Finance for a sustainable economy

Implications for policy and practice

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Abstract

With his September 2015 speech “Breaking the tragedy of the horizon”, the President of the Central Bank of England, Mark Carney, put climate change on the agenda of financial market regulators. Until then, climate change had been framed mainly as a problem of negative externalities leading to long-term economic costs, which resulted in countries trying to keep the short-term costs of climate action to a minimum. Carney argued that climate change, as well as climate policy, can also lead to short-term financial risks, potentially causing strong adjustments in asset prices. Analysing the effect of a sustainability transition on the financial sector challenges traditional economic and financial analysis and requires a much deeper understanding of the interrelations between climate policy and financial markets.

This dissertation thus investigates the implications of climate policy for financial markets as well as the role of financial markets in a transition to a sustainable economy. The approach combines insights from macroeconomic and financial risk analysis. Following an introduction and classification in Chapter 1, Chapter 2 shows a macroeconomic analysis that combines ambitious climate targets (negative externality) with technological innovation (positive externality), adaptive expectations and an investment program, resulting in overall positive macroeconomic outcomes. The analysis also reveals the limitations of climate economic models in their representation of financial markets. Therefore, the subsequent part of this dissertation is concerned with the link between climate policies and financial markets. In Chapter 3, an empirical analysis of stock-market responses to the announcement of climate policy targets is performed to investigate impacts of climate policy on financial markets. Results show that 1) international climate negotiations have an effect on asset prices and 2) investors increasingly recognize transition risks in carbon-intensive investments. In Chapter 4, an analysis of equity markets and the interbank market shows that transition risks can potentially affect a large part of the equity market and that financial interconnections can amplify negative shocks. In Chapter 5, an analysis of mortgage loans shows how information on climate policy and the energy performance of buildings can be integrated into risk management and reflected in interest rates.

While costs of climate action have been explored at great depth, this dissertation offers two main contributions. First, it highlights the importance of a green investment program to strengthen the macroeconomic benefits of climate action. Second, it shows different approaches on how to integrate transition risks and opportunities into financial market analysis. Anticipating potential losses and gains in the value of financial assets as early as possible can make the financial system more resilient to transition risks and can stimulate investments into the decarbonization of the economy.

Zusammenfassung

Mit der Rede "Die Tragödie des Horizonts durchbrechen" im September 2015 hat der Präsident der englischen Zentralbank, Mark Carney, den Klimawandel auf die Agenda der Finanzmarktregulierer gebracht. Bis dahin wurde der Klimawandel vor allem als Problem einer negativen Externalität verstanden, welche langfristige Kosten verursacht. Dies führte dazu, dass sich die meisten Länder darauf konzentrieren, die kurzfristigen Kosten für Klimaschutzmaßnahmen auf ein Minimum zu reduzieren. Carney argumentierte, dass der Klimawandel, sowie Klimapolitik, auch zu kurzfristigen finanziellen Risiken führen kann, welche zu starken Anpassungen der Vermögenspreise führen können. Solche Auswirkungen zu untersuchen, stellt die traditionellen Wirtschafts- und Finanzmodelle jedoch vor Herausforderungen und erfordert ein tiefgreifenderes Verständnis der Zusammenhänge zwischen Klimapolitik und Finanzmärkten.

Die vorliegende Arbeit untersucht daher die Auswirkungen der Klimapolitik auf die Finanzmärkte sowie die Rolle der Finanzmärkte in der Transformation zu einer nachhaltigeren Wirtschaft. Der Ansatz kombiniert Erkenntnisse aus der makroökonomischen Modellierung und der finanziellen Risikoanalyse. Nach einer Einführung und Einordnung in Kapitel 1, zeigt Kapitel 2 eine makroökonomische Analyse, welche ehrgeizige Klimaziele (negative Externalität) mit technologischer Innovationen (positive Externalität), adaptiven Erwartungen, sowie einem Investitionsprogramm kombiniert und damit zu positiven makroökonomischen Ergebnissen führt. Die Analyse zeigt auch die Grenzen klimaökonomischer Modelle in ihrer Darstellung der Finanzmärkte auf. Aus diesem Grund beschäftigt sich der nachfolgende Teil dieser Dissertation mit dem Zusammenhang zwischen Klimapolitik und Finanzmärkten. In Kapitel 3 wird eine empirische Analyse der Reaktionen von Aktienmärkten auf die Ankündigung klimapolitischer Ziele durchgeführt. Die Ergebnisse zeigen, dass sich internationale Klimaverhandlungen auf die Vermögenspreise auswirken und dass Investoren zunehmend Transformationsrisiken bei CO_2-intensiven Firmen erkennen. Kapitel 4 zeigt, durch eine Analyse der Aktienmärkte und des Interbankenmarktes, dass Transformationsrisiken einen großen Teil des Aktienmarktes beeinflussen können und dass finanzielle Verflechtungen negative Schocks verstärken können. Kapitel 5 zeigt, durch eine Analyse von Hypothekenkrediten, wie Informationen über Klimapolitik und die Energieeffizienz von Gebäuden in das Risikomanagement integriert und sich damit im Zinssatz widerspiegeln können.

