furthermore, framing can play an important role to guide behavior in sustainability transitions and is important in every stage of it. In the predevelopment phase of a transition, the framing of environmental bads is important. Talking about carbon pollution instead of carbon emissions, for example, can influence people's perceptions. In the take-off and acceleration phase, the framing of the environmental goods becomes very important for diffusion. Examples for the relevance of structuring decision options range from school canteens where the arrangement of food has a significant influence on choices to climate change communication whose effectiveness largely depends on the proper management of risk perceptions (CRED, 2009). Because many decisions have default options, often there is no neutral choice architecture. Therefore, devising choice options wisely – e.g., putting the healthiest and most sustainable food products at the front – is very important. Breaking unconscious habits with such unconscious tricks can be very effective. Appropriately framed messages about environmentally relevant consumption – such as in advertisements of new green products – can help create the necessary conditions for pro-environmental behavior at the individual cognitive level.

Discounting in climate change and other environmental problems has been subject to much discussion. One important behavioral feature connected to discounting is called temporal myopia (or short-sightedness). This is especially important in the first stages of sustainability transitions as this is where investments with long time horizons have to be made by firms that are not yet financially strong. One complicating behavioral issue is that people have been found to discount more strongly in the context of environmental decisions – like investing in energy conservation equipment – than in purely financial contexts (van den Bergh, 2008). In addition, for savings decisions or bad habits like smoking and other addictions, a number of studies have shown that agents' preferences are not constant over time and inconsistent with exponential discounting (Ashraf et al., 2006; Thaler and Sherfin, 1981; Wertenbroch, 1998). In various cases, agents discount the value of later rewards by a factor that decreases with the length of the delay, which results in so-called hyperbolic discounting.

Another important behavioral aspect that needs more attention in sustainability transitions – especially during predevelopment – is uncertainty or loss aversion, which can result in status quo bias that is environmentally disadvantageous (Gal, 2006).

Behavioral features that are important at a producer, or company level, such as satisfactory strategies and career aspirations are more important at the predevelopment stage of a transition. It is in this stage that companies have to consider new opportunities and evaluate new strategies, and not stick to the old, satisfying ones. Career aspirations may mean a conflict between the firm's interest and the managers' personal interest. Investments in green electricity, for example, are usually associated with long term rewards. For this reason, managers may not see such investments very positively and opt for projects that give short term rewards, so as to advance their careers. Over-optimism, or the subjective perceptions of CEOs that everything works fine, may distort the projects are evaluated. This is especially important in the first two stages of a transition, when important financial decisions have to be made. Anchoring is especially important in the take-off phase of a transition where feedback from the market has to be evaluated to devise further strategies. Even if such feedback is not so positive, managers will often stick to the prior design of the project and not try to modify it.

Governments have a range of behavioral features that are relevant to understand or guide sustainability transitions. Examples are political myopia, lobbying and regulatory capture. Political myopia is important for sustainability transitions as it means a conflict between long term transition goals and short term election cycles. Lobbying is perhaps most important in the take-off phase of a transition. When a transition starts to grow, regime actors will use their lobbying power to block policies protecting and helping to expand a transition. Regulatory capture is important in the stable phases of a transition (predevelopment and stabilization) characterized by dominant interest groups and moderate competition for economic and political influence.

2.5 Behavioral underpinnings of environmental innovation

The spreading and diffusion of environmental innovation is often difficult compared to other technological innovation. This is due to the fact that environmental innovation is characterized by diffuse public benefits and concentrated private losses. Furthermore, successful environmental innovation is complicated as it tends to focus on factor saving rather than quality improvement. Examples of such innovations are green electricity which is more expensive than grey electricity even though it does not deliver any quality improvements.

Behavioral features at individual and organizational levels may hinder or limit environmental innovations. Innovators are crucial agents in sustainability transitions. Like all others, they show deviations from rational decision-making. Studies on environmental innovation are, however, quite disconnected from behavioral research. As a result, knowledge about the behavioral aspects of the innovation process at the niche, regime and landscape level is scarce. Table 2.3 lists the behavioral features and indicates to which barriers to environmental innovation they can be related. We have classified these using the MLP niche, regime and landscape levels.

Table 2.3 Relevance of behavioral features for environmental innovation at various transition levels

Stakeholder group	*Behavioral feature*	*Niche*	*Regime*	*Landscape*
Consumers/households	Altruism	X		
	Fairness	X		
	Status		X	
	Norms	X		
	Imitation	X		
	Habits and routines	X		
	Affect	X		
	Endowment effect	X		
	Framing	X		
	Discounting	X	X	X
	Status quo bias		X	
	Loss aversion		X	
Producers/Investors	Satisfactory strategies		X	
	Overoptimism	X		
	Career aspirations	X		
	Anchoring	X		
Governments	Political myopia			X
	Lobbying			X
	Regulatory capture			X

The niche level is the most important place where innovation happens. Firms, communities, NGOs and other niche actors generate diversity by changing the way they create products, provide services and organize activities. As part of this process, technology, the quality of products and services, and social practices can change. In the different steps of the innovation process, various behavioral biases can play a role (Suurs, 2009). First, when choosing a problem to be addressed by the innovation team certain proposals may encounter barriers because of psychological or practical resistances to change, e.g. habits or routines. As innovation is often a long-term process, predictions (about future preferences, market conditions, etc.) are important and the limited forecasting ability of innovators increases the role of subjective expectations. If these expectations are influenced by the opinions of colleagues or competitors, a herd effect can follow. Next, in the collaborative phase when ideas are generated, combined and selected, in-group relations and the personal characteristics of innovators become important. The dominance of certain members in the innovation team and individuals' career aspirations on the one hand, and mutual help and reciprocity on the other hand, can significantly influence the outcomes of group decisions. In addition, over-optimism and organizational pressure introduce biases similar to the ones explained in the *Producers* subsection. Later, when ideas and products are tested, the context can be different from real-life situations. Different perspectives taken or even the different presentation of trial results can influence decisions (Schultz, 2000; Biswas and Pechmann, 2011). This is especially important for the assessment of the policy relevance of small-scale local experiments in sustainability transitions. Finally, reviewing the performance of innovations can be costly, so decisions about continuing in the same track or switching directions is often made without complete information which can increase the role of behavioral biases. Anchoring, for example, may influence these reviews and affect the benchmarks that decision makers use in the assessment. To achieve the long-term goals of sustainability transitions, such biases have to be considered in periodical progress reviews.

Although the transitions literature focuses on niche-level innovations and talks about regimes often as resisting these changes, regime actors themselves also generate novelty. In fact, as firms grow in scale and diversity they increase investments in research and development (R&D), which is a basis of innovation (Baker and Sinkula, 1999). These innovations, however, often work against sustainability goals, as they aim to create demands for new (dirty) products and services and shape consumer preferences in line with these. Furthermore, even if innovations are improving environmental performance of sold products, they are rarely radical, partly because of the status quo bias (Samuelson and Zeckhauser, 1988; Kahneman et al., 1991). Nevertheless, even incremental changes can be very important from a resource use perspective due to the size of the associated markets. More fundamental changes can be expected if the status quo bias and the perceived risks of losing ground through unsuccessful “green” investments can be reduced.

At the landscape level, innovation refers to changes in high-level policies or large-scale changes in social practices. Policy makers, of course, are not exempt from behavioral biases, so providing decision-support tools for them can often improve their choices. Research institutes, universities and consulting agencies can provide these tools. At the same time, rationality at the individual and public level can be at odds with each other in the “commons dilemmas” of politics. One example is corruption that hampers innovative policies at the landscape level. On the other hand, landscape level changes such as population growth, ageing and climate change stress the need for innovations at all three levels. Perceptions of these changes are subject to numerous cognitive and behavioral biases that often hinder sustainability transitions (Takács-Sánta, 2007). Therefore, helping consumers, producers, investors and policy makers to overcome such barriers can foster innovation for sustainability.

Prices and price corrections are crucial in guiding innovation. Taking bounded rationality of firms and other agents as a starting point does not imply that prices are irrelevant. As argued extensively in van den Bergh (2013b), correct prices reflecting environmental externalities are a necessary condition for environmental innovations, for many reasons. Among others, without correct prices innovations are likely to go in the wrong direction or come about too slowly. However, agents do not respond efficiently or optimally to price information as is assumed by the rational actor model, which suggests an improved understanding of agent responses to pricing policy and probably the need for additional instruments like information provision.

The connection between innovation studies and gender differences has not received much attention. Samson (2006), in a review on gender and innovation, states that gender issues are usually not considered in science, technology and innovation studies. This results in an incomplete understanding of innovation at the firm level and potential gaps in innovation policy advice. Investigating gender and innovation in Norway, Ljunggren et al. (2010) point out that innovation studies have focused almost exclusively on industries dominated by men while there is a lack of research in industries dominated by women, such as service and public sectors.

2.6 Translating behavioral insights into policy fostering a sustainability transition

In this section we use the previous insights on behavior of the various stakeholders in transitions to identify policy instruments that can foster such transitions in the future. Table 2.4 links the most important behavioral features to particular policies. Here behavioral factors are classified into two main categories, namely other-regarding preferences and bounded rationality. Note that Table 2.2 and 2.3 can be connected to this as providing links to the specific stakeholders and transition levels and phases. This allows us to define more specific policies for each transition level, as shown in Table 2.5. Both tables are discussed in detail below.

With regard to Table 2.4, the following comments are in order. A first set of behavioral features important for policy design are altruism and reputational concerns. These may stem from intrinsic motivations that can be discouraged by extrinsic motivations like rewards and punishments. Shimshack and Ward (2005), investigating the case of conventional water pollutants in the US, find that concerns about reputation have very strong effects. If certain plants in a regulatory area are fined, their neighbors carefully observe their case and learn from this experience: they respond nearly as strongly to a sanction as the fined firm itself. According to Caplan (2003), repeated interaction between a firm and its consumers can lead to self-regulation. As a result, when an environmentally damaging firm is continuously interacting with consumers, the firm will tend to improve its image and become “cleaner” so as to improve its reputation. In response, policy makers may periodically request public reports from firms, which stimulates concerns about reputation to contribute to better environmental performance.

Public perception of environmental policies depends on behavioral features of stakeholders. One example is inequity aversion, which suggests that fairness is crucial for gaining public support for policy. This has been shown to be relevant in the case of road pricing (Jakobsson et al. 2000, Fujii et al., 2004), travel demand management measures (Eriksson et al., 2006), and a CO_2 emission tax in the transport sector (Hammar and Jagers, 2007). To increase the social-political acceptability of Pigouvian taxes and reduce tax evasion, the fairness of revenue recycling from such taxes is essential (Kallbekken et al., 2011).

The behavioral features of stakeholders in a transition can be used in different ways in transition policy design in order to facilitate behavioral change and overcome inertia. If, for example, self-image and status considerations stimulate environmentally damaging consumption, then one may try to re-direct these aspirations towards more sustainable alternatives through the use of ’green’ role models (Martikainen, 2009). For this purpose, green status goods would be needed. In addition, the transmission of unsustainable norms can be discouraged by paying more attention to the environmental behavior of influential people and organizations. Furthermore, community values can be strengthened to reduce the emphasis on status and image in society. This seems very difficult today in our “anonymous society without borders”, but a number of small-scale community-based movements illustrate the increasing dissatisfaction with dominant consumer behaviors (O’Riordan, 2013). These new values may arise as voluntary actions and bottom-up initiatives. However, for diffusion some of above mentioned behavioral barriers need to be overcome. In order to be more easily and broadly accepted by different groups in society, community-based movements and NGOs focused on environmental issues and transitions to sustainability may be helpful or even critical.

Information provision by the government can affect perceptions of climate change and associated decisions by stakeholders. In this context framing of information is important (Gifford and Comeau, 2011). It has been shown that focusing on the benefits of mitigation instead of the negative consequences of inaction can increase positive attitudes towards mitigation (Spence and Pidgeon, 2010). The complexity of communication is a further important aspect of framing.

Too complex messages about environmental behavior can provide opportunities for people to use psychological defense mechanisms that hinder behavior change (Antal and Hukkinen, 2010).

Policy needs to understand the reasons for the reluctance to change unsustainable consumption behaviors. The endowment effect and the affect attributed to things we own are important here. For example, the modal shift from car use to public transport is often perceived as a loss of individual freedom. This calls for policy efforts to more carefully explain the various benefits that citizens may derive from an envisioned policy change. For example, proposals for car free pedestrian areas in downtown districts often meet with strong resistance from shop owners, local residents and visitors coming by car. However, once implemented many of these people turn out to highly value such pedestrian areas, which suggests that communication with citizens about policy consequences can and should be improved. In addition, understanding of how positive emotions relate to environmentally harmful consumption is crucial because giving up behaviors associated with these emotions is very difficult due to the endowment effect. Another strategy is to build affective connections with the natural environment to sort of foster an endowment effect with the environment. This may then contribute to creating strong motivations for environmental conservation (Hinds and Sparks, 2008).

Policy should reckon with additional reasons for inertia, notably firm routines and consumer habits. Without awareness and self-reflection, managers and consumers often stick to their traditional ways of doing things (Carrus et al., 2008). The first step to change these routines and habits is building awareness. In the case of industrial routines, for example, awareness training of appropriate experts can stimulate the incorporation of environmental standards in the design and management of the production system (UNIDO, 2008). In the case of consumers, a combination of incentives, regulatory tools, and norms can be effective to change habits. In practice, this means that besides traditional policies like pollution pricing or regulation, insights from social psychology can be implemented in the form of particular instruments to change habits. Examples are providing information about environmentally relevant, comparative behaviors (e.g., regarding energy or water use) of neighbors, households with similar socio-economic features, or other users such as in the context of tourism or transport (Schultz et al. 2007; 2008).

Table 2.4 Policy instruments classified along behavioral features

	Behavioral feature	Policy implications and instruments
Other-regarding preferences	Altruism/Reputation	The supply of public goods strongly depends on the level of altruism. Repeated interaction between a firm and its consumers can lead to self-regulation. By reinforcing the interactions between firms and consumers or obliging firms to periodically report their environmental performance, this can improve as a result of concerns about reputation.
	Fairness	Different examples such as road pricing, travel demand management measures, and a CO_2 emission tax in the transport sector show that fairness is crucial for policy acceptance.
	Moral and normative concerns	The literature shows that taking into account the probability of being caught in evading taxes, people should evade more. The motivation of doing the right thing increases people's willingness to pay. For example, if a particular behavior is normally considered shameful, the introduction of fines might lead to counter-productive results. Similarly, if a particular behavior is considered as the right thing to do, financial rewards can erode this feeling (crowding out).
	Status	In order to re-direct aspirations that stimulate environmentally damaging consumption towards more sustainable options, green status goods may be useful. Community values can be strengthened to reduce the emphasis on status and image in society.
	Reciprocity	Different experimental studies show that people act favoring members of the same group compared to out-group members. Creating niche networks will improve collaboration between niches and thereby increase the power the overcome or resist regime backlashes.
	Imitation/Critical masses	Imitation can both hinder and foster a transition. Imitation of environmentally damaging habits can act as a barrier to transitions. On the other hand, imitation of environmentally beneficial habits can contribute to the likelihood of sustainability transitions. When a critical mass of people imitating and diffusing the same innovation is reached, imitation becomes a force that helps the transition instead of hindering it. The use of influential role models is important for achieving critical masses.
	Lobbying	Structural reasons of bounded rationality at the collective level include political myopia (election cycles, party interests and personal interests of politicians and public officers), stakeholder involvement in power games (e.g., lobbying), the lack of direct accountability to voters, and regulatory capture. These biases are important for transition policies which have to balance long-term societal goals with short-term concerns.

Bounded rationality	Habits, routines/satisfying	Policy should reckon with additional reasons for inertia, notably firm routines and consumer habits. Managers and consumers often stick to their traditional ways of doing things. These routines can be changed by building awareness. Awareness training of appropriate experts can stimulate the incorporation of environmental standards in the design and management of the production system in the case of industrial routines. A combination of incentives, regulatory tools, and norms can be effective to change consumer habits. Insights from social psychology facilitate changes in habits.
	Affect	Understand the reasons for reluctance to change unsustainable consumption behavior. Insight into consumers' psychological valuation of consumer goods is important. Crucial aspects are to understand how positive emotions relate to environmentally harmful consumption and how to build affective connections with the natural environment.
	Framing	Information provision by the government can affect perceptions of climate change and associated decisions by stakeholders. Focusing on the benefits of mitigation instead of the negative consequences of inaction can increase positive attitudes towards mitigation.
	Discounting	People have been found to discount more strongly in contexts of environmental impacts, like investing in renewable energy or energy conservation equipment, than in a purely financial context.
	Over-confidence	Investors overestimate the probabilities of certain outcomes (and their own ability to predict these outcomes). Understanding the basis of investor behavior can help to devise appropriate incentive schemes, information strategies and regulations. Overconfidence can make regulatory intervention necessary to reduce cyclicality in the economy.
	Over-optimism	Organizational pressure and two cognitive biases known as anchoring and competitor neglect make firms overly optimistic. In the case of environmental problem solving this can have detrimental effects that need to be addressed.
	Disposition effect	Investors sell winning shares quickly and hold loosing shares for longer periods. The perception of potential losses and gains determine people's choices in risky situations, not the expected utility that can be calculated from a concave utility-of-wealth function. Understanding such behavioral biases is crucial in dealing with transitions of complex systems where uncertainties abound.
	Equity premium puzzle	Investors buy bonds even if stocks in the long run perform consistently better. This behavior can be caused by loss aversion combined with frequent evaluation of portfolios by agents relying on "mental accounting". Here, more frequent access to information about stock/bond returns can be disadvantageous, because it shifts investments to the least risky assets offering the lowest returns in the long run. This may be bad news for investments in risky sustainability projects.

Table 2.5 Transition policies in a multi-level perspective framework and stakeholders affected

Level	Policy measure	Example	Consumers	Innovators	Producers	Investors	Financial Sector
Niche	Policies supporting niches	Grants for conversion to organic farming		X			
	Support for the creation of niche networks between various stakeholders	Fostering communication between stakeholders, fostering access to credit		X		X	X
	Stimulation of local experiments	Public co-funding of bottom-up initiatives		X		X	X
	Policies to escape lock-in	Reforming fossil fuel subsidies, setting strict long term environmental goals, creating infrastructure conditions for new technologies		X	X		
Regime	Support for the expansion of a sector through subsidies or price guarantees	Feed-in tariffs for renewable electricity	X	X	X	X	X
	Policies limiting the power of regimes	Limiting size of firms, no privileges or more frequent contacts with particular firms or representative organizations, transparency of lobbying processes		X	X		
	Promotion of technical or resource diversity	Public R&D investments and subsidizing private R&D		X	X		
	Regulating dirty activities	Pollution taxes or tradable permits, command-and-control of pollutive technologies and products	X	X	X	X	X
Landscape	Promotion of civic debate	Public participation in policy development (round tables).	X		X		
	Information provision	Informative campaigns for consumer behavior	X	X	X		
	Creation of informed debate	Supporting public participation in setting the policy agenda	X		X		
	Developing policy integration (technology, environment, consumers)	Making one ministry responsible for coordinating all initiatives and policies concerning long term sustainability transition	X	X	X		

With regard to Table 2.5, we can comment on the policy relevance of the three-part level division. The first set of policies in the table is aimed to support innovative niches. An example is providing grants in the agricultural sector for conversion to organic farming. The second measure considered is those of supporting the creation of niche-networks. These measures try to create a network between producers, innovators, investors and the financial sector in order to help innovators get access to credit, for example. Other policies, which focus on the niche level, are those designed to stimulate local experiments and elevate these to a national level. They influence mostly innovators carrying out local experiments and the financial sector and investors, which may direct the financial flows thereby supporting these experiments. Finally, measures that are on the border between the niche and regime level are policies stimulating escape from existing lock-in of regime-related technologies or practices.

At the regime level we classify policies supporting the expansion of a whole sector, such as subsidies in favor of renewable energy options, which have a major effect on all the stakeholders. Consumers, producers and innovators are especially affected because the support reduces the price of energy. Subsidies will also create a market for innovators who can invest in R&D in order to produce more efficient products, such as PV cells. Producers are affected since they may qualify for the grants and thereby sell renewable energy at subsidized prices. Financial companies and investors may take advantage in order to invest in the sector. These policies influence mostly producers and innovators, and their market opportunities. The last types of policies at a regime level treated are those supporting the development of a sector by pricing pollutants, for example CO_2. In this case, producers are affected negatively since the cost of producing dirty goods will increase as a result of taxation or price changes. Consumers are also influenced since they may change their consumption behaviors as a result of a change in prices. Innovators are affected as altered prices will change the profits associated with certain directions of innovation. In turn, investors and financial organizations are affected negatively or positively depending on the sector (dirty or clean) in which their investments are concentrated.

Measures at the landscape level can be the promotion of civic debate, for example, on the use of chemicals. Consumers are affected since they are involved in the civic debate and producers because the measures may affect the way they produce or test their products. Similar measures are those based on information provision. To highlight the potential effectiveness of behaviorally sound environmental policies, Abrahamse et al. (2007) demonstrate how a number of interventions such as customized information, goal setting and tailored feedback can improve energy saving behavior. These measures have to take into account people's ability to imitate and use cheap channels of learning. Here the identification and use of the most influential role models and actors, perhaps by awarding prizes (Nannen and van den Bergh, 2010), may increase policy effectiveness. Another type of measure at a landscape level are policies creating informed debate – such as public participation in policy development – through mechanisms like meetings and round tables. Involving citizens in policy design may positively influence the likelihood of a sustainability transition. Frey and Stutzer (2002) find that the participatory program used by Swiss districts in the form of referendums makes people feel involved and happier. Comparing eligible voters with non-eligible foreigners living in these districts, it becomes clear that two-thirds of the well-being improvement can be attributed to participation itself while only one third is the result of actual policy improvements. Broader citizen participation in political decisions can improve the social-political feasibility of new policies.

2.7 Conclusions

The need for a future transition to a sustainable economy is widely recognized. How to realize it is subject to much debate and disagreement. This paper was aimed at contributing to this debate with insights about the behavioral foundations of transitions – in terms of barriers as well as opportunities. The findings of this article offer new perspectives on transition policies.

Transitions are difficult to foster given impeding factors such as increasing returns to scale and path-dependency, which regularly result in lock-in into suboptimal solutions. Moreover, the power of vested interest groups and behavioral anomalies such as non-rational resistance to change can hamper a transition. Various social theories emphasize different enabling and hampering factors of transitions. Whether they see stakeholders as fully rational, e.g. in their response to policies, consider agents as boundedly rational, or pay more attention to power relations, has an influence on their policy recommendations. Since behavioral biases constitute important causes of inertia, stakeholders involved in transitions (consumers, producers, investors and governments) have been examined from the perspective of behavioral economics. Insights will help to formulate transition policies that can effectively influence the direction and speed of sustainability transitions.