Während die Kosten von Klimaschutzmaßnahmen in großem Umfang untersucht wurden, leistet diese Arbeit zwei wesentliche Beiträge. Erstens wird die Bedeutung eines grünen Investitionsprogramms zur Stärkung des makroökonomischen Nutzens von Klimaschutzmaßnahmen hervorgehoben. Zweitens zeigt diese Arbeit unterschiedliche Ansätze, wie Transformationsrisiken und -chancen in die Finanzmarktanalyse integriert werden können. Eine frühzeitige Erkennung und Einpreisung potenzieller Risiken und Chancen kann das Finanzsystem widerstandsfähiger machen und Investitionen in die Dekarbonisierung der Wirtschaft stimulieren.

Contents

List of Abbreviations

AR	Abnormal Returns
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
CGE	Computable General Equilibrium
COP	Conference of the Parties
DJSI	Dow Jones Sustainability Index
DSGE	Dynamic Stochastic General Equilibrium
EBA	European Banking Authority
ECB	European Central Bank
ECL	Expected Credit Loss
EMH	Efficient-Market Hypothesis
EPCs	Energy Performance Certificates
ESG	Environmental Social Governance
ESA	European System of Accounts
ETS	Emission Trading System
FiT	Feed-in-Tariff
GDP	Gross Domestic Product
GRI	Global Reporting Initiative
GHG	Greenhouse gas
IAM	Integrated Assessment Model
IEA	International Energy Agency
IFRS9	International Financial Reporting Standard 9
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
LBD	Learning-by-Doing
MBS	Mortgage-Backed Securities
NACE	Nomenclature Statistique des Activités économiques dans la Communauté Européenne (Classification System of Economic Activities)
NDC	Nationally Determined Contribution
NGFS	Network on Greening the Financial System
OECD	Organization for Economic Co-operation and Development
REH	Rational Expectation Hypothesis
R&D	Research and Development
SDGs	Sustainable Development Goals
SRI	Socially Responsible Investor
TCFD	Task Force on Climate-related Financial Disclosure
TFP	Total Factor Productivity
UNEP FI	United Nations Environment Program Finance Initiative
UN PRI	UN Principles of Responsible Investment
VaR	Value at Risk
WEF	World Economic Forum

Chapter 1

Introductory Chapter

Climate change economics is a sub-field of environmental economics. While environmental economics addresses different effects of economic production on the environment, climate change economics focuses on the effects of economic production on the global climate system (Smith; 2011). Climate change is a particularly complex phenomenon since greenhouse gas (GHG) emissions have an influence on different components of the earth system (such as oceans, ice sheets, etc.) and some of these biophysical processes are non-linear and irreversible in their effects (Lenton et al.; 2008; Steffen et al.; 2015). The negative effects of climate change are unequally distributed at a global scale and will become evident only in the future. Since the production of GHG emissions is embedded in almost all economic supply chains, ambitious - yet necessary - climate action[1] requires far-reaching structural changes in the system of economic production.

Despite the complex nature of the causes and effects of climate change, most macroeconomic models include climate change solely as a negative external effect, which needs to be managed to ensure long-term growth (Stern; 2007; Nordhaus; 2007). This narrow view reduces the task of policy makers to keeping the costs of climate action to a minimum, often by means of static cost-benefit analyses. The benefits of taking action against climate change are usually left aside in these calculations. However, the mitigation of climate change triggers new technological innovation, which has distinctly positive effects on long-term growth, e.g. by reducing the costs for low-carbon technologies (Romer; 1990, 1994; Acemoglu et al.; 2012). This broadened view expands the task of policy makers to finding the right balance between the economic costs and benefits of action against climate change. Moreover, the structural changes necessary to reduce GHG emissions in economic production rely on changes in the capital stock, which to a large extent is financed via financial markets. Identifying financial markets as an important actor results in additional tasks for policy makers, namely ensuring that financial markets can (1) cope with the structural changes and (2) provide the financial resources required in order to renew the capital stock.

This dissertation contributes to a deeper understanding of the interconnections between climate change and financial markets. The starting point is a macroeconomic study, identifying financial markets as an important actor in the transition to a sustainable economy. However, financial markets are insufficiently represented in traditional macroeconomic models. Therefore, the subsequent parts

[1] In this dissertation ambitious climate action or ambitious climate policy stands for policy measures that go beyond the current policies and aim at reaching net zero GHG emissions by 2050, in line with the 1.5°C target of the Paris Agreement (UNFCCC; 2015).

of this dissertation take a microeconomic perspective, investigating what role financial markets might play in a sustainability transition.

1.1 Background and problem statement

Financial markets and climate economic models

Macroeconomic models have a long tradition in assessing the economic impacts of climate policy. Integrated Assessment Models (IAMs), Computable General Equilibrium (CGE) models, and occasionally macro-econometric models, are the most commonly used types of models for the economic assessment of climate policies. In 2018, William Nordhaus, who has made major contributions to the development of such models, received the Prize in Economic Sciences in Memory of Alfred Nobel for "integrating the environment into long-run macroeconomic analysis" (Nordhaus; 2018). However, these models are not without limitations and criticism. One of the major academic debates is about the choice of the discount rate applied to economic damages of climate change, since short-term costs of mitigation are weighted against these long-term damages. The *Stern Review* for example, applies a much lower discount rate, leading to lower macroeconomic costs and speaking in favour of early and fast policy action (Stern; 2007; Nordhaus; 2007). A second topic in the academic debate is technological innovation, the major driver of long-term growth, which is not explained in so-called "exogenous growth models"[2]. Paul Romer, who received the Nobel Prize along with W. Nordhaus in 2018 has made major contributions to "integrating technological innovation into long-run macroeconomic analysis" (Romer; 2018), often referred to as "endogenous growth theory"[3] (Romer; 1990, 1994). Furthermore, Robert Pindyck, an outspoken critic of IAMs, states that "IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading" (Pindyck; 2013). Similarly, Rosen and Guenther (2015); Rosen (2016) and Farmer et al. (2015) discuss the main shortcomings of IAMs, such as the insufficient treatment of uncertainty, technological innovation, the aggregation of (homogeneous) agents and the specification of the damage function.

Due to these methodological limitations, climate economic models have focused on calculating the macroeconomic costs of climate change mitigation. Wolf et al. (2016) provide an analysis of the critical mechanisms in macroeconomic models, such as the role of technological innovation and expectations, that lead to negative economic effects of climate policy by design and do not allow for

[2] A well-know example of exogenous growth models is the Solow-Swan growth model (Solow; 1956), where output is a function of labour (L), physical capital (K) and technology (A). What characterizes all exogenous growth models is that the only source of growth in the long-run is technological progress, which is an exogenous factor in these models.

[3] Endogenous growth models were developed due to the dissatisfaction with the role of technological progress (A) in exogenous growth models. The Romer growth model (Romer; 1990) developed an innovation-based growth theory, where investments in human capital are the source of technological progress and therefore growth.

a different growth path. Furthermore, all models used for the assessment of climate policy assume a gradual transition to a low-carbon economy. The transition is driven by increasing carbon prices and enabled by efficient financial markets. Potential inefficiencies in financial markets and the behavior of financial actors, which can restrain the transition to a sustainable economy, are mostly unaddressed. This leads to two problems. First, these models do not address how the investment needs for low-carbon infrastructure and technology will be financed. Second, they cannot evaluate the effect of a sudden shift in investors' expectations as a result of policy, market or technological disruptions. Pollitt and Mercure (2018) provide a detailed description of why the financial sector needs to be introduced and improved in both CGE and macro-econometric models. So far, little progress has been made in this regard. This dissertation aims to contribute to this development by discussing potential inefficiencies and expectation dynamics in financial markets.