A first stakeholder group whose decisions have important consequences for the environment are consumers or households. A number of consumer behaviors that involve bounded rationality or other-regarding preferences may be considered in transition policy design. Important biases such as habits, status quo bias, affect and imitation contribute to inertia. Transition strategies need to reduce the strength or effects of these biases. Altruism, fairness and effects of framing influence levels of cooperation, acceptance of policies and perceptions of environmental and technological risks. These relationships should not be neglected when crafting transition policies. Norms and rules evolving in groups have important consequences too. Understanding group behavior and the role of leaders in organizations, role models, and potential change agents suggests on which actors sustainability transition policy should focus more attention.

A second group of stakeholders consists of producers and investors. Producers are often over-optimistic and their decisions are affected by anchoring. Instead of perfect profit-maximization firms usually stick to satisfactory strategies, convert these into routines, and change only when profits drop below the market average (or profits of competitors). Changing existing routines through awareness training of appropriate experts and consumer habits by a combination of incentives, regulatory tools, and norms will help firms and consumers accept changes and thereby foster a sustainability transition. Similarly, investors – who allocate capital and thereby have a very large influence on the speed of transitions – show different behavioral anomalies.

A third group of stakeholders includes governments at various levels. In the context of sustainability transitions, it is important to keep in mind that governments are made up by groups and individuals that have their own self-interests and behavioral characteristics. They usually operate outside markets, so that they are not subject to the same incentives as producers (and to a lesser extent consumers) to behave rationally. Furthermore, the policies made by governments have to consider the behavioral features of economic actors. Issues that matter for policy effectiveness are framing that changes risk perceptions, fairness that influences policy acceptance, and status, affect and habits that contribute to inertia.

Processes of innovation, at different transition levels and by different stakeholders, are crucial to a sustainability transition. The change in preferences from consumers, technological innovation of producers, the adoption of new ethical standards by investors, and innovative policies of governments are examples of this. Behavioral issues throughout the innovation process have been analyzed at the niche, regime and landscape level. At the niche level where most innovation happens, barriers to change include habits and routines. The innovation process can be affected by over-optimism, organizational pressure, career aspirations of group members and various group interactions. At the regime level status quo bias has been identified as a potential obstacle to change. At the landscape level problems associated with the perceptions of changes such as population growth, aging and climate change, have been pointed out as relevant.

After depicting the behaviors of the various stakeholders, we moved on to the next step, namely defining policies linked to each specific stakeholder and behavior, intended to foster a sustainability transition. We used here the classification of levels (niche, regime and landscape) following the MLP framework. In addition, we described the impact that such policy measures may have on the different actors, and indirectly on the sustainability transition. We introduced the approaches or concepts of 'strategic niche management', transition management and niche networks, as they consider the different actors involved in transitions and their interaction. Our conclusion is that these approaches shed insufficient and non-systemic light on the particular behavioral features of the various stakeholders in the design of transition policies.

It is clear that a transition toward sustainability is a very complex process in which different stakeholders play specific roles at each stage and level. We have derived general and specific implications for transition policy of recognizing bounded rationality and social interactions by various stakeholders. This included giving attention to multiple levels, different stakeholders, and behavioral biases as well as social interactions. Periodical request of public reports from policy makers can attribute to a better environmental performance from firms. Re-directing consumption aspirations towards more sustainable alternatives through the use of "green role" models or the creation of green status are two other important behavioral issues which transitional studies should take better into account. We underline the importance of the endowment effect and in sustainability transition studies. Building affective connections with natural environment contribute to create strong motivations for environmental conservations. Furthermore, information framing is another issue requiring attention since people can use psychological defense mechanisms that hinder behavior change when exposed to complex messages about environment behavior.

The methodological added value of our framework is that it adds a coherent behavioral basis for theoretical or empirical research (including case studies of transitions that otherwise run the risk of being ad hoc and not well connected to general behavioral insights as presented here, and thus providing non-robust insights about effective transition policies and strategies. Our framework can guide such studies with the aim to improve conditional forecasting of individual and system responses when subject to a set of transition policies.

Chapter 3

How realistic is green growth? Sectoral-level carbon intensity versus productivity[5]

3.1 Introduction

A rapid transition to a sustainable economy requires not only technological innovation and diffusion but also the development and growth of relatively clean sectors and the decline of relatively pollutive ones. To solve one of the most difficult environmental problems of our times, namely human-induced global warming, this needs to hold for greenhouse gas emissions as well. In fact, most economic studies on climate policy find that the major part of the reduction of greenhouse gas emissions in the coming decades is to be realized through structural changes in demand and supply, meaning that the composition of these alters considerably, whereas a minor contribution should be expected from technological progress (see the studies mentioned in van den Bergh, 2013, Section 2.1). Therefore, differences between sectoral growth rates will determine whether continued economic growth will be compatible with sufficiently stringent climate targets, that is, whether green growth is possible from the perspective of climate goals. Here we will offer a new empirical approach involving sector-level analysis to test the potential conflict between growth and climate change mitigation. To investigate this we do not focus on just one economic indicator but consider a variety of economic indicators. Given our focus on CO_2 emissions, this study can be interpreted as a kind of impact assessment of policies developed under the Kyoto protocol in terms of changes in the economic sector structure.

No other study exists that addresses this research question, and combines similar data, countries, two carbon intensity indicators and the variety of economic indicators. Several studies have examined the linkage between economic growth and environmental pollutants, including so-called environmental Kuznets curve studies that try to test for de-linking of per capita income and specific environmental pressure indicators (Dinda, 2004; Soyats et al., 2007; Zhang and Cheng, 2009; Menyah and Wolde-Rufael, 2010). However, all of these use aggregate data rather than sector-level data. Other studies using EEIOs and the WIOD database present an environmental impact approach without linking to economic indicators as we do, and in line with this they address other research questions (e.g., Cansino et al., 2015; Jiang and Liu, 2015; Mundaca et al., 2015; Voigt et al., 2014; Pascual-Gonzalez et al., 2015). Another study by Gilli et al. (2014) focuses on the link between environmental and economic issues, but does not include two types of carbon intensity indicators and does not perform a correlation analysis of these with various economic indicators as we do.

We employ sector-level data to test a number of specific questions or hypotheses related to green growth. The indicators we will use allow to capture different aspects of economic change, namely whether sectors that are more pollutive in terms of CO_2 emissions per monetary output

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(what we call carbon intensity[6]) generally are associated with a higher rate of growth (in output, final demand or value added terms), an increase in the share in total output, a higher labor productivity (in output or value added terms), and a higher labor productivity growth (in output or value added terms). We suspect that a high intensity of technology is at the basis of both a combination of high and increasing labor productivity, which fuels growth, and high emission intensity, which fuels climate change. The reason for the latter might be that intense technology use is generally associated with high energy use.

Our study is motivated by the following questions:

- Is green growth difficult to realize as dirtier sectors grow quickly in absolute terms?
- Is green growth difficult as the share of dirtier sectors (even if they become cleaner) increases in the economy?
- Is the dynamics of final demand consistent with green growth?
- Are sectors with high carbon intensity important for longer-term growth in view of sectoral growth patterns in value added terms?
- Is it in view of labor productivity dynamics likely that future output growth (or long-term growth reflected by value added dynamics) will be generated disproportionally in relatively dirty sectors?

In our empirical analysis aimed at testing these (and other) questions we focus on three European countries with quite different economic structures: Denmark, a small country having the image of being one of more decarbonized economies among the rich countries (OECD); Germany, which represents a large industrial economy in Europe with a relatively heavy, technology-intensive industry but also with an image of being at the forefront of renewable energy and decarbonization; and Spain, a peripheral country whose economy is mostly based on sectors such as agriculture and tourism, while it had a booming construction sector in the last decades (see Table 3.2). We considered adding more countries, but finally decided to not do this for a number of reasons: the overall method is very data- and labor-intensive; since the overall method is new, our empirical study serves as a test case; and it is difficult to decide which countries first to add given that we have already contrasting examples. We are aware that other studies dealing with related issues (i.e. economic structure and emissions), often using EEIO methods, cover more countries. However, it should be realized that our study is broader than just an EEIO analysis incorporating the construction of various carbon intensity and economic indicators, as well as analyzing their relationships.

We use environmental and productivity data obtained from the World Input-Output Database (WIOD, 2014). Although this database includes environmental data for the period 1995 to 2009 and economic data for the period 1995-2011, we limit our study to the period 1995-2007 in order to exclude any effects of the financial-economic crisis which started in 2008. Including the crisis years would distort the picture arising from our analysis: it would make interpretations of the results considerably more difficult as productivity indicators would strongly fluctuate (due to falling demand rather than supply side factors), and ultimately the test would likely result to be less clear and meaningful.

We calculate two types of carbon intensity indicators, namely reflecting direct and total emissions. The direct carbon intensity of each sector accounts for emissions from its own

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[6] Carbon intensity is also used (notably by the International Energy Agency and the IPCC) to denote carbon dioxide emissions per unit of energy (e.g., http://www.iea.org/etp/tracking/esci/). A more general name for this is emission intensity. But this is not how it will be meant here. Carbon intensity in this paper strictly means CO_2 emissions per monetary output (kilotons/million US$).

technological processes, some of which deliver inputs for other sectors while others deliver the final products of the sector. Even in this "process-based" analysis we will, however, reallocate intermediate carbon emissions from energy sectors that deliver energy to other sectors to avoid an extremely unbalanced picture of emissions distribution which is merely due to the existence of separate energy sectors in the classification. For the direct carbon intensity measure only domestic sectoral CO_2 emissions are considered. In the second approach, the so-called total carbon intensity approach, CO_2 emissions are more comprehensively reallocated using environmentally extended input-output tables (Proops et al., 1993; Kondo et al., 1998; Munksgaard and Pedersen, 2001) to obtain the total, direct and indirect, emissions associated with the final goods/services produced by each sector. This approach can be seen to account for the overall emissions of a sector, taking into account the complex web of interactions among sectors, as captured by the input-output matrix of intermediate deliveries. As a result, some sectors, such as "Construction", which look relatively clean in direct intensity terms because indirect emissions associated with the production of construction materials are disregarded, appear (as intuitively expected) more pollutive according to the total intensity indicator. In this second approach we consider also carbon emissions associated with imported goods. This gives an indicator of the total pollutiveness of economic sectors in terms of direct and indirect, including international, CO_2 emissions. Note that both approaches reflect emissions from production and not consumption, that is, our approach is production-based. A consumption-based approach would instead require assessing which part of production and imports ends up in national consumption. However, we include all production and all imports, including intermediate ones.

To analyze the combined economic and carbon intensity performance of sectors we perform a correlation analysis between the carbon intensity indicators calculated with the two approaches and a range of economic indicators:[7] correlation between carbon intensity and the rate of change in total sectoral output and relative sectoral output growth allows testing if growth in total output and carbon emissions was correlated or not; correlation between carbon intensity and the change in final demand allows testing the role of consumer demand (versus inter-industry demand); and correlation between carbon intensity and sectoral value added allows testing the long term relation between pollutiveness and sectoral growth. To answer the questions related to labor productivity issues, we use two indicators of labor productivity, namely the ratio of annual sectoral output and annual hours worked, and the ratio of annual sectoral value added and annual hours worked. These two indicators serve complementary roles. The second can be regarded as capturing longer-term aspects than the first, in the sense that if a sector generates much output but relatively little value added then its long-run viability would be at stake. Of course, one cannot expect value added to capture all relevant long term aspects, that is, it is not a perfect indicator of long-run performance and viability of a sector.

The remainder of this article is organized as follows. Section 2 introduces the data. In Section 3 we calculate carbon intensity with the direct and total emissions approaches. Section 4 presents calculations for the economic and productivity indicators. In section 5 we answer the specific and general questions by calculating correlations between the two carbon intensity measures on the one hand, and the economic and productivity indicators on the other. Section

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[7] Regressions do not make much sense in this case as we are looking at the relations between two variables without assuming any one-directional causality. Another alternative, namely time series analysis, is unsuitable because of the limited time period. Moreover, our concern, as expressed in the research questions in Table 3.5, is not with particular temporal fluctuations over time, which makes time series analysis anyway less relevant for our purpose. As we are interested in correlating long term changes (trends) for carbon intensity and various economic indicators, it is sufficient to focus on average/total changes over the entire period. This is in a nutshell the approach followed here.

6 pulls all the different empirical insights together, providing interpretations and a general conclusion.

3.2 Data and method

In order to test our hypotheses, we used data from the WIOD database with environmental, input-output and other socio-economic data (WIOD, 2014). The database includes observations from 1995 to 2011 for 40 different countries. The data are classified into 34 different economic sectors corresponding to the categories used by Eurostat.[8]

Environmental data include energy use, carbon emissions, waste, land use etc. Based on the carbon emissions data we derive a carbon intensity index as the ratio between sectoral carbon emissions and sectoral output.

For the process-based analysis we use National Input-Output Tables (NIOTs), which are of the industry-by-industry type (Miller and Blair, 2009). The values in these tables are basic prices expressed in US dollars.[9] As the tables are presented in current year prices, they are deflated to 1995 in order to exclude the effects of inflation.[10] The carbon emissions from the 34 industrial sectors are used in the calculation of the carbon intensity in the process-based analysis. We note that the 34-sector classification is not optimal for our analysis as it includes energy sectors with very high CO_2 emissions, which however can be regarded as the direct responsibility of other sectors to the extent they use electricity and other types of energy supplied by the energy sectors. For this reason, we redistribute the intermediate deliveries of the energy sectors on the basis of the yearly input values presented in the NIOTs.

In the product-based analysis, we redistribute emissions connected to intermediate interactions of all economic sectors using the relevant NIOTs, including emissions related to intermediate deliveries that are imported. The World Input-Output Tables (WIOTs) are used to obtain these import values. They are consistent with the country-level NIOTs, and are also expressed in basic, current year prices. Again yearly deflators are applied to express values in 1995 US dollars. From the WIODs we can see the cross-national intermediate transactions (imports from the perspective of the country studied), that is, from a sector A in country 1 to a sector B in country 2. After adding up the emissions embodied in imports and those emitted within the country, environmentally extended input-output analysis using the NIOTs is applied to complete the product-based analysis.

The study covers three countries: Denmark, Spain and Germany. Table 3.1 provides an overview of basic indicators for the three countries studied. It shows that aggregated domestic carbon intensity increased by 4.76% in Denmark and decreased by 26.57% and 13.37% in Germany and Spain, respectively. Improvements happened as a result of innovation, the adoption of cleaner technologies and practices in sectors such as ‘Electricity gas and water supply’, ‘Air transport’, or relocation of the most pollutive sectors, like ‘Mining and quarrying’ or ‘Leather, leather and footwear’, to other countries. Simultaneously, clean tertiary sectors increased their share in the economy. The rapid and unsustainable growth of the financial sector in the run-up to the crisis produced a virtual improvement, especially in Spain. Table 3.1 also

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[8] The database was originally developed with the purpose of analyzing environmental pressure and socio-economic development, and the effects of globalization on trade patterns, for a wide set of countries. The database covers 27 EU countries and 13 other major countries in the world for the period from 1995 to 2011. All other countries are included in an aggregate category called “rest of the world”.

[9] The main reason to opt for NIOTs in basic prices rather than in purchaser’s prices is that the first excludes costs associated with transportation and trade, which better reflects the underlying cost structures of industries.

[10] In order to deflate the input-output tables we used sectoral level deflation indicators obtained from the WIOD project.

reports total carbon emissions for the two years in each country, and the rate of change in these during the period observed. This shows that while average carbon intensity went down in two of the three countries, total carbon emissions increased considerably in Denmark and Spain (52.61 and 41.45% increase, respectively) and remained roughly constant in Germany (namely, a reduction of only 2.90%). Finally, all economic indicators reported in Table 3.1 are positive in the studied period.[11]

Table 3.1Overview of core indicators for the three countries

Year	Indicator	Denmark	Germany	Spain
1995	Carbon intensity	0.213	0.169	0.179
	Carbon emissions	63631	724704	203336
	Total output	298141	4282897	1137233
	Final demand	198195	2674537	650863
	Value added	157259	2277173	550710
	Output labor productivity	84.06	87.71	61.86
	Value-added labor productivity	44.34	46.63	29.95
2007	Carbon intensity	0.224	0.124	0.155
	Carbon emissions	97109	703170	287621
	Total output	434315	5658954	1856952
	Final demand	586840	3603271	1057414
	Value added	201207	2756611	839574
	Output labor productivity	105.28	119.96	65.22
	Value-added labor productivity	48.77	58.44	29.49
Rate of change	Carbon intensity	4,76%	-26.57%	-13.37%
	Carbon emissions	52.61%	-2.90%	41.45%
	Total output	45.67%	32.13%	63.29%
	Final demand	44.73%	34.73%	62.46%
	Value added	27.95%	21.05%	52.45%
	Output labor productivity	25.24%	36.78%	5.44%
	Value-added labor productivity	10.00%	25.31%	-0.02%

The rate of change in carbon intensity at the sector level is presented in Table 3.2. In the case of Denmark, the sector 'Leather, leather and footwear' increased its carbon intensity with 135.83%. Other sectors that increased carbon intensity were 'Water transport', 'Construction' and 'Inland transport', while the majority of sectors reduced their carbon intensity. Germany's large average reduction in carbon intensity (26.57%) is due to the fact that all but one sector saw their intensity drop. The exception is the sector 'Other community, social and personal services' which increased its carbon intensity with 15.20%. Of all three countries, Spain shows the smallest number of sectors with decreasing carbon intensity. Like in Denmark, 'Leather, leather and footwear' and certain transport sectors show a sharp increase in intensity.

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[11] Appendix 1 displays the carbon emissions, total output and value added for the three countries in absolute values and percentages at a sectoral level.

Table 3.2 Changes in carbon intensity of sectors (1995-2007)

Denmark		**Germany**		**Spain**	
Leather, Leather and Footwear	135.83%	Other Community, Social and Personal Services	15.20%	Leather, Leather and Footwear	94.20%
Water Transport	36.17%	Mining and Quarrying	-3.08%	Air Transport	75.18%
Construction	19.63%	Inland Transport	-4.58%	Water Transport	47.13%
Inland Transport	13.64%	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	-7.59%	Textiles and Textile Products	37.78%
Basic Metals and Fabricated Metal	4.05%	Air Transport	-7.96%	Hotels and Restaurants	29.23%
Other Community, Social and Personal Services	3.94%	Other Non-Metallic Mineral	-8.70%	Real Estate Activities	9.26%
Other Non-Metallic Mineral	3.83%	Hotels and Restaurants	-16.19%	Inland Transport	7.99%
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	1.16%	Pulp, Paper, Paper , Printing and Publishing	-17.89%	Mining and Quarrying	7.75%
Mining and Quarrying	-0.59%	Construction	-20.95%	Food, Beverages and Tobacco	6.74%
Transport Equipment	-1.40%	Basic Metals and Fabricated Metal	-24.58%	Education	6.35%
Pulp, Paper, Paper , Printing and Publishing	-3.74%	Coke, Refined Petroleum and Nuclear Fuel	-25.06%	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	1.32%
Manufacturing, Nec; Recycling	-4.16%	Manufacturing, Nec; Recycling	-28.33%	Other Community, Social and Personal Services	1.10%
Education	-4.88%	Food, Beverages and Tobacco	-29.34%	Public Admin and Defence; Compulsory Social Security	-1.03%
Air Transport	-5.47%	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	-31.37%	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	-3.74%
Health and Social Work	-9.26%	Education	-31.72%	Health and Social Work	-5.10%
Real Estate Activities	-10.35%	Electricity, Gas and Water Supply	-31.84%	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	-5.13%
Rubber and Plastics	-11.75%	Health and Social Work	-34.51%	Pulp, Paper, Paper , Printing and Publishing	-5.62%
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	-13.77%	Real Estate Activities	-34.95%	Wood and Products of Wood and Cork	-5.68%
Machinery, Nec	-14.66%	Chemicals and Chemical Products	-36.55%	Construction	-6.46%
Food, Beverages and Tobacco	-17.29%	Post and Telecommunications	-37.62%	Manufacturing, Nec; Recycling	-10.76%
Renting of M&Eq and Other Business Activities	-22.90%	Wood and Products of Wood and Cork	-37.67%	Electrical and Optical Equipment	-14.98%
Agriculture, Hunting, Forestry and Fishing	-24.98%	Public Admin and Defence; Compulsory Social Security	-37.79%	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	-15.36%
Coke, Refined Petroleum and Nuclear Fuel	-28.03%	Renting of M&Eq and Other Business Activities	-38.03%	Agriculture, Hunting, Forestry and Fishing	-16.90%
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	-28.82%	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	-44.04%	Chemicals and Chemical Products	-16.97%
Electricity, Gas and Water Supply	-30.91%	Rubber and Plastics	-44.10%	Rubber and Plastics	-22.06%
Hotels and Restaurants	-31.95%	Financial Intermediation	-45.57%	Renting of M&Eq and Other Business Activities	-23.13%
Textiles and Textile Products	-32.07%	Machinery, Nec	-50.05%	Financial Intermediation	-26.52%
Wood and Products of Wood and Cork	-32.43%	Agriculture, Hunting, Forestry and Fishing	-50.14%	Machinery, Nec	-27.25%
Public Admin and Defence; Compulsory Social Security	-35.07%	Transport Equipment	-59.20%	Transport Equipment	-27.40%
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	-36.78%	Electrical and Optical Equipment	-64.39%	Basic Metals and Fabricated Metal	-29.27%
Electrical and Optical Equipment	-41.21%	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	-66.54%	Other Non-Metallic Mineral	-33.07%
Financial Intermediation	-55.31%	Textiles and Textile Products	-67.33%	Electricity, Gas and Water Supply	-34.14%
Chemicals and Chemical Products	-59.49%	Leather, Leather and Footwear	-80.43%	Coke, Refined Petroleum and Nuclear Fuel	-46.45%
Post and Telecommunications	-67.89%	Water Transport	-90.41%	Post and Telecommunications	-54.96%
Total	4.76%	Total	-26.57%	Total	-13.37%

3.3 Carbon intensity

3.3.1 Calculating carbon intensity using the direct intensity emissions approach

In the direct emissions analysis only CO_2 emissions produced by the different sectors in the given country are considered. Direct carbon intensity, i^d, is calculated for each sector *s* by dividing the sum of direct sectoral carbon emissions in year *t* by sectoral output in the same year.[12] Note that the sectoral classification in WIOD is not ideal for this study since the carbon emissions that are accounted in energy sectors, such as 'Electricity, gas and water supply' and 'Coke, refined petroleum and nuclear fuel', are used in the production of other sectors. For this reason, a reallocation of carbon emissions of energy sectors is undertaken in accordance with the intermediate economic interactions presented in the yearly NIOTs. By realizing such a reallocation, only the part of CO_2 emissions used by the energy sectors itself is left attributed to these sectors, while the part used by other sectors for their production is redistributed to these (i.e. reallocated).

The resulting carbon intensity values for the different economic sectors in the three countries are displayed in Table 3.3. These represent the averages of carbon intensity in 1995 and 2007. The table shows that the most carbon-intensive sector in Denmark and Germany is 'Electricity, gas and water supply', while in Spain it is 'Other non-metallic mineral'. Other sectors which are high in the ranking in all three countries are transport sectors such as 'Water transport' and 'Air transport', and sectors such as 'Coke, refined petroleum and nuclear fuel' and 'Mining and quarrying'. The cleanest sectors, showing very low carbon intensity, are the tertiary sectors: 'Financial intermediation', 'Education' and 'Real estate activities'.

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[12] Note that for each year a first redistribution of carbon emissions according to the intermediate economic interactions (in NIOTs) was made.

Table 3.3 Carbon intensity (average of 1995 and 2007) according to the direct intensity emissions approach; sectors for each country ranked from high to low

Denmark		**Germany**		**Spain**	
Electricity, Gas and Water Supply	2.880	Electricity, Gas and Water Supply	1.693	Other Non-Metallic Mineral	1.746
Water Transport	1.926	Air Transport	1.130	Water Transport	1.129
Coke, Refined Petroleum and Nuclear Fuel	1.535	Other Non-Metallic Mineral	0.869	Air Transport	0.933
Other Non-Metallic Mineral	1.192	Mining and Quarrying	0.46	Electricity, Gas and Water Supply	0.869
Air Transport	1.105	Water Transport	0.444	Coke, Refined Petroleum and Nuclear Fuel	0.65
Mining and Quarrying	0.751	Basic Metals and Fabricated Metal	0.399	Inland Transport	0.641
Inland Transport	0.311	Coke, Refined Petroleum and Nuclear Fuel	0.396	Mining and Quarrying	0.472
Agriculture, Hunting, Forestry and Fishing	0.242	Chemicals and Chemical Products	0.274	Basic Metals and Fabricated Metal	0.296
Food, Beverages and Tobacco	0.108	Agriculture, Hunting, Forestry and Fishing	0.211	Chemicals and Chemical Products	0.289
Chemicals and Chemical Products	0.086	Inland Transport	0.203	Agriculture, Hunting, Forestry and Fishing	0.228
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0.081	Textiles and Textile Products	0.151	Pulp, Paper, Paper , Printing and Publishing	0.172
Basic Metals and Fabricated Metal	0.08	Pulp, Paper, Paper , Printing and Publishing	0.144	Textiles and Textile Products	0.138
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0.072	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0.13	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0.138
Rubber and Plastics	0.07	Food, Beverages and Tobacco	0.115	Rubber and Plastics	0.107
Other Community, Social and Personal Services	0.067	Leather, Leather and Footwear	0.115	Wood and Products of Wood and Cork	0.106
Hotels and Restaurants	0.062	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.111	Food, Beverages and Tobacco	0.099
Wood and Products of Wood and Cork	0.06	Hotels and Restaurants	0.103	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.082
Construction	0.058	Rubber and Plastics	0.098	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.081
Textiles and Textile Products	0.058	Wood and Products of Wood and Cork	0.097	Other Community, Social and Personal Services	0.078
Education	0.057	Post and Telecommunications	0.084	Public Admin and Defence; Compulsory Social Security	0.066
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.056	Education	0.077	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0.061
Pulp, Paper, Paper , Printing and Publishing	0.055	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0.077	Transport Equipment	0.057
Public Admin and Defence; Compulsory Social Security	0.053	Other Community, Social and Personal Services	0.066	Leather, Leather and Footwear	0.056
Transport Equipment	0.049	Public Admin and Defence; Compulsory Social Security	0.064	Machinery, Nec	0.054
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.047	Manufacturing, Nec; Recycling	0.064	Health and Social Work	0.048
Leather, Leather and Footwear	0.047	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.059	Manufacturing, Nec; Recycling	0.047
Manufacturing, Nec; Recycling	0.043	Health and Social Work	0.055	Post and Telecommunications	0.043
Health and Social Work	0.041	Machinery, Nec	0.054	Construction	0.04
Machinery, Nec	0.036	Transport Equipment	0.053	Hotels and Restaurants	0.04
Post and Telecommunications	0.029	Construction	0.053	Electrical and Optical Equipment	0.038
Renting of M&Eq and Other Business Activities	0.026	Electrical and Optical Equipment	0.045	Renting of M&Eq and Other Business Activities	0.033
Electrical and Optical Equipment	0.019	Renting of M&Eq and Other Business Activities	0.045	Education	0.031
Financial Intermediation	0.013	Real Estate Activities	0.03	Financial Intermediation	0.025
Real Estate Activities	0.008	Financial Intermediation	0.027	Real Estate Activities	0.009

3.3.2 Calculating carbon intensity using the total emissions approach

In order to test our hypotheses on the relation between carbon intensity and sectoral economic growth and labor productivity change we need to account for certain aspects of complex economies. First, energy sectors producing a lot of carbon dioxide emissions tend to supply their services to other sectors. This holds for sectors like 'Electricity, gas and water supply' and 'Coke, refined petroleum and nuclear fuel'. They do not provide energy only to households. A large part of their output goes as intermediate inputs to other production sectors. Such inputs are even essential for these to function and survive. Second, manufacturing of most products is increasingly multi-sectoral and even international as some companies may acquire certain parts of their final products from other countries. For these two reasons, in the following we undertake a more ambitious and complicated analysis taking into consideration the carbon dioxide emissions related to intermediate deliveries, including those related to imports.

NIOTs (34x34 tables) are obtained from the WIOD database. These tables depict all of the yearly monetary transactions between sectors of the national economy. The environmental data in terms of sectoral CO_2 emissions are obtained from the environmental section of the WIOD.

In this study we use the WIOTs (for 1995-2007) to redistribute the carbon emissions associated with intermediate deliveries by other sectors in other countries (i.e. imported goods) (Serrano and Dietzenbacher, 2010).[13]

If there were no intermediate sales between businesses in this economy and all products were purchased directly by final consumers, then the vector of direct carbon intensities i^d would be the same as the vector of total carbon intensities. However, intermediate sales going from one industry to another have to be considered. Environmentally extended input-output (EEIO) analysis provides a method for tracking how embodied impacts "move" from sector to sector, or from nation to nation, in the forms of raw and manufactures products. This is captured by the approach of input-output analysis:

$$x = \boldsymbol{A}x + y \qquad (1)$$

Here x is the vector of total output and y is the vector of final demand. The technical coefficients matrix, commonly denoted by ***A,*** gives the amount of input that a given sector must receive from every other sector in order to create one dollar of output. If we consider the first, second, third and so on layers of intermediate transactions between industries, then a geometric series results whose sum can be expressed as (Leontief, 1953):

$$x = (\boldsymbol{I} - \boldsymbol{A})^{-1}y \qquad (2)$$

To calculate total, direct and indirect, emissions intensity associated with the final products of a sector, two steps are taken. First, to address emissions associated with imports, we construct a vector as the sum of direct emissions and import-related emissions associated with each sector. Then we divide the components of this vector by the sector's output to obtain the vector of (direct and imported emissions) emission intensities i^{d+i}. Then the following equation gives the vector i^y of total carbon emissions per unit of final demand.

$$i^y = i^{d+i}(\boldsymbol{I} - \boldsymbol{A})^{-1} \qquad (3)$$

The vector i^y reflects the total amount of upstream emissions that occur in sector of the economy, including abroad, to ultimately produce one monetary unit of output to final consumers from a given sector. In the case of carbon, this can be seen as the total (direct and indirect) emissions intensity of a sector's final products.

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[13] Several studies assess the emissions associated with imports and exports, such as for Brazil (Machado et al., 2001; Tolmasquim and Machado, 2003), Spain (Sánchez-Choliz and Duarte , 2004), Italy (Mongelli et al., 2006), India (Mukhopadhyay and Chakraborty, 2005; Dietzenbacher and Mukhopadhyay, 2007), and Turkey (Tunç et al., 2007).

In order to calculate the total carbon intensity per unit of output, i^x, the vector i^y is multiplied by the vector of final demand transformed into a diagonalized matrix (ŷ) and the inverse of the vector of total output, also transformed into a diagonalized matrix ($\hat{x}$).

$$i^t = i^y \hat{y} \hat{x}^{-1} \qquad (4)$$

Now i^t is the vector of carbon intensities per dollar of output of each sector according to the total emissions approach.

As in the previous section, we calculate the average carbon intensities for the years 1995 and 2007. The results are presented in Table 3.4. The reader may now wonder why these i^t values are presented (rather than only the i^y values); the reason is that they have the same denominator as the direct intensity measure i^d of the first approach (namely output), making their values comparable.

Table 3.4 Carbon intensity (average of 1995 and 2007) according to the total intensity emissions approach; sectors for each country ranked from high to low

Denmark		Germany		Spain	
Electricity, Gas and Water Supply	2.962	Electricity, Gas and Water Supply	1.706	Water Transport	0.967
Coke, Refined Petroleum and Nuclear Fuel	2.134	Air Transport	0.934	Coke, Refined Petroleum and Nuclear Fuel	0.952
Water Transport	1.998	Coke, Refined Petroleum and Nuclear Fuel	0.802	Air Transport	0.897
Air Transport	0.791	Water Transport	0.528	Electricity, Gas and Water Supply	0.711
Other Non-Metallic Mineral	0.650	Other Non-Metallic Mineral	0.438	Other Non-Metallic Mineral	0.443
Mining and Quarrying	0.487	Chemicals and Chemical Products	0.388	Chemicals and Chemical Products	0.367
Food, Beverages and Tobacco	0.264	Basic Metals and Fabricated Metal	0.376	Construction	0.308
Chemicals and Chemical Products	0.219	Textiles and Textile Products	0.304	Inland Transport	0.281
Construction	0.211	Leather, Leather and Footwear	0.247	Textiles and Textile Products	0.237
Inland Transport	0.203	Food, Beverages and Tobacco	0.244	Food, Beverages and Tobacco	0.230
Textiles and Textile Products	0.201	Mining and Quarrying	0.242	Transport Equipment	0.224
Leather, Leather and Footwear	0.200	Construction	0.214	Manufacturing, Nec; Recycling	0.203
Transport Equipment	0.192	Transport Equipment	0.212	Leather, Leather and Footwear	0.193
Manufacturing, Nec; Recycling	0.173	Manufacturing, Nec; Recycling	0.207	Basic Metals and Fabricated Metal	0.183
Rubber and Plastics	0.162	Hotels and Restaurants	0.200	Hotels and Restaurants	0.177
Agriculture, Hunting, Forestry and Fishing	0.162	Machinery, Nec	0.185	Agriculture, Hunting, Forestry and Fishing	0.169
Basic Metals and Fabricated Metal	0.149	Inland Transport	0.162	Machinery, Nec	0.166
Machinery, Nec	0.148	Pulp, Paper, Paper , Printing and Publishing	0.162	Electrical and Optical Equipment	0.159
Wood and Products of Wood and Cork	0.136	Rubber and Plastics	0.153	Health and Social Work	0.146
Hotels and Restaurants	0.121	Agriculture, Hunting, Forestry and Fishing	0.139	Public Admin and Defence; Compulsory Social Security	0.145
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0.119	Electrical and Optical Equipment	0.125	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0.142
Electrical and Optical Equipment	0.114	Public Admin and Defence; Compulsory Social Security	0.116	Pulp, Paper, Paper , Printing and Publishing	0.141
Education	0.110	Health and Social Work	0.114	Other Community, Social and Personal Services	0.137
Public Admin and Defence; Compulsory Social Security	0.108	Wood and Products of Wood and Cork	0.112	Rubber and Plastics	0.122
Health and Social Work	0.101	Education	0.110	Mining and Quarrying	0.117
Other Community, Social and Personal Services	0.098	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.098	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.108
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.095	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0.090	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0.106
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0.091	Other Community, Social and Personal Services	0.081	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.080
Pulp, Paper, Paper , Printing and Publishing	0.068	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0.081	Real Estate Activities	0.074
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.061	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.071	Education	0.070
Real Estate Activities	0.045	Post and Telecommunications	0.064	Wood and Products of Wood and Cork	0.062
Post and Telecommunications	0.032	Real Estate Activities	0.043	Post and Telecommunications	0.055
Renting of M&Eq and Other Business Activities	0.030	Financial Intermediation	0.026	Renting of M&Eq and Other Business Activities	0.051
Financial Intermediation	0.017	Renting of M&Eq and Other Business Activities	0.020	Financial Intermediation	0.022

We can see from Table 3.4 the ranking of the sectors differs from that obtained with the direct intensity emissions analysis (Table 3.3). In the case of Denmark for example, sectors that show a worse performance and went up in terms of carbon intensity are ‘Transport equipment’, ‘Chemicals and chemical products’, ‘Construction’ and ‘Textile and textile products’. In the case of Germany, the sectors that come out as more carbon intensive are ‘Coke, refined petroleum and nuclear fuel’, ‘Textile and textile products’, ‘Construction’, ‘Transport equipment’, ‘Manufacturing, nec; recycling’ (here “nec” denotes “Not elsewhere classified”), and ‘Electrical and optical equipment’. Finally, in the case of Spain, sectors with a worse performance are ‘Construction’, ‘Coke, refined petroleum and nuclear fuel’, ‘Textile and textile products’ and ‘Electrical and optical equipment’. There are, however, sectors in each country that improved their relative performance (ranking) in terms of carbon intensity. These sectors are usually relatively clean sectors like ‘Post and telecommunications’ in Denmark, ‘Education’ in Germany, or ‘Agriculture, hunting, forestry and fishing’ in Spain.

3.4 Construction of economic and productivity indicators

The socio-economic data we use in this analysis to calculate the growth of the economic sectors are the rate of change in sectoral output, relative sectoral output change, the change in final demand and the change in value added. To test the change in productivity of the different economic sectors we use output and value-added labor productivity change. Output labor productivity is calculated as the ratio of output to hours worked in a given sector, while value-added labor productivity is given as the ratio of value added to hours worked in a given sector.

3.4.1 Indicators of economic change

In this section the indicators of economic change are presented. The results are presented in Appendix 2. The different economic indicators we will use, expressed and interpreted in Table 3.5, are expressed as the change between the values they take between the two extreme years of our study (1995-2007). In effect, this means we focus on average values over this period. The last two columns of Table 3.5 specify the specific question/hypothesis addressed and the connection with green growth. The variety of interpretations underpins the difficulty of capturing the richness of the processes underlying green growth (or its absence). Our aim is to avoid simplifying green growth by considering, instead of only one indicator, a set of indicators, so as to look at green growth from various angles.

Table 3.5 Economic indicators and connections with general and specific questions about green growth

Number	*Indicator*	*Interpretation*	*Question*	*Link with green growth test*
1	$\Delta x = \frac{(x_{2007} - x_{1995})}{x_{1995}}$	Rate of change in sectoral output	Are sectors with high carbon intensity generally associated with high rate of output growth?	A positive answer would make green growth difficult unless sectoral intensity improvements would sufficiently compensate the high sectoral growth.
2	$\Delta x_r = \frac{x^s_{2007}}{x^T_{2007}} - \frac{x^s_{1995}}{x^T_{1995}}$	Change in the sectoral share in the total output	Are sectors with higher carbon intensity generally associated with an increase in their share in total output?	This would contrast with green growth, as the share of dirtier sectors (even if they become cleaner) would increase in the economy.
3	$\Delta f = \frac{(f_{2007} - f_{1995})}{f_{1995}}$	Rate of change in final demand	Are sectors whose final products have higher carbon intensity generally associated with a higher rate of change in final demand?	This could be seen as the demand or preference test behind green growth.
4	$\Delta VA = \frac{(VA_{2007} - VA_{1995})}{VA_{1995}}$	Rate of change in value added	Are sectors with high carbon intensity generally associated with a high rate of change in value added?	This would suggest that sectors with high carbon intensity are important for longer term growth (not only short term as measured more by output).
5	$LP^x = \frac{x}{h}$	Labor productivity in output terms	Are sectors with higher carbon intensity generally associated with higher labor productivity?	This would give support to the assumption that a high intensity of technology is at the basis of a combination of high labor productivity (in output terms) and high emission intensity (as technology uses energy).
6	$LP^{VA} = \frac{VA}{h}$	Labor productivity in value-added terms	Are sectors with higher carbon intensity generally associated with higher labor productivity?	Same as above but for productivity in value added terms.
7	$\Delta LP^x = \frac{({LP^x}_{2007} - {LP^x}_{1995})}{{LP^x}_{1995}}$	Rate of change in labor productivity in output terms	Are sectors with higher carbon intensity generally associated with higher labor productivity growth in output terms?	This would give support to the assumption that intensity of technology is the basis of both carbon intensity (since technology uses energy) and the pace at which labor productivity can be increased (since increasing labor productivity may be easier through improving technology than through other means available in less carbon intensive sectors, such as improving organizational efficiency). If demand for the products of a sector is not yet saturated, then labor productivity growth can translate into output growth. In case of a positive correlation, this would happen disproportionally in relatively dirty sectors.
8	$\Delta LP^{VA} = \frac{({LP^{VA}}_{2007} - {LP^{VA}}_{1995})}{{LP^{VA}}_{1995}}$	Rate of change in labor productivity in value-added terms	Are sectors with higher carbon intensity generally associated with higher labor productivity growth in value-added terms?	If so, then it may mean that longer term labor productivity growth (associated with productivity in terms of value added), and therefore likely future growth, will be generated disproportionally in relatively dirty sectors.

Labor productivity measures output per hour worked in a certain period of time. It is an important indicator for determining the productive potential of the economy. It is normally found as a ratio between a measure of output and a measure of input. As a measure of output the sectoral total output or value added can be used, and as a measure of input the total hours worked (OECD, 2008). Countries with high labor productivity growth tend to have high growth rates. An increase in labor productivity enables a higher long run trend rate of growth.[14]

Output labor productivity takes into consideration intermediate output and technological change. The reason is that improvements in productivity can result from more efficiency in the use of intermediate inputs, through reduction in wastage of materials. This will reduce the input cost and therefore increase the net output in monetary terms, thus improving labor productivity. In addition, improvements in productivity of supplying industries may contribute to improvements in the using industry (after some time). The disadvantage of this measure is that it is sensitive to substitution between factor inputs (including labor) and intermediate inputs, particularly through outsourcing.

Value added labor productivity does not have this disadvantage, as intermediate inputs are excluded from consideration (Gullickson, 1995). A further reason for using this measure is that it excludes the effect of taxes on productivity. Moreover, as we mentioned already in Section 1, this measure can be seen as reflecting better longer-run viability of a sector than the first measure.

3.5 Correlation analysis in the direct and total intensity emissions approaches

3.5.1 Change in sectoral total output

By ranking the sectors according to the rate of growth (or change), we can see that the sectors that expanded the most in the three countries were those with high values of carbon intensity, such as ‘Water transport’, ‘Basic Metals and Fabricated Metal’, ‘Other Non-Metallic Mineral’, ‘Coke, Refined Petroleum and Nuclear Fuel’. Other sectors that expanded considerably but have low carbon intensity are ‘Financial intermediation’ and ‘Post and telecommunication’.[15] The correlation between the rate of change in sectoral output and carbon intensity is shown in Table 3.6. The results show that in the case of Denmark, Germany and Spain, correlations are positive but weak. The conclusion is that they are not statistically different from zero.

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[14] For more information see http://www.economicshelp.org/blog/5887/economics/uk-labour-productivity/.

[15] The complete data set with the changes in total output, final demand and value added is listed in Appendix 2.

Table 3.6 Correlation between carbon intensity (CI) and rate of change in sectoral output (formula 1 in Table 3.5)

Indicator	CI measure	Country	Pearson correlation	p-value
Rate of change in total output	Direct	Denmark	0.0993	0.5762
		Germany	0.1229	0.4888
		Spain	0.0829	0.6411
	Total	Denmark	0.0712	0.6891
		Germany	0.1824	0.3019
		Spain	0.0141	0.9370

Correlations for both the direct and total carbon intensity measures are positive. In the case of Germany the tests show a slightly higher value.

Table 3.7 shows the result of the correlations between carbon intensity and the indicator of relative sectoral growth.

Table 3.7: Correlation between carbon intensity (CI) and the change in the sectoral share in total output (formula 2 in Table 3.5)

Indicator	CI measure	Country	Pearson correlation	p-value
Rate of change in relative growth	Direct	Denmark	0.1136	0.5223
		Germany	0.0150	0.9327
		Spain	0.1239	0.4852
	Total	Denmark	0.1020	0.5661
		Germany	0.0307	0.8630
		Spain	0.0748	0.6742

As can be noted from Table 3.7, the results for relative growth are positive but also very small, almost insignificant. However, correlations are never negative, which would be necessary for moving in a direction that would be consistent with green growth.

3.5.2 Change in final demand

This indicator excludes intermediate goods which were taken into account in the case of total output change. The results here, except for some little differences, are similar to those obtained for total output growth in terms of the ranking of the sectors. This means that an important driver of growth is final demand as the sectors which grew the most in terms of total output, grew also in terms of final demand. Table 3.8 shows the outcomes of the correlation analysis between carbon intensity and the rate of change in final demand. In this case again, correlations are quite low in values and not significant, meaning that there is no significant relation between the two series.

Table 3.8 Correlation between carbon intensity (CI) and the rate of change in final demand (formula 3 in Table 3.5)

Indicator	CI measure	Country	Pearson correlation	p-value
Rate of change in final demand	Direct	Denmark	0.1523	0.3899
		Germany	0.1116	0.5298
		Spain	-0.0709	0.6902
	Total	Denmark	0.0784	0.6595
		Germany	0.1176	0.5076
		Spain	-0.1353	0.4454

The difference with Table 3.7 is that correlations between final demand and carbon intensity for Spain are slightly negative, but insignificant. However, a much larger and significant negative correlation would be needed to support changes consistent with green growth.

3.5.3 Change in value added

Sectors with a high rate of change in value added for Denmark are ´Financial intermediation, ´Post and telecommunications´ and 'Electrical and optical equipment´. The results for Germany shows that the sectors connected to transportation had a high growth in value added. Sectors such as 'Water transport' and 'Other Supporting and Auxiliary Transport Activities: Activities of Travel Agencies' and 'Transport equipment' are leading the ranking. For Spain tertiary sectors such as 'Post and telecommunications' and 'Financial intermediation' have a high rate of change in value added. In addition, the 'Construction' sector which expanded a lot in Spain during the considered period ranks as fourth in the classification of sectors. The result of the correlation analysis between the change in value added and carbon intensity is shown in Table 3.9.

Table 3.9 Correlation between carbon intensity (CI) and the rate of change in value added (formula 4 in Table 3.5)

Indicator	CI measure	Country	Pearson correlation	p-value
Rate of change in value added	Direct	Denmark	-0.0714	0.6882
		Germany	0.0122	0.9456
		Spain	-0.1978	0.2621
	Total	Denmark	-0.0892	0.6158
		Germany	0.0711	0.6896
		Spain	-0.3252	0.0606

The correlation results presented in Table 3.9 show that there is no high correlation between the two indicators. Denmark and Spain show negative correlations, but with a so low significance that one can conclude these values to be close to zero. This means there is no clear evidence of a positive or negative relation between carbon intensity and the change in value added between 1995 and 2007 for the three countries.

3.5.4 Correlation between labor productivity and carbon intensity

In this section we perform correlation analyses between carbon intensity and labor productivity for the years 1995 and 2007, and for average values between the two.[16] A positive correlation of carbon intensity and labor productivity means that labor productivity values tend to be high in those sectors where carbon intensity is also high. The results of the analysis are presented in Table 3.10.

Table 3.10 Correlation between carbon intensity (CI) and labor productivity (formulas 5 and 6 in Table 3.5)

				1995		2007		Average	
Indicator	CI measure	Labor productivity type		Pearson correlation	p-value	Pearson correlation	p-value	Pearson correlation	p-value
Labor productivity	Direct	Output labor productivity (formula 5)	Denmark	0.4427	0.0088	0.5480	0.0008	0.5033	0.0024
			Germany	0.1264	0.4763	0.1412	0.4257	0.1930	0.2741
			Spain	0.2291	0.1924	0.1626	0.3581	0.2232	0.2046
		Value-added labor productivity (formula 6)	Denmark	0.1400	0.4296	0.2009	0.2545	0.1804	0.3073
			Germany	-0.0036	0.9837	0.0265	0.8817	0.0391	0.8260
			Spain	0.0617	0.7290	0.0978	0.5823	0.0838	0.6376
	Total	Output labor productivity (formula 5)	Denmark	0.5747	0.0004	0.6039	0.0002	0.6030	0.0002
			Germany	0.2420	0.1680	0.3395	0.0495	0.3560	0.0388
			Spain	0.6000	0.0002	0.3633	0.0347	0.5345	0.0011
		Value-added labor productivity (formula 6)	Denmark	0.0868	0.6253	0.1275	0.4725	0.1124	0.5268
			Germany	-0.0103	0.9540	0.0394	0.8248	0.0402	0.8215
			Spain	0.2092	0.2350	0.1328	0.4539	0.1951	0.2688

As can be seen from the table, all correlations are positive, except two (namely between value added labor productivity and CI for Germany in 1995 and 2007). However, not all values are significant at the 5% level (only 11). The number of observations in the correlation analysis equals the number of industrial sector (*n=34*). In view of this number, relatively small (positive or negative) correlation values will not be easily result to be statistically significant; only larger correlation values tend to be significant. Together with the fact that all non-significant correlation values are positive except for two (which are very small, i.e. close to zero), for all countries the tendency is a zero to positive correlation. Note that sectors whose final products have relatively high carbon intensity (according to the total intensity approach) tend to show a high level of labor productivity. This holds for all three countries, both years (1995, 2007, and evidently then the average values) and both methods. Finally, note that when correlations are significant, the correlation coefficient is higher in the total carbon intensity approach than in the direct carbon intensity approach. This suggests that one will tend to be less optimistic about green growth when accounting for total rather than direct emissions at the sectoral level.

3.5.5 Correlation between carbon intensity and the change in labor productivity

In this section we display the results of the correlation analysis between direct and total carbon intensity measures and the rate of change in output and value-added labor productivity

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[16] More extensive tables displaying output and value-added labor productivity for years 1995, 2007 and the average values are shown in Appendices 3 and 4.

between years 1995-2007.[17] Table 3.11 shows the correlations between carbon intensity for all countries, and the rate of output and value-added labor productivity change. The table shows that the correlations are positive for the three countries.

Table 3.11 Correlation between carbon intensity and the rate of change in output labor productivity (formula 7 in Table 3.5)

Indicator	Analysis	Country	Pearson correlation	p-value
Rage of change in output labor productivity	Direct	Denmark	0.2776	0.1120
		Germany	0.2139	0.2245
		Spain	0.1841	0.2972
	Total	Denmark	0.2592	0.1388
		Germany	0.2985	0.0864
		Spain	0.1170	0.5098

As in Table 3.10, the correlation coefficients take positive values meaning that the indicators are positively correlated. Again, probably as a result of the small number of sectors, *p-values* are not below the 5% significance threshold. Given that all correlations presented in Table 3.11 are positive, we conclude that not only labor productivity was somewhat higher in those sectors where carbon intensity is high (Table 3.10), but also that the rate of change in labor productivity in the years 1995-2007 was higher in sectors with a relatively high carbon intensity.

Table 3.12 shows the results of the correlation analysis between the rate of change in value-added labor productivity and carbon intensity for both the direct and total carbon intensity measures.

Table 3.12 Correlation between carbon intensity (CI) and the rate of change in value-added labor productivity (formula 8 in Table 3.5)

Indicator	CI measure	Country	Pearson correlation	p-value
Rate of change in value-added labor productivity	Direct	Denmark	0.1212	0.4948
		Germany	0.1589	0.3695
		Spain	-0.0103	0.9541
	Total	Denmark	0.1230	0.4882
		Germany	0.2653	0.1294
		Spain	-0.1653	0.3501

In the case of value-added labor productivity, which is given by the ratio of value added with the yearly hours worked by employees in the sector, Table 3.12 shows that for Denmark and Germany correlations are positive, while for Spain they are negative. However, p-values again do not show a high level of statistical significance, and in fact indicate a lower significance generally than for the output-based correlations in Table 3.11.

Here, the majority of correlations are positive for both (direct and total) carbon intensity measures. An exception is Spain, where the correlations are negative, although the one for the direct CI measure is very insignificant and small.

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[17] In Appendix 5 we show the rate of change in output and value-added labor productivity for all the economic sectors.

3.6 Conclusions

In this paper we investigated the compatibility of combining economic growth with controlling climate change. For this purpose we tested the relationship between various indicators of economic growth and productivity (growth) with carbon intensity calculated in two different ways. This allowed us to test a number of questions answers to which, as summarized in Table 3.13, provide insight into the possibility of green growth.

In order to answer these questions we considered three European countries: Denmark, Germany and Spain for the time period 1995-2007. One of the novelties introduced in this study is the use of two different carbon intensity measures, namely direct and total carbon intensities. The first only considers carbon emissions directly released by the industrial processes in a sector, while the second represents direct and indirect carbon dioxide emissions, which can be attributed to final products of a sector, including emissions through intermediate deliveries from other sectors and imports. In the latter case we reallocate emissions through the use of environmentally extended input-output tables. The second important novelty of this study is the broad set of economic indicators we use to test the potential conflict between green growth and climate performance at a sectoral scale.

The results show that sectors with high carbon intensity show an absolute growth in terms of output and associated emissions. This makes green growth difficult and requires that, for instance, the carbon intensity improvement of dirty sectors sufficiently compensates the growth of these sectors. In the same line, the results of the analysis of sectoral share of output show that the share of dirtier sectors does not decrease in the economy. In view of this, realizing green growth would require a radical change or huge technological improvements. The only other option is that the economy as a whole would shrink to achieve climate targets (so not green growth).

The test on the correlation between the rate of change in final demand and carbon intensity shows a higher challenge for green growth for Denmark and Germany than for Spain, where the shift to demand for cleaner final products may be the result of economically unsustainable trends (a bubble), however. More positive news for green growth comes from the correlation results for carbon intensity and the rate of change in value added, which was argued to capture long term growth potential of the respective sectors. The results suggest that pollutive sectors seem to become slightly less important for long-term growth, especially in Denmark and Spain.

We also studied indicators of labor productivity motivated by the idea that technological intensity – many machines per worker and per unit of output, which use and process energy – is at the basis of both high labor productivity and high CO_2 emissions, whether of a firm or an entire production sector. In addition, having many machines may allow for much technological progress as existing machines or parts thereof can be improved or replaced by new, better performing ones, thus increasing productivity. The correlation results for carbon intensity and productivity measures suggest that a high intensity of technology may be at the basis of a combination of high labor productivity in output terms and high emission intensity. The bad news for green growth following from the results is that relatively clean sectors do not seem to be more productive than dirtier ones in output or value added terms.

Table 3.13 Insights from the correlation analyses between the economic indicators and carbon intensity measures

Economic Indicator	*Question/hypothesis*	*Findings from the correlation analysis*	*Connection with green growth*
Rate of change in sectoral output	Are sectors with high carbon intensity generally associated with high rate of output growth?	Cannot be refuted for the three countries.	Dirtier sectors show an absolutely increasing level in terms of output and associated emissions, which makes the challenge of green growth harder.
Change in the sectoral share in the total output	Are sectors with higher carbon intensity generally associated with an increase in their share in total output?	Cannot be refuted for the three countries.	The share of dirtier sectors in the economy is increasing, which itself makes the challenge of green growth harder.
Rate of change in final demand	Are sectors with high carbon intensity generally associated with a high rate of change in final demand?	Cannot be refuted for Denmark and Germany. Weakly refuted for Spain (might be a consequence of the bubble that burst in the economic crisis).	Final demand trends show a less pronounced discrepancy with green growth for Spain than for Denmark and Germany.
Rate of change in value added	Are sectors with high carbon intensity generally associated with a high rate of change in value added?	Cannot be refuted for Germany. Weakly refuted for Denmark and Spain.	Sectors with high carbon intensity seem to become slightly less important for long-term growth, which suggests a change in the direction of green growth.
Labor productivity in output terms	Are sectors with higher carbon intensity generally associated with higher labor productivity?	Cannot be refuted for the three countries.	A high intensity of technology seems to be at the basis of a combination of high labor productivity in output terms and high emission intensity (as technology uses energy). This suggests that realizing green growth will be difficult.
Labor productivity in value-added terms	Are sectors with higher carbon intensity generally associated with higher labor productivity?	Cannot be refuted for the three countries.	Relatively clean sectors do not seem to be more productive in value added terms than dirtier ones, which is not good news for long-term green growth.
Rate of change in labor productivity in output terms	Are sectors with higher carbon intensity generally associated with higher labor productivity growth in output terms?	Cannot be refuted for the three countries.	Labor productivity growth tends to be slightly higher in relatively dirty sectors, which is not good news for green growth.
Rate of change in labor productivity in value-added terms	Are sectors with higher carbon intensity generally associated with higher labor productivity growth in value-added terms?	Cannot be refuted for Denmark and Germany. Weakly refuted for Spain.	Long-term growth (associated with productivity in terms of value added) is generated disproportionally in relatively dirty sectors for Denmark and Germany, which complicates green growth here. In Spain, the conclusions are more neutral – green growth is not becoming more complicated, and may even become slightly easier to realize.

Except for the results of the correlation analysis between the change in value added and carbon intensity, which were negative for at least two countries we studied, all the other tests confirm the great challenge green growth implies because they do not give statistically significant (and large) negative values that point at decoupling at the sectoral level. The correlations of the economic and productivity indicators with both direct and total carbon intensity are similar.

On a method level, the total carbon intensity may be regarded as better capturing the total (or product-based), direct (or process-based) and indirect, contribution to total emissions by a production sector or its final product. The reason is that it is a more complete measure of the impact of the production of each sector on all direct and indirect emissions, including those in other countries. The direct carbon intensity indicator represents a measure to account for the specific technological processes within each sector. So the two intensity indicators can be seen to be both useful and rather complementary.

All in all, we conclude that in view of the correlations between the various economic and productivity (growth) indicators, the challenge of green growth is enormous and easily underestimated. While this was already clear from aggregate level analyses, our results for three countries and the period 1995-2007 shows that there are no indications at the sectoral level that a green growth pattern is taking off. Using a set of indicators as we have pursued offers a rich perspective, supporting the robustness of the results. There are no indications, in terms of clear negative correlations, that at the sectoral production level something has started that can be regarded as a clear indication of a shift to green growth.

Our study can be interpreted as finding that past climate policies implemented after the Kyoto international agreement have hardly affected economic sector structure. As the economy is a complex system dependent on products and sectors that are closely interlinked, effective change in structure to contribute to emissions reduction is unlikely to result from tinkering with only one element in the system. Instead one would need to change the web of intermediate (as well as international) relations making up the system. This requires much tougher climate regulations than have been implemented so far, requiring international policy coordination.

Appendix 1. Carbon emissions, total output and value added

	Denmark						**Germany**						**Spain**					
Sector	**Carbon emissions**	**Carbon emissions in %**	**Total output**	**Total output in %**	**Value added**	**Value added in %**	**Carbon emissions**	**Carbon emissions in %**	**Total output**	**Total output in %**	**Value added**	**Value added in %**	**Carbon emissions**	**Carbon emissions in %**	**Total output**	**Total output in %**	**Value added**	**Value added in %**
Agriculture, Hunting, Forestry and Fishing	2518.33	3.13%	12460.03	3.40%	4328.6	2.42%	9138.86	1.28%	67093.185	1.35%	28924.24	1.15%	10494.2	4.27%	55151.606	3.68%	32825.75	4.72%
Mining and Quarrying	1848.89	2.30%	2521.36	0.69%	2006.427	1.12%	8025.875	1.12%	24220.662	0.49%	9961.49	0.40%	1449.64	0.59%	5170.1359	0.35%	2185.162	0.31%
Food, Beverages and Tobacco	1808.79	2.25%	21510.28	5.87%	4877.884	2.72%	10339.92	1.45%	179059.29	3.60%	46511.35	1.85%	5298.41	2.16%	83113.092	5.55%	17821.28	2.56%
Textiles and Textile Products	80.09	0.10%	2095.29	0.57%	698.3386	0.39%	2685.665	0.38%	35391.656	0.71%	11613.42	0.46%	1776.515	0.72%	18981.095	1.27%	5824.249	0.84%
Leather, Leather and Footwear	5.78	0.01%	216.15	0.06%	53.469	0.03%	295.09	0.04%	4757.4547	0.10%	1441.635	0.06%	200.475	0.08%	7172.312	0.48%	1682.835	0.24%
Wood and Products of Wood and Cork	77.51	0.10%	2357.74	0.64%	837.5397	0.47%	1087.91	0.15%	30978.505	0.62%	10368.54	0.41%	641.6	0.26%	9979.9843	0.67%	2933.094	0.42%
Pulp, Paper, Paper , Printing and Publishing	243.95	0.30%	7054.24	1.93%	2721.669	1.52%	8511.245	1.19%	107257.99	2.16%	41566.13	1.65%	3365.24	1.37%	30938	2.07%	10893.18	1.57%
Coke, Refined Petroleum and Nuclear Fuel	1171.93	1.46%	1552.82	0.42%	50.36819	0.03%	20138.425	2.82%	37786.042	0.76%	2942.412	0.12%	19008.265	7.74%	21359.076	1.43%	2235.667	0.32%
Chemicals and Chemical Products	438.2	0.55%	8824.73	2.41%	3317.366	1.85%	33281.925	4.66%	168650.59	3.39%	59757.33	2.37%	7781.94	3.17%	39364.836	2.63%	11542.24	1.66%
Rubber and Plastics	114.37	0.14%	3464.84	0.95%	1436.515	0.80%	2015.595	0.28%	73963.807	1.49%	27751.08	1.10%	583.725	0.24%	17139.677	1.14%	5168.034	0.74%
Other Non-Metallic Mineral	3555.79	4.42%	3113.13	0.85%	1283.81	0.72%	42776.885	5.99%	55268.206	1.11%	22370.54	0.89%	44347.615	18.07%	29194.991	1.95%	9870.496	1.42%
Basic Metals and Fabricated Metal	392.26	0.49%	7658.11	2.09%	2887.832	1.61%	65085.385	9.12%	209590.5	4.22%	72002.84	2.86%	13297.15	5.42%	62820.862	4.20%	19557.02	2.81%
Machinery, Nec	233.69	0.29%	10958.03	2.99%	4309.109	2.40%	3731.65	0.52%	224093.27	4.51%	86356.94	3.43%	622.625	0.25%	24687.701	1.65%	8700.023	1.25%
Electrical and Optical Equipment	86.81	0.11%	10718.14	2.93%	3849.181	2.15%	2757.96	0.39%	261690.8	5.26%	100511.5	3.99%	250.485	0.10%	29735.595	1.99%	8371.43	1.20%
Transport Equipment	86.67	0.11%	2885.22	0.79%	929.8175	0.52%	4835.965	0.68%	316485.13	6.37%	87994.31	3.50%	1792.965	0.73%	64193.332	4.29%	13822.99	1.99%
Manufacturing, Nec; Recycling	92.31	0.11%	4353.36	1.19%	1590.726	0.89%	720.39	0.10%	43715.942	0.88%	15934.78	0.63%	509.395	0.21%	19199.871	1.28%	5675.701	0.82%
Electricity, Gas and Water Supply	26694.47	33.21%	6293.44	1.72%	3503.855	1.95%	359280.71	50.32%	116152.71	2.34%	55361.13	2.20%	89095.245	36.29%	48967.69	3.27%	18815.56	2.71%
Construction	1230.88	1.53%	24466.7	6.68%	8876.621	4.95%	10812.98	1.51%	293876.32	5.91%	130938.9	5.20%	4559.185	1.86%	167733.17	11.20%	58167.2	8.37%
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	286.87	0.36%	5944.4	1.62%	2843.592	1.59%	2412.355	0.34%	61391.43	1.24%	40586.11	1.61%	2702.09	1.10%	28161.243	1.88%	12159.22	1.75%
Wholesale Trade and Commission Trade, Except	717.19	0.89%	27561.87	7.53%	14149.59	7.89%	6517.635	0.91%	226710.57	4.56%	133104.1	5.29%	1589.975	0.65%	54079.083	3.61%	29703.23	4.27%

of Motor Vehicles and Motorcycles																		
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	259.79	0.32%	12515.15	3.42%	7844.772	4.38%	11312.37	1.58%	165743.65	3.33%	96942.18	3.85%	1110.175	0.45%	55364.278	3.70%	36346.52	5.23%
Hotels and Restaurants	107.86	0.13%	6062.15	1.66%	2678.222	1.49%	3463.36	0.49%	78603.961	1.58%	37356.05	1.48%	418.62	0.17%	77322.58	5.16%	43760.41	6.30%
Inland Transport	2589.85	3.22%	8780.61	2.40%	4185.706	2.34%	10059.95	1.41%	78640.377	1.58%	39423.9	1.57%	21353.295	8.70%	37570.821	2.51%	17420.13	2.51%
Water Transport	31191.57	38.81%	15119.96	4.13%	2089.191	1.17%	4903.07	0.69%	22087.678	0.44%	6295.721	0.25%	2555.08	1.04%	2325.262	0.16%	868.7998	0.12%
Air Transport	2692.61	3.35%	2485.16	0.68%	657.6661	0.37%	27981.025	3.92%	25678.757	0.52%	7567.991	0.30%	5655.36	2.30%	6256.4633	0.42%	2051.46	0.30%
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	140.53	0.17%	4687.63	1.28%	2455.122	1.37%	10017.935	1.40%	95106.553	1.91%	35238.65	1.40%	608.7	0.25%	28974.57	1.94%	10802.19	1.55%
Post and Telecommunications	90.93	0.11%	9717.85	2.65%	4951.858	2.76%	6219.175	0.87%	106641.29	2.15%	61646.43	2.45%	222.12	0.09%	38881.634	2.60%	20871.09	3.00%
Financial Intermediation	35.51	0.04%	20383.65	5.57%	12445.72	6.94%	2214.455	0.31%	247117.61	4.97%	111597.8	4.43%	326.775	0.13%	64595.69	4.31%	41197.57	5.93%
Real Estate Activities	79.02	0.10%	24116	6.58%	17124.52	9.55%	7319.71	1.03%	392048.31	7.89%	301623.6	11.98%	65.12	0.03%	72311.831	4.83%	53407.53	7.68%
Renting of M&Eq and Other Business Activities	305.82	0.38%	29508.62	8.06%	14672.84	8.19%	11994.835	1.68%	440112.14	8.85%	292175.5	11.61%	190.175	0.08%	85030.171	5.68%	46931.51	6.75%
Public Admin and Defence; Compulsory Social Security	576.39	0.72%	17255.44	4.71%	11238.74	6.27%	7523.835	1.05%	222161.81	4.47%	155010.3	6.16%	473.08	0.19%	62678.998	4.19%	43767.11	6.30%
Education	135.98	0.17%	12520.44	3.42%	9382.475	5.23%	4717.36	0.66%	127226.04	2.56%	101531.3	4.03%	31.355	0.01%	38622.272	2.58%	33257.94	4.78%
Health and Social Work	202.33	0.25%	25036.56	6.84%	18013.36	10.05%	5456.4	0.76%	253815.58	5.11%	175322	6.97%	910.74	0.37%	55344.782	3.70%	35888.17	5.16%
Other Community, Social and Personal Services	277.42	0.35%	12029.12	3.28%	6940.415	3.87%	6301.715	0.88%	177807.68	3.58%	109161.8	4.34%	2191.83	0.89%	54669.602	3.65%	30617.43	4.40%

Appendix 2. Economic indicators for the three countries per sector

	Denmark			Germany			Spain		
Sector	**Change in total output**	**Change in final demand**	**Change in value added**	**Change in total output**	**Change in final demand**	**Change in value added**	**Change in total output**	**Change in final demand**	**Change in value added**
Agriculture, Hunting, Forestry and Fishing	0.11289523	0.40362811	-0.41647520	0.37003283	0.45914556	-0.00936780	0.29177819	0.49120365	0.18708401
Mining and Quarrying	0.57137965	0.68685240	0.97119234	0.36414054	0.22845217	-0.52258070	0.08201995	0.6887957	-0.08806800
Food, Beverages and Tobacco	0.06056165	0.02046639	0.01591288	0.20998095	0.14931186	-0.02992940	0.22350953	0.25800538	0.14989369
Textiles and Textile Products	-0.29978110	-0.27971000	-0.40707490	0.75770471	-0.15629820	-0.24376940	-0.04415920	-0.0560122	-0.10937060
Leather, Leather and Footwear	-0.84374990	-0.84390780	-0.83588540	0.65898226	-0.06595980	-0.27021510	-0.30229520	-0.0851444	-0.12961440
Wood and Products of Wood and Cork	0.21571180	-0.01375670	0.20896696	0.56411566	0.63767120	-0.19309610	0.49423490	0.67497523	0.40127351
Pulp, Paper, Paper , Printing and Publishing	0.08245702	0.05816952	-0.08311700	0.64579479	0.51162507	0.07596687	0.38298940	0.45398591	0.48281840
Coke, Refined Petroleum and Nuclear Fuel	-0.01517220	-0.2602461	0.27280170	0.79902794	0.44009677	0.15362541	1.04014167	1.3532067	-0.11467540
Chemicals and Chemical Products	0.94053078	1.02910049	0.59333642	0.84559650	0.57649522	0.19512590	0.47198446	0.84568942	0.28837573
Rubber and Plastics	0.36830667	0.38469580	0.41230372	0.47162981	0.76475773	0.17237525	0.67004499	1.01761592	0.43958862
Other Non-Metallic Mineral	0.07814603	0.15418935	0.03927899	0.41883672	0.58996880	-0.16952920	1.03582110	0.76774313	0.50844882
Basic Metals and Fabricated Metal	0.19152397	0.15228391	-0.01700730	0.45993502	0.62058282	0.10718457	0.85577640	1.07241815	0.50294708
Machinery, Nec	0.19491774	0.33156399	0.04885724	0.55428136	0.55148369	0.29759397	0.80728941	1.0744024	0.67028324
Electrical and Optical Equipment	1.29895512	1.11758052	0.97335428	1.46808097	1.37544253	0.87146370	0.61720300	0.7030228	0.28210514
Transport Equipment	-0.10474230	-0.10814010	-0.36007890	0.93967491	1.04080320	0.63577849	0.77145046	0.78003129	0.46374299
Manufacturing, Nec; Recycling	0.02489931	-0.05701150	-0.08071990	0.54053633	0.06508382	-0.00801620	0.56866227	-0.1078594	0.42534025
Electricity, Gas and Water Supply	0.11057847	0.08968087	-0.16636010	1.14546052	0.47698681	0.24364344	1.27336247	0.7805493	0.65047725
Construction	0.40077910	0.38457336	0.41187556	0.29275721	-0.24434060	-0.30331090	0.82587671	0.69173917	0.81490512
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0.20293346	0.21488171	0.13511535	0.17656814	0.18062842	0.34922836	0.64563747	0.84658191	0.52489851
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.63285451	0.73499761	0.50642866	0.46452547	0.26403421	0.21741657	0.57286419	0.53936114	0.55965057

Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.40022594	0.32721852	0.31216842	0.15304893	0.08364113	0.05456531	0.64899021	0.69481797	0.47200385
Hotels and Restaurants	0.26699022	0.16303004	0.22123705	-0.23132680	0.09707226	0.31710444	0.21396076	0.25114372	0.29386012
Inland Transport	0.12902971	0.16755087	-0.04184860	0.30855570	-0.48994860	-0.0724555	0.48096647	0.67336581	0.26461674
Water Transport	2.07109405	2.49964941	0.45970403	3.60050804	3.19298965	1.92169860	0.40404371	0.25845763	0.32655517
Air Transport	0.34649274	1.90290493	-0.02688010	0.40522039	0.48822773	0.30800105	0.30610120	0.77205498	0.21649683
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0.44160256	0.42449743	0.45286215	0.18644755	0.28614237	1.03972318	0.74534836	1.28554347	0.57416978
Post and Telecommunications	1.93435445	2.28020627	1.00106739	1.68783100	1.18565342	0.23313857	2.39036596	2.26537639	1.21627973
Financial Intermediation	1.10980171	2.22959293	1.05022315	0.78072626	1.43687451	0.12158980	1.07779751	4.40159601	1.08531176
Real Estate Activities	0.22141006	0.17227170	0.07532164	-0.05121200	0.20030150	0.35609222	0.36218246	0.28165844	0.36473240
Renting of M&Eq and Other Business Activities	1.21797197	1.37226662	0.83155701	-0.12690100	0.53212997	0.41557198	1.00356945	1.67101216	1.00391423
Public Admin and Defence; Compulsory Social Security	0.15081666	0.19329534	0.08517289	0.28362775	0.05826882	0.01538253	0.54254461	0.49786357	0.46551217
Education	0.19512094	0.19577718	0.15284422	0.01950163	-0.03383970	0.05285377	0.43549797	0.38946961	0.44023631
Health and Social Work	0.38393187	0.36652382	0.27403621	0.21017576	0.39779488	0.45030698	0.65119273	0.58547382	0.60051878
Other Community, Social and Personal Services	0.22510105	0.12760263	0.02915732	0.05668067	0.03858278	0.08802401	0.64547243	0.60922754	0.55824483

Appendix 3. Output labor productivity

	Denmark			**Germany**			**Spain**		
Sector	**1995**	**2007**	**Average**	**1995**	**2007**	**Average**	**1995**	**2007**	**Average**
Agriculture, Hunting, Forestry and Fishing	150.7101	182.6959	166.703	80.57251	110.387	95.47975	70.25938	76.84645	73.55292
Mining and Quarrying	338.8207	600.8235	469.8221	102.2611	139.4985	120.8798	79.61541	92.77251	86.19396
Food, Beverages and Tobacco	167.307	233.1106	200.2088	125.4126	151.7468	138.5797	116.0196	127.884	121.9518
Textiles and Textile Products	87.63164	152.8788	120.2552	84.75892	148.9812	116.8700	52.82899	65.78277	59.30588
Leather, Leather and Footwear	132.6294	141.1091	136.8692	82.20607	136.3784	109.2922	71.26036	59.47385	65.3671
Wood and Products of Wood and Cork	89.02358	115.7773	102.4004	97.43988	152.4072	124.9236	62.95554	80.73944	71.84749
Pulp, Paper, Paper , Printing and Publishing	92.64971	127.7245	110.1871	89.31685	146.9972	118.1570	94.97277	101.4419	98.20731
Coke, Refined Petroleum and Nuclear Fuel	1093.427	1349.347	1221.387	784.2627	1410.91	1097.587	1094.066	1964.797	1529.432
Chemicals and Chemical Products	136.8007	245.5583	191.1795	161.2803	297.6583	229.4693	137.4114	180.2136	158.8125
Rubber and Plastics	97.53997	125.0327	111.2863	99.96722	147.1147	123.5410	86.56383	108.7883	97.67605
Other Non-Metallic Mineral	95.21283	128.5546	111.8837	107.7739	152.9136	130.3438	77.58395	121.4994	99.54169
Basic Metals and Fabricated Metal	82.41272	102.095	92.25385	106.8484	155.9918	131.4201	84.13046	108.4644	96.29745
Machinery, Nec	87.7285	121.5615	104.645	107.8234	167.5879	137.7057	72.92911	95.58762	84.25836
Electrical and Optical Equipment	99.98772	208.6425	154.3151	100.4128	247.8268	174.1198	87.38128	131.9346	109.658
Transport Equipment	83.11741	129.9532	106.5353	167.6843	325.2531	246.4687	113.2524	175.0182	144.1353
Manufacturing, Nec; Recycling	87.04802	124.6503	105.8492	81.88297	126.1437	104.0133	50.86535	62.31646	56.59091
Electricity, Gas and Water Supply	206.6355	291.8723	249.2539	156.0046	334.7017	245.3532	270.1005	494.8122	382.4563
Construction	97.87842	101.5378	99.7081	73.19679	94.62567	83.91123	61.55329	52.27947	56.91638
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	76.68207	77.6806	77.18133	56.06106	65.95966	61.01036	51.90403	53.12441	52.51422
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	92.65659	121.5109	107.0838	93.89851	137.5168	115.7076	61.69319	54.47592	58.08455

Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	54.90521	61.92612	58.41566	41.08412	47.372	44.22806	21.70567	30.29536	26.00052
Hotels and Restaurants	61.13202	56.54818	58.8401	59.03682	45.38002	52.20842	57.00893	46.37994	51.69444
Inland Transport	82.73616	78.44174	80.58895	49.19172	64.3701	56.78091	46.42304	58.96514	52.69409
Water Transport	207.8449	603.9225	405.8837	238.8758	1098.95	668.9129	109.7637	110.2688	110.0163
Air Transport	170.9182	279.5929	225.2555	250.359	351.8095	301.0842	122.5739	101.1717	111.8728
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	90.59335	94.67835	92.63585	117.9061	139.8894	128.8977	142.9268	89.29574	116.1113
Post and Telecommunications	68.55112	192.21	130.3806	71.66825	192.6321	132.1502	69.1355	196.3	132.7177
Financial Intermediation	105.8464	202.6569	154.2517	112.2617	199.9073	156.0845	86.71203	137.6359	112.174
Real Estate Activities	542.917	414.0722	478.4946	874.9879	830.1781	852.583	606.6216	299.1159	452.8687
Renting of M&Eq and Other Business Activities	83.71703	89.22939	86.47321	101.7294	88.81983	95.27461	47.69694	46.12863	46.91279
Public Admin and Defence; Compulsory Social Security	56.83196	66.56048	61.69622	46.71757	59.96797	53.34277	33.24949	34.32368	33.78659
Education	40.01669	46.56108	43.28889	43.88639	44.74224	44.31431	37.38118	32.75224	35.06671
Health and Social Work	37.39392	41.17309	39.2835	51.01878	61.74169	56.38024	41.398	34.24322	37.82061
Other Community, Social and Personal Services	64.23485	69.34192	66.78838	87.02606	91.95876	89.49241	33.69277	31.24302	32.4679

Appendix 4. Value-added labor productivity

	Denmark			Germany			Spain		
Sector	**1995**	**2007**	**Average**	**1995**	**2007**	**Average**	**1995**	**2007**	**Average**
Agriculture, Hunting, Forestry and Fishing	69.85925	44.40331	57.13128	37.30469	44.49477	40.89973	43.81956	44.04341	43.93148
Mining and Quarrying	233.3426	519.0616	376.2021	45.71182	49.14499	47.42840	36.64303	35.98659	36.31481
Food, Beverages and Tobacco	38.78050	51.75854	45.26952	34.62697	37.14902	35.88800	25.72899	26.65372	26.19136
Textiles and Textile Products	31.17401	46.05163	38.61282	28.48841	47.40024	37.94433	16.76942	19.45671	18.11306
Leather, Leather and Footwear	32.58676	36.41524	34.50100	26.60249	38.01352	32.30801	15.17614	15.80081	15.48847
Wood and Products of Wood and Cork	31.72045	41.02432	36.37238	36.40992	45.17317	40.79154	19.21878	23.11434	21.16656
Pulp, Paper, Paper , Printing and Publishing	38.83379	45.34643	42.09011	36.51663	54.33440	45.42552	32.09509	36.75579	34.42544
Coke, Refined Petroleum and Nuclear Fuel	30.97314	49.39915	40.18614	67.31868	101.6872	84.50296	184.6613	143.9104	164.2859
Chemicals and Chemical Products	58.31058	85.94103	72.12580	61.18057	99.95267	80.56662	43.52339	49.96050	46.74194
Rubber and Plastics	39.70232	52.52927	46.11579	40.41918	52.00189	46.21053	28.56677	30.94689	29.75683
Other Non-Metallic Mineral	40.01279	52.07696	46.04488	46.32569	57.83103	52.07836	31.74486	36.83551	34.29019
Basic Metals and Fabricated Metal	34.34548	35.10163	34.72356	40.13938	49.74711	44.94324	29.88303	31.20159	30.54231
Machinery, Nec	36.95749	44.95069	40.95409	44.39787	61.54085	52.96936	27.01908	32.72907	29.87407
Electrical and Optical Equipment	39.84053	71.36016	55.60034	41.05609	92.19977	66.62793	28.21260	33.77090	30.99175
Transport Equipment	30.9568	34.59627	32.77653	55.60275	82.30558	68.95416	27.43285	35.03022	31.23154
Manufacturing, Nec; Recycling	33.55794	43.10189	38.32992	32.24108	42.77804	37.50956	15.92493	17.72750	16.82621
Electricity, Gas and Water Supply	132.4191	140.4002	136.4097	83.92740	146.1261	115.0267	128.1749	170.4743	149.3246
Construction	35.34732	36.95932	36.15332	33.84789	40.06388	36.95589	21.42890	18.09099	19.75995
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	37.84713	36.17845	37.01279	36.73016	43.90030	40.31523	23.48234	22.27108	22.87671
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	49.96697	60.45373	55.21035	55.48290	80.31638	67.89964	34.06024	29.82299	31.94161

Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	35.72650	37.76088	36.74369	25.08779	26.64210	25.86494	15.26995	19.02530	17.14762
Hotels and Restaurants	27.56406	24.57648	26.07027	24.24341	24.49156	24.36749	31.14016	27.00169	29.07093
Inland Transport	42.88197	34.50288	38.69243	26.58484	29.93418	28.25951	23.5809	25.57619	24.57855
Water Transport	47.53298	65.64605	56.58951	84.16164	294.0173	189.0895	42.37752	40.22299	41.30026
Air Transport	53.79050	63.59246	58.69148	87.78109	92.41909	90.10009	41.81608	32.14687	36.98148
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	47.22998	49.74518	48.48758	37.78784	56.12667	46.95726	56.82881	32.02249	44.42565
Post and Telecommunications	45.79416	87.56301	66.67859	55.66239	92.23065	73.94652	50.65808	94.02556	72.34182
Financial Intermediation	65.88940	122.5915	94.24043	60.63517	78.76737	69.70127	55.16815	87.88375	71.52595
Real Estate Activities	412.6576	277.0827	344.8702	639.7188	664.3194	652.0191	447.5509	221.0936	334.3223
Renting of M&Eq and Other Business Activities	47.30814	41.63843	44.47329	69.06256	58.05714	63.55985	26.32280	25.46167	25.89224
Public Admin and Defence; Compulsory Social Security	38.18085	42.16598	40.17341	33.56474	40.68598	37.12536	23.94265	23.48188	23.71227
Education	30.57629	34.31827	32.44728	36.43360	34.43961	35.43660	32.12672	28.24136	30.18404
Health and Social Work	28.20444	28.58888	28.39666	34.80109	43.02279	38.91194	27.36751	21.94287	24.65519
Other Community, Social and Personal Services	40.64024	36.85456	38.74740	54.51506	55.44038	54.97772	19.51285	17.13492	18.32388

Appendix 5. Change in productivity indicators for the three countries

	Denmark		Germany		Spain	
Sector	Change in output labor productivity	Change in value-added labor productivity	Change in output labor productivity	Change in value-added labor productivity	Change in output labor productivity	Change in value-added labor productivity
Agriculture, Hunting, Forestry and Fishing	0.212234	-0.364388889	0.370033	0.19274	0.093754	0.005108589
Mining and Quarrying	0.773279	1.224461152	0.364141	0.075105	0.165258	-0.017914460
Food, Beverages and Tobacco	0.393311	0.334653708	0.209981	0.072835	0.102262	0.035941236
Textiles and Textile Products	0.744562	0.477244359	0.757705	0.663843	0.245202	0.160249413
Leather, Leather and Footwear	0.063935	0.117485791	0.658982	0.428946	-0.165400	0.041161233
Wood and Products of Wood and Cork	0.300524	0.293308455	0.564116	0.240683	0.282484	0.202695890
Pulp, Paper, Paper , Printing and Publishing	0.378574	0.167705590	0.645795	0.487936	0.068115	0.145215428
Coke, Refined Petroleum and Nuclear Fuel	0.234053	0.594903007	0.799028	0.510535	0.795867	-0.220678993
Chemicals and Chemical Products	0.795007	0.473849627	0.845597	0.633732	0.311489	0.147899866
Rubber and Plastics	0.281861	0.323078195	0.471630	0.286565	0.25674	0.083317647
Other Non-Metallic Mineral	0.350182	0.30150802	0.418837	0.248358	0.566038	0.160361426
Basic Metals and Fabricated Metal	0.238826	0.022015947	0.459935	0.239359	0.289241	0.044124181
Machinery, Nec	0.385656	0.216280712	0.554281	0.386122	0.310692	0.211331947
Electrical and Optical Equipment	1.086681	0.791144646	1.468081	1.245702	0.509873	0.197014794
Transport Equipment	0.563489	0.117566091	0.939675	0.480243	0.545383	0.276944064
Manufacturing, Nec; Recycling	0.431972	0.284402329	0.540536	0.326818	0.225126	0.113191517
Electricity, Gas and Water Supply	0.412498	0.060271455	1.145461	0.741101	0.831956	0.330012865
Construction	0.037387	0.045604452	0.292757	0.183645	-0.150660	-0.155766885
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0.013022	-0.044089798	0.176568	0.195211	0.023512	-0.051581924
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.311412	0.209874010	0.464525	0.447588	-0.116990	-0.124404763
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.127873	0.056943407	0.153049	0.061955	0.395735	0.245930687
Hotels and Restaurants	-0.074980	-0.108386582	-0.23133	0.010236	-0.186440	-0.132898305

Inland Transport	-0.051900	-0.195398839	0.308556	0.125987	0.270170	0.084614535
Water Transport	1.905641	0.381063265	3.600508	2.493484	0.004602	-0.050841444
Air Transport	0.635828	0.182224755	0.405220	0.052836	-0.174610	-0.231232005
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0.045092	0.053254239	0.186448	0.485310	-0.375230	-0.436509504
Post and Telecommunications	1.803893	0.912099808	1.687831	0.656965	1.839352	0.856082092
Financial Intermediation	0.914631	0.860564328	0.780726	0.299038	0.587276	0.593016049
Real Estate Activities	-0.237320	-0.328541004	-0.051210	0.038455	-0.506920	-0.505992178
Renting of M&Eq and Other Business Activities	0.065845	-0.119846284	-0.126900	-0.159350	-0.032880	-0.032714233
Public Admin and Defence; Compulsory Social Security	0.171180	0.104375029	0.283628	0.212164	0.032307	-0.019244857
Education	0.163541	0.122381884	0.019502	-0.054730	-0.123830	-0.120938603
Health and Social Work	0.101064	0.013630164	0.210176	0.236248	-0.172830	-0.198214526
Other Community, Social and Personal Services	0.079506	-0.093150910	0.056681	0.016974	-0.072710	-0.121864766

Chapter 4

Real options analysis of investment in solar vs. wind energy: Diversification strategies under uncertain prices and costs

4.1 Introduction

The energy sector is currently facing different challenges connected to environmental problems, strongly varying energy prices, peak oil, foreign dependence and nuclear risks. For this reason, issues connected to energy are high at national, European and Global agendas. The easiest way to reason about these problems is by considering a most likely definite solution to the core problem, that is, the emission of greenhouse gases, notably carbon dioxide (van den Bergh, 2010). While nuclear power involves the concern of calamity risks and insurance against them, renewable energy really offers the only definite solution, as it can in principle support the supply of electricity and other types of energy carriers in a carbon-free way. Of course, this requires the equipment and indirect support of renewable energy themselves to be produced with renewable, carbon-free energy. In order to allow for the wide-spread adoption of renewable energy, it needs to produce electricity at market-competitive prices, or perhaps these prices needs to be fixed by feed in tariffs or other support mechanisms as long as these new technologies becomes competitive (Chen and Funke, 2015).

Renewable energy sources (RES) are considered to play a fundamental role in decreasing the above mention problems and creating new business opportunities. However, because of high initial costs of investments, low rates of return and uncertainty about future markets (competition, prices) and technological developments complicate firms' decisions on such investments (Menegaki, 2008; Muñoz et al., 2009). Within renewable energy, one can identify wind turbines, water power, biomass energy (including biofuels), concentrated (solar) heat power, and solar photovoltaics (PV) as the main candidates for future dominance. However, which technology will ultimately emerge as the most attractive is uncertain. These are different technologies, with distinct initial costs and learning curves. A community or investor may want to diversify the investment in such technologies as a response to any uncertainty about their future costs and learning curves.

Traditional evaluation models such as cost-benefit analysis, notably using the net present value (NPV) criterion, fail to assess the strategic dimension of investments in RES by leaving out risk and uncertainty associated with future rewards (Brealey and Myers, 2003). More sophisticated evaluation techniques are needed to deal with these. One is real options theory which sees the firm as an investor holding a financial option. It gives it the flexibility to exercise the option now or wait (at a cost) in order to acquire more information on uncertain market (competition and prices) and technological conditions. In line with investments in RES, the initial investment cost is considered irreversible, that is, once the firm decides to invest, it kills the option and the investment cost is considered sunk. The aim of this study is to develop a decision-making model considering the factors affecting firms' willingness to invest in renewable energy projects, such as wind or solar energy (see Table 4.2).

The problem we try to solve concerns the choice of a firm or community having to decide about how much to invest in two types of renewable energy technologies, namely wind and solar PV. The earnings from the two technologies are calculated as revenues minus costs (investment and maintenance costs). Revenues are obtained by selling the energy (electricity) produced with the two technologies (which is not storable) at a single market price. We consider three different cases with our model, motivated by the fact that one cannot solve the model for two learning curves (wind and solar) with both stochastic learning rates, or for one stochastic learning rate and a stochastic price. Even numerical analysis is difficult in these cases as no intermediate analytical solutions to work with are available. The three cases are: 1) a general case where the two technologies have different electricity production cost curves, with the solar technology starting at a higher initial cost than wind but showing a faster (steeper) learning curve and thus cost reduction rate; 2) a specific case where only the cost of solar PV electricity decreases over time according to a learning or experience curve, while the cost of electricity produced with wind technology is constant; 3) price as deterministic and the cost of the solar technology and its learning rate as stochastic. In the first two cases we consider uncertainty at the price level and solve the problem by finding the minimum price level and optimal timing, for which it is profitable of the firm to invest. We show the difference between the NPV method and the real option approach which takes into account important factors such as drift and uncertainty in the stochastic prices of electricity. In the third case, we investigate how the learning rate of solar PV and stochasticity of the cost of electricity production with this technology affect the decision to invest. We identify the maximum value in the production cost at which the firm is willing to invest a part of the capital in a determinate technology.

The reminder of the paper is organized as follows. Section 2 reviews the literature on applications of real options theory to investment in renewable energy. In Section 3 the basic set-up for the model is presented, and general analytical results are derived. In Section 4 we offer numerical analysis of the three model cases. Section 5 concludes.

4.2 Real options and renewable energy

Investments are an important part of the continuity of a firm as bad investments taken in the present can lead to unsustainable situations in the future or even to the bankruptcy of the firm. That is why not only the intuition of good investments but also the method of evaluation acquires so much importance.

Investments share three important characteristics:

- The investment is partially or completely irreversible, meaning that the initial cost of the investment is partially or totally sunk and cannot be recovered.
- There is uncertainty connected to the future rewards of the investment. It is better to associate probabilities to the future cash flows.
- The time when to incur the investment is important. The investment decision can be postponed in order to have more information, however, this will not reduce completely uncertainty.

Traditional methods such as NPV or discounted cash flows (DCF) are used to evaluate investments. However, these methods are not very sophisticated dealing with complex investments such as those in RES for example. The DCF approach for example is not ideal since it bases its prediction on the certain future rewards the investment will generate thereby not considering important aspects such as risk and uncertainty. The NPV on the other hand considers the investment as a now or never option, thereby leaving out the important option to postpone or delay an investment for the sake of acquiring information or waiting to see how market conditions develop. In addition, these methods do not consider the irreversibility of the investment cost. As the firm undertakes the investment, it will not be able in the future to recover the initial investment cost if market conditions turn out to be not favorable anymore.

Irreversibility and the possibility of postponing the investment in time are two important characteristics of investments. Thereby, a firm with the option to invest is seen as holding an "option" which is similar to a financial option. In this case the firm has the right, but not the obligation to exercise such option. When the firm decides to exercise the option, it "kills" the option to invest giving up the possibility to wait for new information (or more results of learning, innovation) to arrive that may be of vital importance (Dixit and Pindyck, 1994). By taking such decision the firm makes an irreversible step as it cannot disinvest should the market conditions turned out bad. This lost option value is an opportunity cost that must be taken into account as part of the costs of the investment.

4.2.1 A typology of real options

Table 4.1 introduces the different types of real options, the definition and their possible application in renewable energy technologies.

Table 4.1 Types of real options

Type	Definition	Renewable energy
Defer option	Gives to the holder the ability to wait to invest the money. This means that the company has the opportunity to invest now or wait and acquire more information for future market conditions. Such types of options are used for the evaluation of investments in natural resource extraction, real-estate development, farming, etc.	The firm having the option to build and operate a PV power plant or wind turbine can defer the construction until demand and technology prices justify such building. In renewable energy technologies this is important looking at the development of technologies.
Time-to-built option	Are used to evaluate project that require a particular time for the construction or start-up and such period is not covered by any profit. This option gives to the holder the possibility to abandon the project if market conditions turn unfavorable. These types of options are suitable to evaluate R&D projects in pharmaceutical companies and long-development capital-intensive projects	Construction of renewable power plants can be developed in stages, thus allowing a continuous review of demand trend, price levels and technologies in order to continue with the next stage or not.
Alter operating scale option or the option to expand contract, shut down and restart	Are used to evaluate projects with the possibility to expand and increase in scale if market condition turns favorable (resource extractions, construction, consumer goods).	The scale of the investment is also important. In favorable market conditions a Wind plant can be extended further, while if market conditions are not favorable, then such plant can be reduced.
Abandon options	Are important in the case when a firm sees that market conditions are turning to be not favorable. By using such an option, the firm can see if and when it is possible to abandon a project in order to organize a resale of the capital equipment and not lose the whole investment by just waiting (airlines, railroads).	Renewable energy projects are very dependent on changing regulations, market conditions and technology. If for example a technology becomes old, then the firm has the option to abandon the project and resume any residual value.
Switch option	Gives the firm the option to switch the inputs or the outputs of their business. Having the flexibility to switch from one product to the other when the market conditions turn out to be more favorable is important for the firm survival.	The option to switch represent a very good tool for firms between different uses of the land for example. An agricultural firm can decide either to continue agricultural production, or if conditions turn out favorably switch to energy production form PV or wind.
Grow option	Can be interpreted as the acquisition of a capability that allows the firm to take a better advantage of future growth opportunities	This type of options is important in renewable energy where we have seen a continuous market deregulation lately. Considering factors such as oil prices shock and environmental concern, renewable energy market can be expected to expand rapidly.

4.2.2 Real options theory applied to renewable energy investments

The energy sector has seen a major transformation in the last years. It has passed from a regulated and state owned sector to a privatized and deregulated one. Currently there are a large number of companies operating in the market thereby introducing a large uncertainty and making the sector highly competitive. Another characteristic of investments in this sector is connected to the high initial costs of investments in these technologies and the irreversibility of such investments. These factors opened the door for the use of real options theory for the evaluation of investments in energy.

The application of the real options technique for the evaluation of investments in the energy sectors has some history. The first application was by Tourinho (1979). Later on, Brennan and Schawrtz (1985) applied the option pricing theory for the evaluation of irreversible natural resources in the Chilean copper mines. In the same years, the real options theory was used for the evaluation of investments in the oil industry (Siegel et al. 1987; Paddock et al., 1988; Ekern, 1988).

The decade 1990-2000 signed the golden decade for the development of the real options theory. In these years were accomplished the works from Dixit and Pindyck (1994), Trigeorgis (1996) and Amram and Kulatilaka (1999). These authors contributed on the publications of different books and papers further developing the real options theory and applying it to investment in different fields including the energy sector also.

The use of real options theory in the energy sector as a result of the continued deregulation is introduced also by Felder (1996). Following on this, Ghosh and Ramesh (1997) investigate the development of an options market for bulk power trading in a market setup while considering power system planning and operational constraints and/ or requirements. In so doing it considers the different market based financial derivative instruments which can be used to trade electrical power in bulk and examines how established tools such as Optimal Power Flow (OPF) may be applied in helping to develop a price for bulk power transactions under a market based setup.

More recent is the use of the real options method for the evaluation of investments in renewable energy projects. Table 4.2 introduces some of the most important studies applying this technique, the types of uncertainties treated and the different tools used.

Table 4.2 Real option studies of renewable energy (in chronological order)

Authors	***Renewable energy***	***Uncertainty***	***Tool***	***Year***	***Theoretical or applied***	***Region***
Hoff et al.	PV	Price	Tree	2003	Applied: Residential	San Jose, California
Fleten and Maribu	Wind	Price	PDE	2004	Applied	Data from Nord Pool financial market
Wang and de Neufville	Hydro	Price	Tree and sim	2004	Applied	China
Zhang et al.	Hydro	Water and price	Simulation	2005	Applied	Not specified
Wang	Hydro	Price	Tree and sim	2005	Theoretical	PhD dissertation
Hedman and Sheble	Hydro and wind	Wind	PDE and sim	2006	Applied: firm	Not specified
Wang and Neufville	Hydro	Price	Tree and sim	2006	Applied	Not specified
Yu et al.	Wind	Price and demand	Sim	2006	Applied	Spain
Zhou et al.	Wind	Price	Sim	2007	Applied	California
Kjarland	Hydro	Price	PDE	2007	Applied	Norway
Sarkis and Tamarkin	PV	Technology and policy	Tree	2008		
Dykes and de Neufville	Wind	Price and policy	Tree	2008	Applied: farm	Ohio
Bockman et al.	Hydro	Price	PDE	2008	Applied:	Norway
Kimbaroglu et al.	Renewable power	Price		2008	Applied	Turkey
Kjaerland and Karlsen	Hydro and thermal	Water and costs	Sim	2009	Applied	Norway
Scatasta and Mennel	Wind	Policy and revenues	PDE	2009	Applied	Germany
Munoz et al.	Wind	Price	Tree and sim	2009	Applied	Spain
Mendez et al.	Wind	Cash flows	Tree and sim	2009	Applied	East Europe
Cheng et al.	Wind	Price, cost and policy	Tree	2010	Applied	2 base cases
Siddiqui and Fleten	Renewable energy	Price and technology	PDE	2010	Applied	Not specified
Ashuri and Kashani	PV	Technology and price	Tree and sim	2011		
Martinez and Mutale	PV	Demand response	Tree and sim	2011	Applied	UK
Martinez and Mutale	Hydro	Price	Tree and sim	2011	Applied	Not Specified
Martinez and Mutale	Wind	Wind	Tree and sim	2012	Applied	US
Martinez et al.	PV	Technology	Sim	2012	Applied	UK
Lin and Wasseh	PV	Price	Tree	2013	Applied	China
Gazheli and di Corato	PV	Price	PDE	2013	Applied	Italy
Di Corato et al.	Biomass	Price	PDE	2013	Applied	Sweden
De Olivera et al.	Biomass	Price	PDE	2014	Applied	Brasil
Zhang et al.	PV	Price and cost	Tree	2014	Applied	China
Kim et al.	Wind	Price	Tree	2014	Applied	Korea
Monjas Barroso	Wind	Price, cost, technology	Sim	2014	Applied	Germany
Kroniger	Wind	Price and wind	PDE and sim	2014	Applied	Germany
Santos et al.	Hydro	Price	Tree	2014	Applied	
Jeon et al.	PV	Energy and environment	Sim	2015	Applied	Korea
Biondi	PV	Price and costs	PDE	2015	Applied	Italy
Wasseh and Boqiang	Renewable power	Price and technology	Tree	2015	Applied	Liberia

Note: extension of overview in Martinez-Cesena et al. (2013).

As shown in the table, these studies are mostly applied and are focuses on particular regions. The main objective of such studies is to provide tools in order to test the different climate or energy policies implemented by different countries.

4.3 Model set-up

Consider a firm or community that wants to diversify investment in renewable energy by considering two options. In our particular case, we interpret the setting as the firm having to choose between investing in wind and solar PV energy. The earnings from the two technologies are calculated as revenues minus costs (investment and maintenance costs). Revenues are obtained by selling the energy (electricity) produced with the two technologies (which is not storable) at a single market price.

In Section 3.1, we consider the case of both technologies having different starting costs and different cost curves, with the solar technology starting at a higher initial cost than wind but showing a steeper learning curve and thus a faster cost reduction rate. Next, in Section 3.2, we consider the case where only the initial cost of production of the solar technology decreases by a learning rate, while the cost of production of wind is constant. This can be motivated by the fact of having a novel technology with high learning rates and an older or even obsolete one. Finally, in Section 3.3, we consider the cost of the solar PV technology to be stochastic and keep the price of energy deterministic. The latter can be motivated by the fact that there are many government policies, such as feed-in tariffs, that keep prices quite stable.

4.3.1 The costs of both technologies decrease with a learning rate

We start by considering the case in which the cost curves of both technologies decrease over time by (distinct) learning rates. The idea is shown in Figure 4.1: the initial cost of solar is higher than of wind ($c_s > c_w$), but its learning rate is higher too ($\gamma_s > \gamma_w$). This means that at some point in time the two costs curves intersect, resulting in a so-called break-even point (t_B, c_B) where the cost of the solar and wind technologies are equal. Beyond that point, as a result of a faster learning of solar, its cost becomes lower than that of wind definitely and ever more so.

In our problem, time is continuous and the duration of investment impacts or the lifetime of the technologies is considered for both to be equal to *T*. The firm holds the option to invest and develop two different technologies where, in this first case, one is characterized by a learning curve.

At the initial time, the firm has no capital invested in neither of the two technologies. The investment is considered to be irreversible and associated with a lump sum up-front cost which is different for the two technologies. A unit of capital cost *i*, so investment in *K* units of capital requires an investment expense of *I(K)=iK*. This capital will be divided between the two technologies, k_s and k_w. Once in place, the lifetime of the facility is considered to be infinite.

Each unit of output is produced at a non-negative marginal cost. The learning curves allow the firm to decrease these costs with accumulated experience. At each point in time, marginal costs are constant with respect to the rate of output but starting from an initial level $c_{s,0}$ and $c_{w,0}$ they decline with cumulative output *Q*.

At each point in time, $Q_{s,t}$ and $Q_{w,t}$ represent the cumulative demand for solar and wind energy at time *t*, and are given by:

$$Q_{s,t} = \int_0^T q_{s,\tau} d\tau \qquad (1)$$

$$Q_{w,t} = \int_0^T q_{w,\tau} d\tau \qquad (2)$$

The cost curves of the two technologies are presented in Figure 4.1. The vertical line represent the cost for the two technologies in Euros and the horizontal line the time.

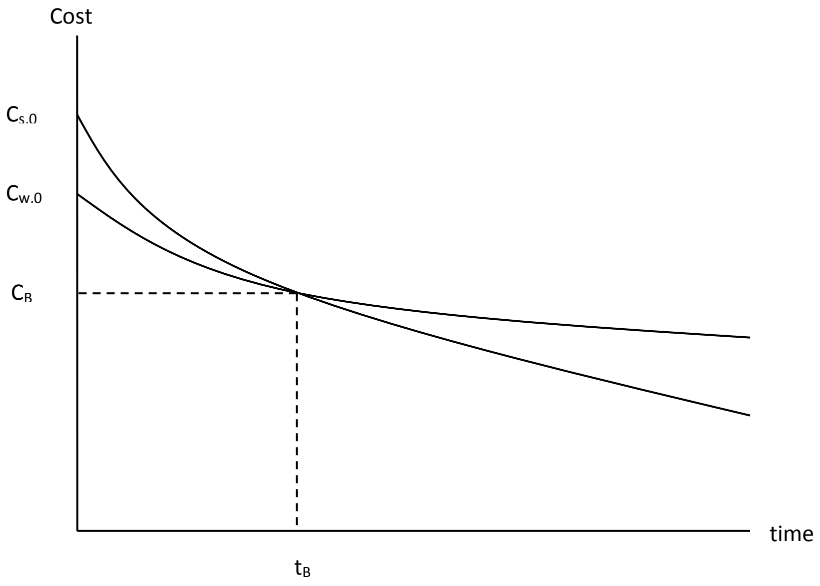

Figure 4.1 Cost curves of wind and solar decreasing due to learning

The cost curves start at different initial cost levels. C_s is the yearly cost of production and maintenance of the solar panels, and C_w is the annual cost of investment and maintenance of wind turbines. The initial cost of the C_s curve is higher than that of the C_w curve. In addition, the cost of the solar PV technology decreases over time with a learning rate γ_s, while the cost of the wind technology decreases with γ_w.

To model the learning curve we follow Majd and Pindyck (1989) and define the instantaneous marginal costs for solar and wind energy as follows:

$$C_{s,t} = c_{s,0} e^{-\gamma_s Q_{s,t}} \qquad (3)$$
$$C_{w,t} = c_{w,0} e^{-\gamma_w Q_{w,t}} \qquad (4)$$

The component γ_s and γ_w describe the learning curve for the two different technologies, i.e. solar and wind, respectively. The parameters γ_s and γ_w (both >0) determine the speed of the learning process (translating in cost reduction). A high (low) value means that the learning curve is steep (flat). As illustrated in Figure 4.1, we can see that the slope of the cost curve for solar energy (in absolute values) is higher than that of the wind technology ($\gamma_s > \gamma_w$).

As illustrated in Figure 4.1, we can see that the slope of the cost curve for solar starts at a higher initial cost, but then, as a result of learning decreases over time.

The firm's output is non-storable and sold at a unit market price denoted by P_t. The investment is done at time t_0 and the technologies become obsolete at time. The net present value of the total profits over the time period is then equal to:

$$NPV = \int_0^T \pi_t \, e^{-\rho t} dt \qquad (5)$$

Profits are discounted at rate ρ.

Here π_t is the total profit obtained from the investments in the two technologies, equal to the sum of profits from each technology, solar and wind:

$$\pi_t = \pi_{s,t} + \pi_{w,t} \tag{6}$$

The profits from solar are equal to its revenues minus its costs, with *C* the decreasing cost curve due to cumulative learning:

$$\pi_{s,t} = (P_t - c_{s,t})k_{s,t} \tag{7}$$

In the same way, the profits from wind are equal to:

$$\pi_{w,t} = (P_t - c_{w,t})k_{w,t} \tag{8}$$

In these two equations, $k_{s,t}$ and $k_{w,t}$ denote the quantities of capital invested in the two technologies at each point in time. P_t is the price from selling the energy (electricity) produced and is equal for wind and solar since their outputs are identical and so perfect substitutes.

We assume that the price is determined by an inverse linear demand function (Della Seta et al., 2012):

$$P_t = a - b(q_{s,t} + q_{w,t}) \tag{9}$$

This simply reflects that more supply leads to a lower price. In equation (9), we consider *b* as a strictly positive constant and *a*, the demand shift parameter, fluctuates according to a geometric Brownian motion with drift α and standard deviation σ. The drift factor implies that the price will follow an increasing trend over time.

$$da = \alpha a dt + \sigma a dz_t \tag{10}$$

We require that $\rho>\alpha$ because if not is not convenient to invest.

The per-period profit for solar can be written as a function of demand shock a, capital stock *K* and cumulative output *Q*.

$$\pi_s = \left[P_t - c_{s,0}e^{-\gamma_s Q_{s,t}}\right]k_{s,t} = \left[a - b(k_s + k_w) - c_{s,0}e^{-\gamma_s Q_{s,t}}\right]k_s \tag{11}$$

And for wind:

$$\pi_w = \left[P_t - c_{w,0}e^{-\gamma_w Q_{w,t}}\right]k_{w,t} = \left[a - b(k_s + k_w) - c_{w,0}e^{-\gamma_w Q_{w,t}}\right]k_w \tag{12}$$

We assume a simple linear production function for translating capital inputs into solar and wind energy output $q_{s,t} = k_{s,t}$ and $q_{w,t} = k_{w,t}$. Total profits can then be written as:

$$\pi_t = \left(a - b(k_s + k_w)\right)(k_s + k_w) - \left(c_{s,0}k_s e^{-\gamma_s k_{s,t}} + c_{w,0}k_w e^{-\gamma_w k_{w,t}}\right) \tag{13}$$

Then the net present value is given by equation (14) below

$$NPV(\pi) = \int_0^T (aK - bK^2 - c_{s,0}k_s e^{-\gamma_s k_s t} - c_{w,0}k_w e^{-\gamma_w k_{w,t}})e^{-\rho t}dt$$

$$= \frac{a_0 K(1-e^{-(\rho-\alpha)T})}{(\rho-\alpha)} - \frac{bK^2(1-e^{-\rho T})}{\rho} - \frac{c_{s,0}k_s(1-e^{-(\gamma_s k_s+\rho)T})}{\rho+\gamma_s k_s} - \frac{c_{w,0}k_w(1-e^{-(\gamma_w k_w+\rho)T})}{\rho+\gamma_w k_w} \tag{14}$$

Taking the real option perspective, the firm or community can be seen as holding an American call like option. The firm with exercise the option at the critical time threshold, *a**, at which, accounting for the uncertainty in the price of electricity, the initial cost of the two technologies and the learning curves, investing gives the maximum benefit to the firm.

Denoting by F(a) the value of the option to invest in the two technologies, the value of such an option is given by:

$$F(a) = e^{-\rho t}E[F(a+da)] \tag{15}$$

By using Ito's Lemma we expand the RHS of the equation to obtain:

$$\frac{\sigma^2}{2}a^2F''(a) + \alpha aF'(a) - \rho F(a) = 0 \tag{16}$$

The solution of (16) takes the following functional form:[18]

$$F(a) = A_1 a^{\beta_1} \tag{17}$$

where β_1 is the positive root of the characteristic equation obtained by substituting eq. 17 in eq. 16: $\left(\frac{1}{2}\right)\sigma^2\beta(\beta-1) + \alpha\beta - \rho = 0$, with A_1 a constant to be determined.

The value of the option and the critical exercise threshold can be determined by imposing value matching and smooth pasting conditions at a^*. That is:

$$F(a^*) = NPV(a^*), F'(a^*) = NPV'(a^*) \tag{18}$$

The system (18) is solved for a^*. It follows that:

$$a^* = \left(\frac{\beta_1}{\beta_1-1}\right)\left[\frac{\frac{bK^2\left(1-e^{-\rho T}\right)}{\rho} + \frac{c_{s,0}k_s\left(1-e^{-(\gamma_s k_s+\rho)T}\right)}{\rho+\gamma_s k_s} + \frac{c_{w,0}k_w(1-e^{-(\gamma_w k_w+\rho)T})}{\rho+\gamma_w k_w}}{\frac{K\left(1-e^{-(\rho-\alpha)T}\right)}{(\rho-\alpha)}}\right] \tag{19}$$

The value of the option takes the form:

$$F(a) = \begin{cases} NPV(a^*)\left(\frac{a}{a^*}\right)^{\beta_1} & for\ a > a^* \\ NPV(a) & for\ a < a^* \end{cases} \tag{20}$$

The critical threshold a^* represents the optimal threshold in the stochastic energy prices where the firm decides to invest in the two technologies. For energy prices lower than a^*, the firm

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[18] The general solution to equation (16) is $F(a) = A_1 a^{\beta_1} + A_2 a^{\beta_2}$, where $\beta_1 > 1$ and $\beta_2 < 0$ are the roots of $F(\beta) = 0$ and *A₁* and *A₂* are two constants to be determined. Since the option to invest should increase as $a \to \infty$, the second term must be dropped, implying $A_2 = 0$.

should keep the option to invest, while for energy prices higher than a^*, the firm should exercise the option and invest in the two technologies. The amount of investment to address to each of the two technologies depends on the initial cost, the learning curves, the drift and volatility of energy prices, and the discount rate. In order to provide a numerical solution on the different combinations on capital in the two technologies the technology invested in the solar PV technology is considered as δK while the capital invested in the wind technology as $(1\text{-}\delta)K$.

4.3.2 Cost of solar PV technology with a learning rate while the costs of wind fixed

In this section we continue by considering the cost of one of the technologies (wind) as constant and the cost of the other (solar) following a learning curve, which causes it to decrease over time. This can be interpreted as a new technology arriving to the market, thus having great potential to reduce its costs due to learning; and having in addition an old, mature and possibly obsolete technology, whose costs are at a historical minimum and constant for the remaining time.

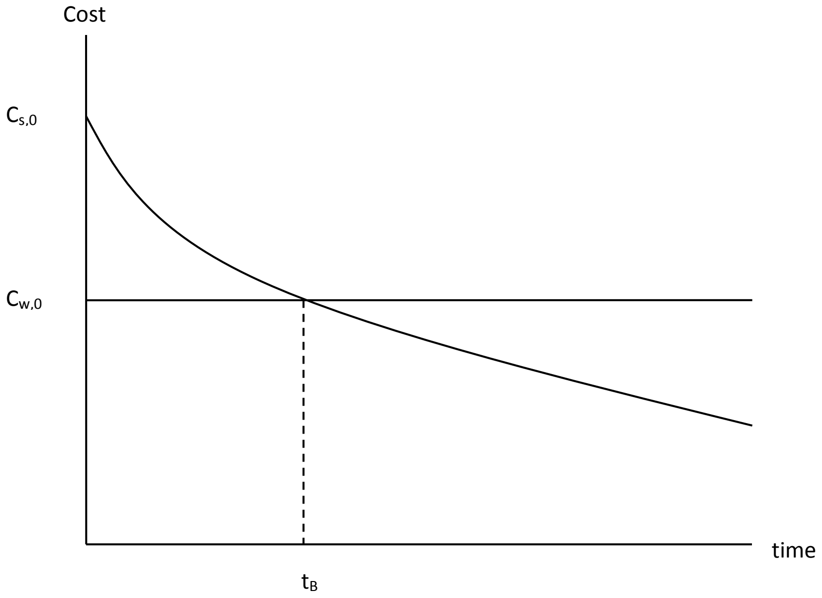

Figure 4.2: Cost curves for wind (constant) and solar (decreasing due to learning)

To model the learning curve we again follow Majd and Pindyck (1989). The cost curve of the solar technology is still expressed by equation 3, while the cost curve of the wind technology is expressed by equation 21 below.

$$C_{w,t} = c_{w,0} \tag{21}$$

This assumption simplifies the model considerably while still reflecting that the relative cost of wind, compared with that of solar PV, is increasing as the latter follows a learning curve.

We still conserve equation 11 expressing the per-period profit for solar, while the per-period profit of wind is now given by:

$$\pi_w = [P_t - c_{w,0}]k_{w,t} = [a - b(k_s + k_w) - c_{w,0}]k_w \tag{22}$$

The total profit will then be equal to:

$$\pi_t = \left[a - b(k_s + k_w) - c_{s,0}e^{-\gamma_{sk_st}}\right]k_s + \left[a - b(k_s + k_w) - c_{w,0}\right]k_w \tag{23}$$

Then the net present value is given by equation (24) below

$$NPV(\pi) = \int_0^T (aK - bK^2 - c_{s,0}k_s e^{-\gamma_{sk_st}} - c_{w,0}k_w e^{-\gamma_{wk_wt}})e^{-\rho t}dt$$
$$= \frac{a_0K(1-e^{-(\rho-\alpha)T})}{(\rho-\alpha)} - \frac{bK^2(1-e^{-\rho T})}{\rho} - \frac{c_{s,0}k_s(1-e^{-(\gamma_s k_s+\rho)T})}{\rho+\gamma_s k_s} - \frac{c_{w,0}k_w(1-e^{-\rho T})}{\rho} \tag{24}$$

By following the steps 15-18 as in the first case, we arrive at the critical threshold

$$a^* = \left(\frac{\beta_1}{\beta_1-1}\right)\left[\frac{\frac{bK^2\left(1-e^{-\rho T}\right)}{\rho}+\frac{c_{s,0}k_s\left(1-e^{-(\gamma_s k_s+\rho)T}\right)}{\rho+\gamma_s k_s}+\frac{c_{w,0}k_w(1-e^{-\rho T})}{\rho}}{\frac{K\left(1-e^{-(\rho-\alpha)T}\right)}{(\rho-\alpha)}}\right] \tag{25}$$

4.3.3 Uncertainty about the learning rate of solar and deterministic electricity price

In the third case we consider price as deterministic. This means that in equation 9 the components *a* and *b* are now both constant and positive. It can be interpreted as the price of electricity being fixed, or having a large deterministic component, due to governmental support mechanisms such as feed-in tariffs, while the cost of the technology decreases over time as a result of learning and innovation. This model version allows us to examine the effect of uncertainty about costs, in particular learning rates. Including both price and cost uncertainty will lead to an overly complicated model, and moreover can be argued to be unnecessary as cost uncertainty will affect price patterns, so that indirectly prices are uncertain as a result.

We assume the cost of solar PV to follow a geometric Brownian motion as in equation 26.

$$dC_{s,0} = \alpha C_{s,0}dt + \sigma C_{s,0}dz_t \tag{26}$$

As in the previous case, we let the initial cost of production of solar PV to decrease with its learning rate. For this reason, we put the drift equal to zero and investigate on different values of volatility to analyze the effect of uncertainty in technology costs.

The per-period profit equations are expressed by equations 22 and 23 of the previous section. We then follow the steps 15-18 to arrive at the critical threshold of the cost of solar PV technology which is expressed by equation 27:

$$c_{s,0}^* = \left(\frac{\beta_1}{\beta_1+1}\right)\left[\frac{\frac{aK\left(1-e^{-\rho T}\right)}{\rho}-\frac{bK^2\left(1-e^{-\rho T}\right)}{\rho}-\frac{c_{w,0}k_w(1-e^{-\rho T})}{\rho}}{\frac{k_s\left(1-e^{-(\gamma_s k_s+\rho)T}\right)}{\rho+\gamma_s k_s}}\right] \tag{27}$$

This equation defines the maximum value of the initial electricity production cost of the solar PV technology for which, given the revenues generated by the investment, it is profitable to exercise the option. For every value of electricity production cost of the solar technology above this critical threshold, it is not convenient to invest and one will maintain the option to invest open. For every value equal or below this level, it is profitable to exercise the option to invest and allocate different shares of capital (depending on the level of cost and learning rate) to the solar PV technology. The choice of shares is illustrated in the next section.

4.4 Numerical application

Since insightful analytical solutions are impossible because of nonlinearities in the model, here we perform numerical analysis with the models to understand the characteristics of optimal investment in wind and solar technologies.

Table 4.3 shows the values of the parameters for the three cases.

Table 4.3 Default values of model parameters for numerical simulations

Description	Symbol	Case 1	Case 2	Case 3
Learning rate of the solar technology	γ_s	0.05	-	-
Learning rate of the wind technology	γ_w	0.03	0	-
Demand parameter	b	0.2	-	-
Drift	α	0.04	-	0
Volatility	σ	0.1	-	-
Discount rate	ρ	0.06	-	-
Intial cost of electricity production by the solar technology	$c_{s,0}$	20	-	Solved by the model
Initial cost of electricity production by wind technology	$c_{w,0}$	15	-	-
Root of fundamental quadratic equation 16	β_1	1.4244289	-	-
Capital invested in the two technologies	K	100	-	-
Investment duration	T	25	-	-
Price intercept parameter	a	Solved by the model	Solved by the model	35

4.4.1 Both technologies with learning

In this case we both the learning curves of the two technologies decreasing with a learning parameter. We set the preliminary condition $\gamma_s > \gamma_w$, as a result the cost curve of solar will be steeper than the one of the wind technology. Thereby, the costs of the solar technology start at a higher initial cost, but perhaps decrease more rapidly compared to the one of the wind technology. The learning parameters for the base case are set equal to 0.05 for the solar and 0.03 for the wind technology.

Figure 4.3 shows the critical threshold a^* for different portions of capital invested in the two technologies. As it can be seen from the figure, when all the edges of the graph show the lower a^* value that makes us exercise the option to invest.

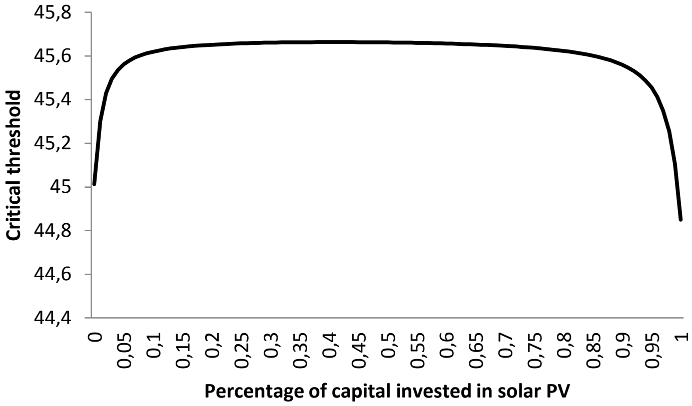

Figure 4.3 Critical threshold with two learning curves

This is a straight forward result of our model since the amount of capital invested has a direct effect on learning and as a result on the costs decrease. Even if solar starts at an initial cost which is higher, compared to the wind technology, as a result of the higher learning parameter, the costs of this technology decrease faster. As a result, we are willing to invest in the solar technology at $a^*=44.84$, while to invest 100% of our capital in wind, we will wait more, until a^* reaches 45.01. However, we are considering the case of an investor who wants to diversify his investment in the two technologies. From the graph we can see that if the price of electricity is below 45.01, then it is profitable to invest all the capital in the solar technology. If the price increases up to 45.40 it is profitable to allocate 95% of the capital in one technology and only 5% in the other. This is because we have to account for the costs of the two technologies, and the fact that cost are falling due to both learning and more capital being invested in a particular technology. This means that investing more capital in one technology generates faster learning and thus reduction of electricity production costs associated with the respective technology. By diversifying the investment, the cost reduction will not be as high. As a result we will postpone the investment and require a higher a^* to exercise the option to invest. The higher value of a^* is 45.66349 and the allocation of capital is $ 41 in the solar technology and the remaining $ 59 in the wind technology.

Figure 4.4 shows the sensitivity analysis of the learning parameter and initial cost in the case when the costs of wind and solar electricity production are affected by learning.

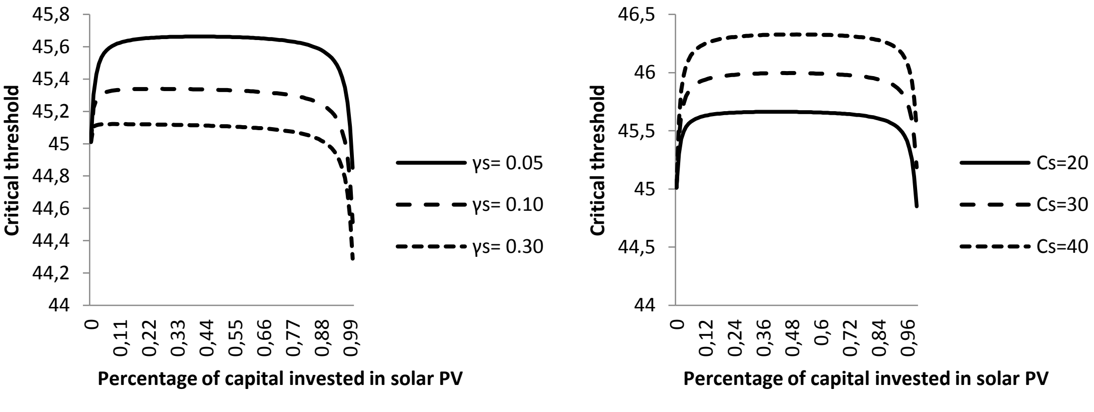

Figure 4.4 Sensitivity analysis of learning and initial cost

As in the case with one cost curve with learning, the effect of an increase in the learning parameter does anticipate the option to invest and decrease the critical threshold as shown form the right graphin Figure 4.4. When the learning parameter of solar is equal to 0.30, it is profitable to exercise the option to invest at a price equal to 44.29 and invest 100% of the capital in the solar PV technology, and hence benefit from its high learning speed. An increase in the initial cost of solar does postpone the option to invest and increase the critical threshold. The right graph in of Figure 4.4 shows that when the cost of solar is equal to 20, as in the base case, we exercise the option to invest earlier and allocate 100% of the capital in the solar technology. As Figure 4.4 shows, when the initial cost of solar is equal to 40, the order of investment is reversed. For electricity prices equal to 45.01 it is profitable to invest 100% of the wind, and the firm has to wait until the price goes up to 45.52. The highest critical threshold at which we exercise the option to invest is equal to 46.32 for the distribution of capital 50% in solar PV and 50% in wind.

Figure 4.5 shows the results of the sensitivity analysis on the volatility of energy prices. The pattern of the lines is the same, but perhaps we will require a lower critical value to exercise the option to invest if there is no volatility in energy prices. In this case, a*=40.09 if all capital is invested in the solar PV technology.

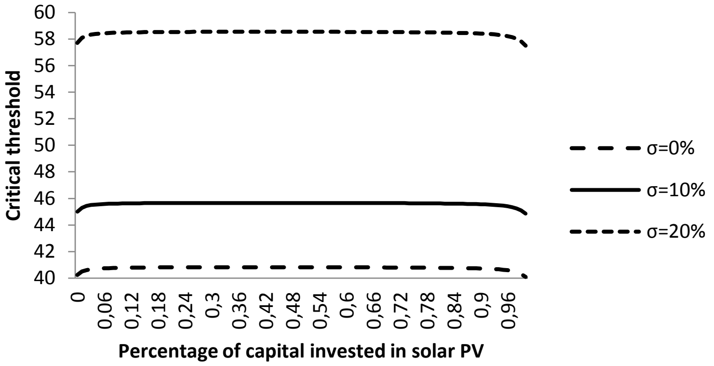

Figure 4.5 Sensitivity analysis on volatility

If the volatility in energy prices is quite high, equal to 20%, the decision to invest will be postponed until a*=57.50 to invest all the capital in the solar PV technology or even higher if we consider a combination of the two technologies. As explained earlier, in order to diversify the investment, the firm will wait until the price of electricity is high enough to cover the costs of both technologies since costs will decrease at a lower rate.

4.4.2 One technology with learning

Here we examine the case when only the costs of the solar technology decrease with a learning rate, while the costs of the wind technology are kept constant during the lifetime of the technology. The other parameters are set as indicated in Table 4.3.

The critical threshold *a** at which it is profitable to exercise the option to invest is given by Figure 4.6.

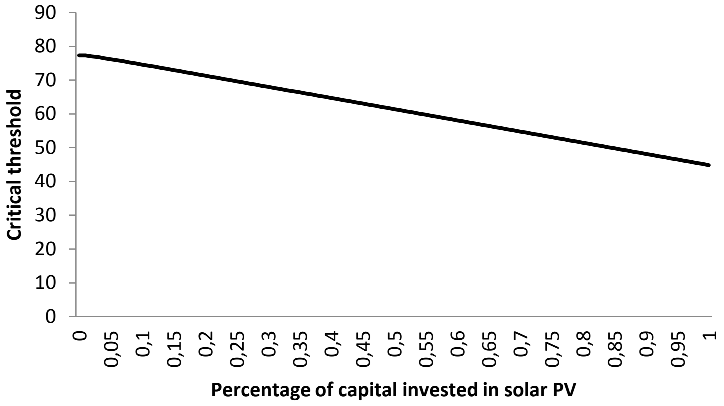

Figure 4.6 Critical threshold a at which it is profitable to exercise the option*

The figure shows that if all capital is invested in the technology with fixed costs, then we postpone the option to invest and require a high value of *a** (*a*=77.31*). As we diversify our investment and invest an increasing part of capital in the solar technology, its costs decreasing with the learning rate, causing exercising of the option to invest to be optimal at lower, decreasing values of *a**. If capital investment is diversified as 50% in the solar and the remaining 50% in the wind technology, then the option is exercised for an electricity price equal to 61.41. If all the capital is invested in the solar technology, then we are willing to exercise the investment earlier at a minimum value of *a*=44.84*, i.e. also for any value larger than this.

Figure 4.7 shows the relationship between the learning rate and the critical threshold on the left side, and between the initial cost and critical threshold on the right side, both for the case where 50% of the capital is invested in solar PV and 50% in wind technology.

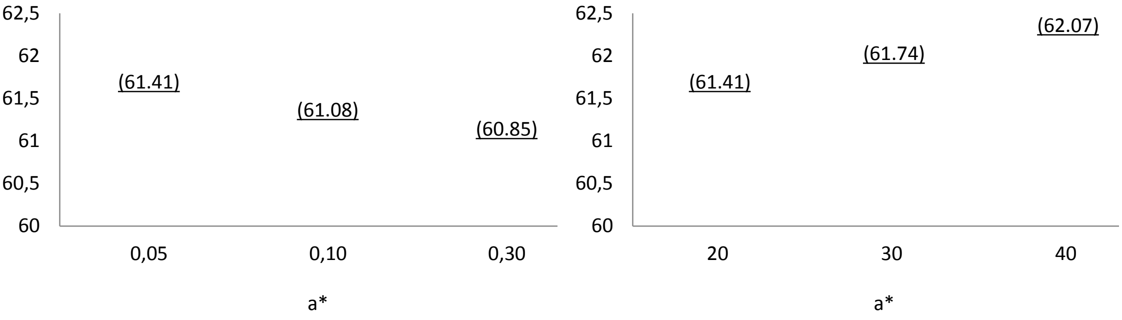

Figure 4.7 Sensitivity analysis of the impact of learning and initial cost on the critical threshold

The figure shows that the higher the learning rate, the earlier we exercise the option to invest and for lower values of *a**, as a result of the cost reduction. On the contrary, the higher the initial cost of the solar technology, the later one invests on average and a higher value of *a** is required. The uncertain time delay results from the fact that prices steadily increase but stochastically. In addition, the costs of production of the solar technology will start at a high value, and even if it falls due to learning, it will be relatively high for a long period. For this reason one will be forced wait and require a higher critical threshold price to exercise the option.

In Figure 4.8 we show a sensitivity analysis of volatility. In line with the literature on real options, we can see that the higher the volatility in the market, the more we are willing to postpone the investment and require a higher value *a** before executing the option.

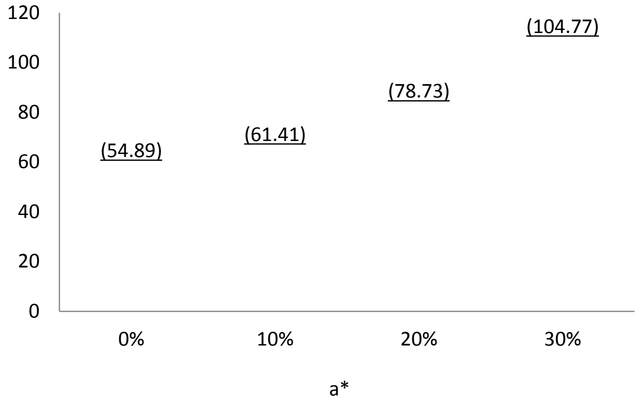

Figure 4.8 Sensitivity analysis of volatility

If volatility is equal to zero and we invest all our capital in the technology with learning, we are willing to invest at a critical threshold of 54.89. On the contrary, if volatility in the market is high, equal to 30%, we wait to invest until the critical threshold is equal to 104.77. This holds for the case of the investor diversifying investment 50% in solar and 50% in wind.

Figure 4.9 shows the effect of γ_s on timing and the critical threshold for σ equal to 0.05, 0.1 and 0.2. As expected, for a given learning rate in the solar technology, the critical threshold increases with uncertainty.

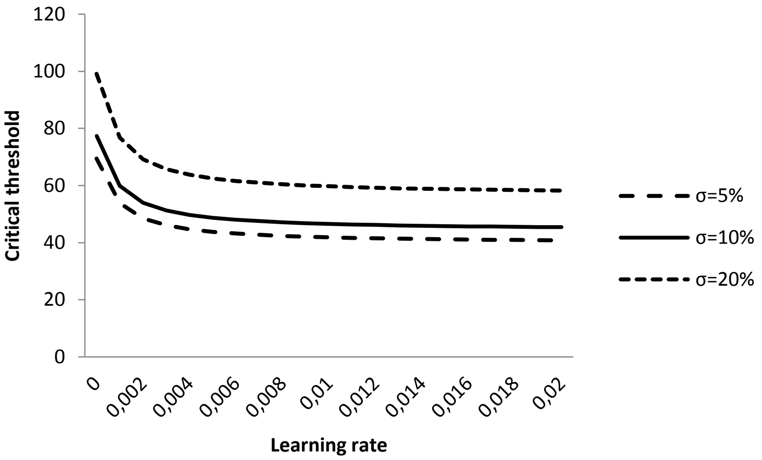

Figure 4.9 Optimal values of the critical threshold for different values of volatility

If the learning rate is low and volatility high, we will postpone the option to invest and require very high values of *a** to exercise the option. As the learning rate increases, or volatility in energy prices decreases, we anticipate the option to invest and *a** decreases in value.

Figure 4.10 shows the option value and the NPV curve. The straight line showing NPV indicates that it is profitable to invest as soon as NPV>0.

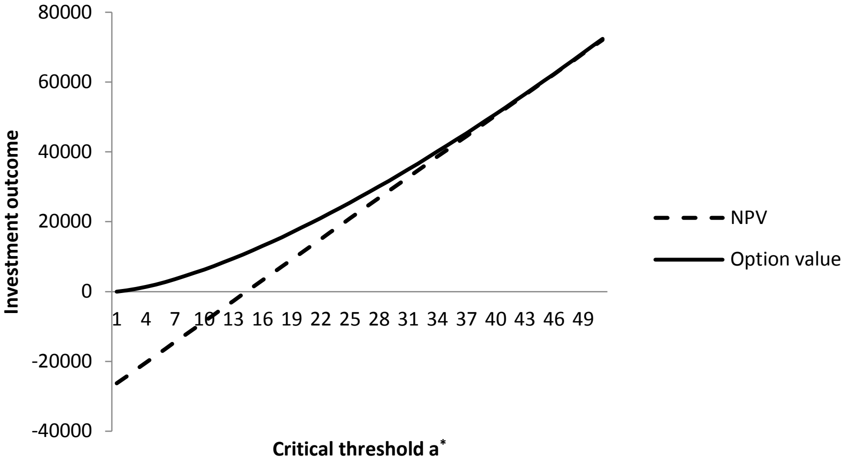

Figure 4.10 Net present value and option value compared

By investing all the capital in the technology with learning, the NPV of the investment becomes positive for a value of a^* equal to 13.31. According to the real options theory, the value of the option to wait, is given by the red line *F(a).*

$$F(a) = \begin{cases} A_1 a^{\beta_1} & for\ a < a^* \\ NPV & for\ a > a^* \end{cases}$$

According to the NPV we should invest 100% of our capital in the technology with learning as soon as $a^*=13.31$. However, from the figure, we can see that the option has a high value in this point. By investing we kill this option value. Following Figure 4.10, we have to wait until the option value equals NPV and then exercise the option to invest. This means that the investor should wait until a^* is equal or greater than 44.62. At this point the option value is zero and its curve touches the NPV curve as shown in the figure. In order to diversify its investment in the two technologies, the investor should exercise the option for values in the electricity price higher than 44.62.

4.4.3 One technology with learning, deterministic price and stochastic costs.

In this part of our study we consider price as deterministic. The price equation (9) still applies, but with fixed parameters *a* and *b*, both strictly positive. Figure 4.11 shows that maximum value of the initial cost of electricity production by the solar technology at which we are willing to invest according to the NPV and the real options approach.

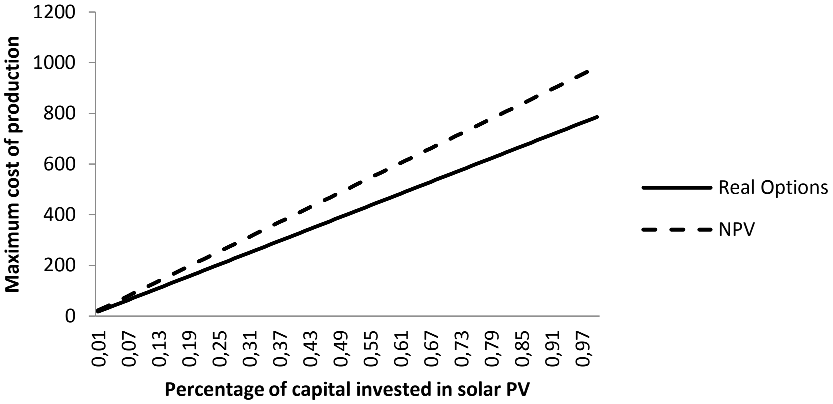

Figure 4.11 Initial cost of solar PV according to NPV and real options

According to this figure, investing little capital in the solar PV technology (i.e. exercising the option to invest) is optimal only if the initial production cost is sufficiently low. On the contrary, a high share of capital invested in solar is optimal already for higher production costs since one has the expectation here that production costs drop rapidly due to faster learning. The reason is that the more capital is invested in solar, the faster its costs drop due to learning. This result derives from the fact that all capital is invested in solar PV and hence the firm can cover higher production costs for this technology. Following the NPV curve, we should invest in the technology and accept even a higher initial production cost before exercising the option. The real options approach, which is more accurate since it considers the volatility in production costs, tells us to wait and not exercise the option to invest until costs are equal or below the value represented by the continuous "Real Options" line.

Figure 4.12 shows a sensitivity analysis of the impact of the *a* parameter of price on the threshold of the initial cost.

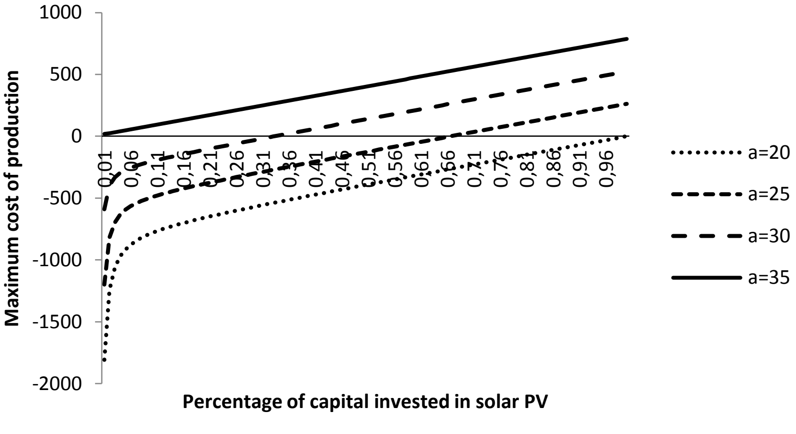

Figure 4.12 Sensitivity analysis of the price intercept a

In Figure 4.12, for *a=20*, the electricity price is too low to give sufficient revenues, even if the initial cost of solar PV is equal to zero. This means it is not profitable to invest any proportion of the capital in solar PV technology. When a=25, as a result of the costs decreasing due to learning it is profitable to invest a large amount of capital in solar PV. As shown in the figure at least 67% of all capital needs to be invested in solar to make execution of the option viable. Raising parameter *a* further, to *30*, the share threshold goes down to 34%. For values of *a* beyond *35* any investment in solar PV is viable.

Figure 4.13 shows the sensitivity analysis of the impact of volatility on the initial cost of solar.

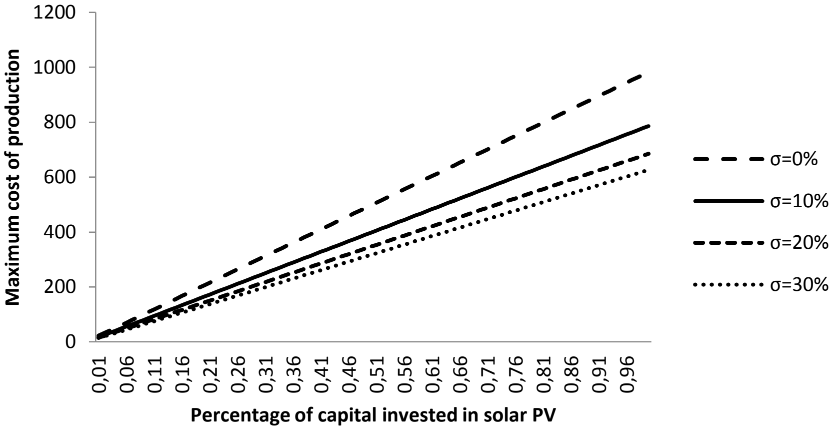

Figure 4.13 Initial cost of technology of solar PV and volatility

The figure shows that the lower the volatility, the higher the maximum cost we are willing to accept to invest some share of capital in the solar PV technology. This is because with lower volatility the chance of positive spikes in costs is lower. In Figure 4.13, the line representing *σ=0* coincides with the NPV line. For high values of volatility in the initial costs, one is eager to postpone the investment and wait until costs go down, as illustrated by the bottom line in the figure (*σ=30*). This result is in line with the literature on real options where a general finding is that uncertainty postpones the investment.

The results of a sensitivity analysis of the learning rate are shown in Figure 4.14.

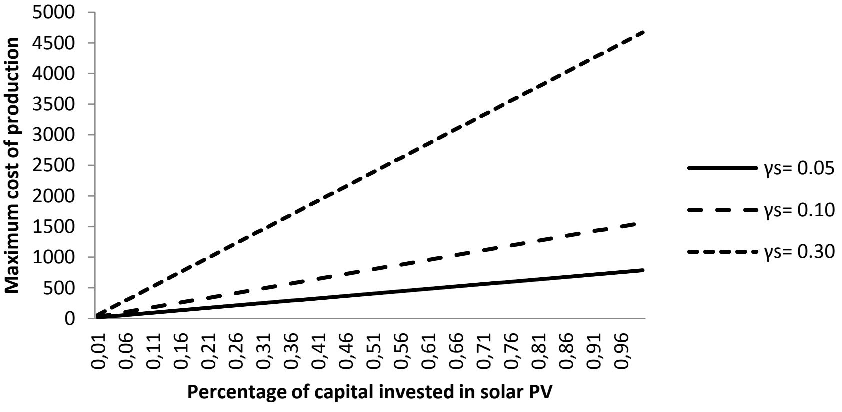

Figure 4.14 Sensitivity analysis of the learning rate

The figure shows that a low value of the learning rate postpones the decision to invest and makes one will wait until the initial cost of the solar PV technology decreases to the level as indicated by the continuous line showed in Figure 4.14. If the learning rate of the technology is very high, up to 0.30, then, since costs decrease more over time with a higher rate, we exercise the option earlier and at even higher levels of initial cost. The higher the portion of capital invested in the solar PV technology, the higher will be the maximum cost that we accept to invest, since the investment can benefit more from the technology that allows learning over time and as a result making more revenues from the associated cost reduction.

4.4.4 Comparison of the three model versions

In the three applications illustrated above, we showed the different roles of the learning rate, the cost of the technology and uncertainty in investments in renewable energy projects. In first place, we pointed out the difference between the NPV and the real options approach. While the first indicates that we should invest as soon as profits are equal or greater than zero, the latter, which more accurately takes into account the drift in future electricity prices and market uncertainty, indicates to wait and exercise the option later when conditions are more favorable.

The results of our model show that uncertainty has the same effect when considered in the electricity prices or technology costs. The higher the uncertainty, the more one is willing to wait before exercising the option. This fact is also explained by the necessity to wait and have more market information in periods of high uncertainty. With high uncertainty the critical threshold in energy prices will grow, and the firm will require a higher price to exercise the option to invest, thereby postponing the option to exercise. A high uncertainty of costs on the other side will lower the critical threshold of production cost indicating the maximum cost the firm is willing to exercise the option.

The effect of learning is quite important in anticipating the option to invest and exercising earlier the option. Learning is straight forward connected to cost reduction. As a result, the higher the learning rate, the higher will be the amount of cost we reduce during the whole investment duration. In addition, the learning parameter is also positively connected with the share of capital in order to reduce costs. The more capital we invest in one technology, the more we learn from that technology, and the more we reduce costs.

The cost of production on the other hand postpones the option to invest. The higher the initial cost of production of the technology, the higher will be the price of electricity required to exercise the option to invest in order to make enough revenues to cover such cost. For this the investment will be postponed until prices will be at a higher level.

In the last part of our application we saw that by applying a fixed parameter of price, a, and having one technology with learning, we can identify the maximum initial cost that make this technology profitable and the share of capital we should invest in this technology. The results shown in Figure 4.12 indicate that for lower values of the parameter a one is willing to wait and accept lower maximum costs of production to exercise the option to invest. This will influence the quantity of capital allocated to this technology. Since the amount of capital cumulatively invested affects the speed of learning, this allows a greater cost reduction. With a low guaranteed value of parameter a, one will be willing to allocate larger parts of capital to solar in order to realize a greater cost reduction. As soon as the a parameter guaranteed is higher, a higher production cost can be accepted to exercise the option to invest and the size of capital allocated can be even smaller.

4.5 Conclusions

In this paper we presented the case of a firm or community having to decide to invest between two different types of renewable energy, such as wind and solar PV. A fixed amount of capital can be invested and so had to be allocated between these two alternatives. In our study, the firm considers diversification of the investment in two technologies. The electricity produced with both technologies is sold at a uniform price on the electricity market. We investigate three different cases: (i) the two technologies have different initial costs of electricity production as well as different learning rates, while the electricity price is stochastic; (ii) only the production cost of one technology follows a learning curve, while the other has a constant cost, and again electricity price is stochastic; (iii) the electricity production cost of solar is uncertain and reduced by the learning parameter while the electricity price is deterministic, due to public support like feed-in-tariffs.

So we have a problem in which investments in renewable energy are irreversible as a result of their high sunk costs. Moreover, they are affected by uncertainty in electricity prices and costs. To deal with this problem, we applied real option theory. A growing literature applies this theory to investments in renewable energy. The original contribution of this study was that it considers two distinct assets in which the firm can invest, with different initial cost and learning parameters.

In the first two cases we solved the problem by determining the critical threshold at which the firm will invest in order to have a profit. For energy prices lower than this critical threshold, the firm should keep the option to invest, while for energy prices that are higher, the firm should exercise the option and invest in the two technologies. The results show that if 100% of the capital is invested in the solar PV technology or in the wind technology, the firm exercises the option earlier and at a lower critical threshold. In order to diversify the investment in the two technologies, the firm has to wait and exercise the option to invest at a higher critical threshold of electricity prices. This is because costs are reduced through learning which depends on the quantity of capital invested in a technology. The more we capital we invest in one technology, the more we learn and as a result cost reduction is greater for that technology, which makes it possible to exercise the option at a lower critical threshold. In the third case, we determine the maximum cost of production of a given technology that the firm will be willing to invest, and the given capital share of the two investments. The results here show that if the firm invests little capital in solar PV, then it has to wait and exercise the option to invest only if the initial production cost is sufficiently low. If the capital invested in the solar PV technology is high, then it is possible to earlier exercise the option to invest, and moreover for higher values in the initial cost. Two reasons for this result are: we invest more capital in solar PV, thereby decreasing the investment in wind; and since more capital is invested, the cost decrease as a result of learning will be higher, which allows the firm to cover higher production costs.

A high learning rate will translate in anticipating the option to invest, requiring a lower critical value to exercise the option in the first two cases, or accepting a higher initial production cost in the third case since it has a direct effect on cost reduction. The higher the learning rate of one technology, the earlier we exercise the option to invest and the larger will be the capital allocated to that technology. A high cost of technology will on the other hand postpone the option to invest, since the firm will need to make sufficient profits to cover the associated stream of costs during the entire period. The higher are the cost of a technology, the higher will be the price required to exercise the option to invest. An increase in the initial cost will postpone the option to invest and make the firm allocate more capital to the other technology. We find that high uncertainty in either electricity prices or technology costs will postpone the investment. Under high uncertainty one will prefer to wait more and see how the market evolves before exercising the option.

When prices are deterministic, the more capital the firm allocates to one technology the higher will be the maximum electricity production cost to exercise the option to invest. This means that for high shares of capital invested one can accept relatively high costs, while on the contrary, for low capital shares the firm will wait until the cost decreases sufficiently, otherwise it cannot cover this with the revenues made. Moreover, such production cost cannot quickly go down at a high rate due to learning when relatively little capital is invested.

In the presence of a deterministic price supported through government subsidies, the results show that its level affects not only the maximum cost the firm can accept to exercise the option to invest, but also the share of capital between the two technologies. From this result we can see that governments employing policies to guarantee a minimum price, will – through reducing future price uncertainty – influence capital allocation between renewable energy options.

The somewhat surprising main insight from this study is that although investing in both solar and wind may be profitable, although it certainly is not under all conditions of price and cost uncertainty, the optimal strategy is to invest in one technology. This is solar or wind, depending on the combination of their initial costs and learning rates. This result goes against a lot of literature which suggests that diversity is preferable because of uncertainty and keeping options open, which is consistent also with the practice in most countries.

This may go against intuition. The explanation for this result is perhaps that although there is uncertainty about prices or costs in our model setting, this is a case of traditional risk, that is, parameterized uncertainty. If, on the other hand, we would conceptualize the uncertainty as deep and pervasive or undefined (Knightian), diversifying would likely come out as a more desirable if not best strategy. Arguably, this is closer to the reality of renewable energy investment: it is difficult to assign credible probabilities about price variation and learning. This case, however, cannot be addressed with the method of real options but requires a different approach.

Finally, certain motivations for diversifying are possibly not or insufficiently covered by our model. This suggests a need for further research employing more complex models that include such motivations. An important one is keeping all significant technological options open so as to remain flexible in the face of unforeseen technological scenarios and undesirable environmental or social consequences of particular renewable energy technologies.

Chapter 5

Conclusions

This thesis has examined the notion of a sustainability transition, particularly in view of combatting climate change, by focusing on three core aspects of it: behavioral barriers and opportunities, limits to green growth from the angle of disaggregate production sectors, and optimal investment in renewable energy under uncertainty. This final chapter aims to summarize the specific studies undertaken and their conclusions, as well as provide recommendations for transition policies.

In order to provide a good understanding of the relevance of behavioral economics and sustainability transitions theory, Chapter 2 reviewed the relevance of bounded rationality and other-regarding preferences, driving social interactions, for policies aimed at fostering a sustainability transition. This built on insights of behavioral economics, transition studies and evolutionary economics, offering insights about barriers as well as opportunities for guiding behaviours of consumers, producers and investors for the benefit of a sustainability transition.

Different factors play a role in helping or impeding a transition to occur. Increasing returns to scale cause path dependency, which may end in a lock-in of undesirable, non-optimal technologies, thereby obstructing a sustainability transition. In addition, power of vested interest groups may work in favor or contrary to a transition. Agents can use any social, political or economic power they possess to achieve their own interests, at the cost of social or environmental goals. While actors involved in a transition are usually considered as fully rational by policy makers or mainstream policy theories, notably in economics, behavioral research supports the idea that they are boundedly rational. In line with this, we zoomed in on various behavioral biases that may play a role in accepting or resisting transition policies. Particularly, behavioral economics sees stakeholders as boundedly rational and bestowed with other-regarding preferences. In this thesis I divided the stakeholders involved in sustainability transitions in three main groups, in order to identify the most important biases for each group and derive policy lessons for these. These groups are: (i) consumers or households, (ii) producers and investors and (iii) governments.

Consumers or households are essential to a transition as their everyday decisions have serious consequences for the environment. In order to increase policy acceptance, a number of behavioral biases and other regarding preferences of this group of stakeholders need to be considered in transition policy design and implementation. Policy makers should especially account for individual biases such as habits, status quo bias, affect and imitation which may increase inertia and thereby resistance to change. Not considering these behavioral aspects in transition policies may complicate achieving a transition since consumers and household will tend to stick to their current patterns of carbon-intensive consumption. Other biases of consumers identified as important in this thesis are altruism, fairness and the effects of framing. Such behavioral anomalies may influence the level of cooperation between stakeholders, acceptance of policies and perceptions of environmental and technological risks. In addition not only individual but also group behavior is relevant. Particularly, norms and rules are important as they affect how groups of individuals function. Understanding group behavior and the role of certain group members, such as leaders in organizations, role models and potential change agents, may help to foster a sustainability transition. Policies might focus their attention on such critical group members.

A second group of stakeholders identified in this chapter are producers and investors. These actors may be seen as more rational than the first group, but nevertheless still showing specific behavioral biases that also can impede transitions. One is that firms usually undertake satisfactory strategies instead of consistently searching profit-maximization ones. They usually end up in particular organizational routines and revise their strategies only when they realize serious losses or become aware of performing much worse than their competitors. A solution to this can take the form of changing existing routines through awareness training of appropriate experts, or a combination of incentives, regulatory rules, and norms. Producers are in addition often over-optimistic while their decisions are affected by anchoring (i.e. an initial outcome serves as a reference point that influences subsequent value judgments).

A third group of transition stakeholders are governments. It plays an important role in policy design and implementation. Governments should be considered not just as single, unitary institutions, but as composed of distinct groups of individuals, each with particular self-interests. These groups will try to influence with their power the different stages of a transition. In addition, we have to consider governments as operating partly outside markets and hence only partly sensitive to market incentives to guide them in the direction of sustainability. Finally, since they are responsible for acceptance of what experts overwhelmingly consider good or best policies, they should take into account also the bounded rationality of economic agents to formulate policies so as to be acceptable for both companies and consumers. Identified issues that matters for policy effectiveness are: adequate framing of climate threats and low-carbon opportunities to change risk perception and avoid that people use psychological defense mechanisms that may hinder behavioral change when exposed to complex issues such as climate change; designing fair policies to increase their acceptance (experiences with CO_2 emission taxes in the transport sector show that fairness is crucial for policy acceptance); accounting for status (In order to re-direct aspirations that stimulate environmentally damaging consumption towards more sustainable options, green status goods may be useful), affect and habits in policies as these contribute to inertia (understand the reasons for reluctance to change unsustainable consumption behavior, insight into consumers' psychological valuation of consumer goods is important).

A crucial element in the different phases of sustainability transition is the innovation process. At the niche level is where most innovations start, and as a result, behavioral biases such as habits and routines are important since they constitute barriers to change here. Furthermore, biases such as over-optimism, organizational pressure and career aspirations are important to consider in group interactions. At the regime level the status quo bias is identified to be a potential obstacle to change.

Chapter 3 investigated the potential conflict between economic growth and environmental protection. Different policies to stimulate green growth were implemented after the Kyoto protocol and most voters, politicians and economists strongly believe in, and focus on, green growth, even though its feasibility is highly uncertain, notably in view of very ambitious climate goals. For this reason we address the question of whether economic growth and carbon dioxide emissions are strongly coupled? This is tackled in a novel manner, among others, as we use disaggregate, sector-level data, and a range of indicators of economic growth and productivity. Another noveltyis the use of two distinct carbon intensity measures, namely direct and total carbon intensities. The first one considers the carbon emissions released by the industrial processes in each economic sector, while the second indicator takes into account the indirect emissions through intermediate deliveries between sectors, includingemissions associated with imports. For calculating the second indicator environmentally extended input-output tables were used to reallocate emissions between sectors. We did this on a global scale, using world input-output tables, to capture the effects of externalization of dirty products. The study considered three European countries with different economic structures and histories: Denmark, Germany and Spain, over the time period 1995-2007.

A main conclusion is that despite past climate policy, as developed under the Kyoto protocol, relatively clean sectors do not seem to be more productive than dirtier ones, and neither show higher productivity growth. Sectors associated with high carbon intensity grew more in absolute terms than those with low carbon intensity. The share of these sectors increased, suggesting that green growth requires an extremely rapid pace of decarbonization through appropriate new technologies in all sectors, or the economy as a whole has to shrink (i.e. "green decline" instead of "green growth"). An important additional finding of this study is that longer-term sectoral growth, as expressed by a change in value added, does not seem to be positively correlated with carbon intensity.

The results of the correlation analysis between final demand and carbon intensity show higher correlations for Denmark and Germany than for Spain, meaning that the challenge for these two countries is higher. Possibly, this reflects that they have already accomplished more emissions or carbon intensity reduction in the past. Value added on the other hand, which may be considered to offer a long-term growth perspective for the economic sectors, provides a positive signal about the possibility of a transition to sustainability. The results of the analysis show a lower correlation, meaning that pollutive sectors grew less in terms of value added.

We further studied indicators of labor productivity, to test the hypothesis that many machines per worker and per unit of output, which use and process energy, is at the basis of both high labor productivity and high CO_2 emissions. The fact of having many machines may also allow for much technological progress as existing machines or parts can be improved and replaced by new, better performing ones increasing productivity. The result of correlation between carbon intensity and productivity indicators suggest that a high intensity of technology may be at the basis of a combination of high labor productivity in output terms and high emission intensity.

Only the results of the correlation analysis between carbon intensity and value added, which are negative for at least two countries, give some hope about green growth. The results of the other correlations confirm the great challenge green growth implies because they do not give statistically significant negative values that point at any decoupling at the sectoral level.

This study underpins that the challenge of green growth is enormous and underestimated. Past climate policies implemented under the Kyoto international agreement have hardly affected economic sector structure. As the economy is a complex system dependent on products and sectors that are closely interlinked, effective change in structure to contribute to emissions reduction is unlikely to result from tinkering with only one element in the system. Instead one would need to change the web of intermediate (as well as international) production relations making up the system. This requires much tougher climate regulations than have been implemented so far, surely requiring international policy coordination. Unfortunately, this still hasn't been accomplished, not even in the recent Paris Climate Agreement.

Chapter 4 addressed the fundamental problem of a firm or community deciding to optimally diversify its investment in two different renewable energy projects, solar PV and wind technology. The firm is assumed to have a fixed amount of capital and has to decide the proportions to invest in each technology. The electricity produced is sold at a uniform price in the market. We investigated three different cases: (i) the two technologies have different initial costs of electricity production as well as different learning rates, while the electricity price is stochastic; (ii) only the production cost of one technology follows a learning curve, while the other has a constant cost, and again electricity price is stochastic; (iii) the electricity production cost of solar is uncertain and reduced by the learning parameter while the electricity price is deterministic, due to public support. These can be explained by real cases when (i) a company has to decide to invest between two different new technologies with decreasing learning rates as a result of R&D, (ii) the case when one technology is new, the costs of which decrease at a learning rate, while the second is obsolete, characterized by fixed technological costs, and (iii) when price is stable due to subsidy mechanisms such as feed-in-tariffs.

Since investments in renewable energy are irreversible, due to high sunk costs, and affected by uncertainty in the electricity prices and costs, we applied real options theory. The originality of this study is that it considers two different assets with different initial costs and different learning parameters.

In the first two case studies we solved the model and identified the critical threshold in the price of electricity which for the firm makes it profitable to exercise the option, i.e. invest. For every level in the electricity prices above the critical threshold, the firm will exercise the option to invest. For levels below the critical threshold, the firm will keep the option to invest and wait. In the third model application we identified the maximum level in the initial cost at which it is still convenient for the firm to exercise the option to invest. For any cost below this level, the firm will exercise the option to invest, and, on the contrary, for every cost above this level, the firm will keep the option to invest and not exercise it.

The results show the importance of the learning rate in terms of anticipating the option to invest and exercising it at a lower critical threshold or for higher initial production cost. The higher the learning rate of one technology, the earlier we exercise the option to invest and the larger will be the amount of capital allocated to that technology. A high initial cost of that technology, on the other hand, will postpone the option to invest since the firm needs to make sufficient earnings in order to cover the high stream of cost during the entire period of investment. As a result, the higher is the cost of one technology the higher will be the price of electricity required to exercise the option to invest. An increase in the initial cost will make the firm postpone the option to invest, requiring a higher critical threshold and leading to allocating more capital to the other technology.

The greater the amount of capital invested, the more learning stimulates earlier exercising of the option to invest, as a result of cost reduction. It is for this reason that when the firm invests 100% of its capital in only one technology, it exercises the option to invest earlier than when it diversifies its investment. This is because the learning effect is higher when all capital is invested in one technology and costs decreases more rapidly. On the contrary, when the investment is diversified, the firm requires a higher critical threshold to exercise the option to invest since costs do not decrease as rapidly.

More uncertainty in energy prices or technology costs postpones the option to invest. In the case of more certain electricity price due to public subsidies, governments implicitly protect investors against price fluctuations and uncertainty, thus stimulating earlier investment in renewable energy.

When the price of electricity is deterministic, the higher the amount of capital allocated to one technology, the higher will be the maximum electricity production cost to exercise the option to invest. As a result, the firm can accept relatively high costs for high shares of capital invested. On the contrary, the firm will wait until the cost decreases sufficiently to invest low capital shares since the cost of production cannot quickly go down due to learning when little capital is invested.

In addition, the results show that in the presence of deterministic prices supported through government subsidies, the level of the subsidy affects not only the maximum cost the firm accepts to exercise the option to invest, but also the amount of capital invested in each technology. From this we can see that governments employing policies to guarantee a minimum price will, unintendedly, influence capital allocation between technologies through reducing future price uncertainty.

A surprising message from this study is that although investing in both solar and wind may be profitable under particular conditions of price and cost uncertainty, the optimal strategy is investing in only one technology, solar or wind, depending on their initial costs and learning rates. This suggests that the practice in most countries of diversifying renewable energy may be mistaken.

On the other hand, certain motivations for diversifying are possibly not or insufficiently covered by our model. This suggests a need for further research employing more complex models that include such motivations. An important one is keeping all significant technological options open so as to remain flexible in the face of unforeseen technological scenarios and undesirable environmental or social consequences of particular renewable energy technologies.

A transition to sustainability is a complex process. It involves different actors and involves structural changes at the level of sectors as well as technological innovation and diffusion. In this thesis I investigated three major ingredients to sustainability transitions. In the first place, I organized the different actors involved in sustainability transitions in distinct categories, and identified the most important behavioral aspects in order to improve transition policy acceptation and implementation. Subsequently, I focused on green growth strategies, which are a debated element of sustainability transitions, and I pointed out the challenges these strategies are facing. From the results it can be seen that we need tougher policies in order to have a decoupling between economic growth and environmental degradation (in terms of CO_2 emissions), or otherwise should account for “green decline”. In the last part of this thesis I focused on investments under uncertainty, which characterized most of not all investments required for a sustainability transition. A surprising result from this study is that diversification is not necessarily the best strategy. In view of costs decreasing due to learning effects, investors will exercise an option earlier if all capital is invested in one rather than two technologies. If it decides to diversify, the firm should wait and keep the option to invest until it meets better market conditions.

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