Investment needs in climate economic models

In order to understand how a transition to a sustainable economy can be financed, an overview of the required investments is needed. The investment needs result from comparing different climate policy scenarios with a business-as-usual scenario, employing the macroeconomic models discussed in the previous section. Since climate change is a global challenge, internationally agreed targets provide the framework for national and sectoral climate targets. Article 2.1a of the Paris Agreement, agreed in December 2015, states the internationally agreed goal of keeping global average temperatures "well below 2°C above pre-industrial levels" and even "pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC; 2015). Furthermore, Article 2.1c defines the goal of:

> "Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development." (UNFCCC; 2015)

Following the Paris Agreement, the Intergovernmental Panel on Climate Change (IPCC) published a special report on the implications of the 1.5°C target in October 2018 (IPCC; 2018). The report highlights the urgency of a faster transformation of the economy, reaching a carbon neutral economy by 2040, or by 2050 at the latest, in order to stay below the 1.5°C target. Depending on the political measures taken, there are different scenarios as to how to reach the 1.5°C target[4]. These different scenarios also come with different macroeconomic costs and investment needs. Ambitious climate policy scenarios will require first, an increase of overall investments and second, a shift of investments from high-carbon to low-carbon technologies.

At global level, McCollum et al. (2018) provide the most detailed insight into the investment needs for a 2°C and 1.5°C scenario through a multi-model analysis, using six different Integrated

[4] When working with such scenarios, one should keep in mind the inherent uncertainties in the physical relations between GHG emission accumulation and temperature increase, as well as possible tipping points in geophysical systems.

Assessment Models (IAMs). Total energy supply and demand side investments for the *1.5°C scenario* are estimated to be around 3,381 bn USD p.a. (average annual investments between 2016 and 2050), compared to 2,481 bn USD p.a. in the *baseline scenario)*, leading to additional investment needs of about 900 bn USD p.a.

At the EU level, according to an in-depth analysis of the 2050 long-term strategy of the European Commission (2018a), investment needs in energy-supply and demand (excluding transport) are between 519 and 576 bn Euro (average annual investments between 2031-2050) for the *1.5°C scenarios*, compared to 377 bn Euro p.a. in the *baseline scenario*, leading to additional investment needs of around 140-200 bn Euro p.a.

Regarding the investment shift, McCollum et al. (2018) find that low-carbon investments need to increase from currently around 35% to 50% of energy-related investments by 2023-2025 (overtaking fossil-fuel based investments) and to 80% by 2040-2050. The following changes in the allocation of average annual investments are estimated:

- Investments in fossil fuel extraction, conversion and fossil fuel-based power production need to decrease by about 688 bn USD p.a. (from 1253 bn to 565 bn USD).
- Investments in renewable energy generation (including nuclear power generation), transmission, storage and CCS need to increase by about 1052 bn USD p.a. (from 942 bn to 1,994 bn USD)[5].
- Demand side energy efficiency investments need to increase by about 500 bn USD p.a. (from 352 bn USD to 822 bn USD).

Although investment needs on the energy-demand side are included in both estimates, they lack details at the level of sectors and technologies. Grubler et al. (2018) present an additional scenario for meeting the 1.5°C target with lower energy demand than the previous scenarios[6]. However, there are currently no estimates of global investment needs for such a high-energy efficiency scenario and there is a lack of reliable data on current investment levels.

Looking at renewable energy capacity, it becomes apparent that current investments do not yet reach the level required for a 1.5 or 2°C scenario. McCrone et al. (2018) find that global investment in new capacity were between USD 243.6 bn in 2010 and USD 279.8 bn in 2017 (with the exception of USD 323.4 bn USD in 2015). Investments in Europe even saw a decrease from more than 100 bn USD in 2011 to only 40.9 bn USD in 2017 (globally, this was compensated by an increase in investments in China, India and Brazil). These figures are in contrast to projected

[5] 1,994 bn USD is divided into 749 bn USD in non-biomass renewable energy and non-fossil hydrogen; 200 bn USD in renewable biomass extraction and conversion; 171 bn USD in nuclear energy; 750 bn USD in transmission and storage; 124 bn USD in carbon capture and storage.

[6] The final energy demand in this scenario is 245 EJ by 2050 (about 40% lower than today). This scenario focuses on major improvements on the demand side and includes social and institutional changes in energy consumption next to technological innovation.

investments into renewable energy for a 1.5°C scenario of 730 bn USD globally (McCollum et al.; 2018), and 93.9 - 120.3 bn Euro for Europe (European Commission; 2018a).

The reasons for the large investment gap in both renewable energy and energy efficiency, and solutions on how to address it, are not investigated in the macroeconomic models used for the assessment of climate policies. In fact, McCollum et al. (2018) state that:

> "From where exactly these investment dollars are summoned is outside the scope of our study and for the most part beyond the capability of the models used." (McCollum et al.; 2018)

This dissertation will address exactly this point by providing an in-depth look into the types of financial instruments used by different financial actors.

Climate scenarios for financial markets

Despite their increasing importance for investors and practitioners (TCFD; 2017; European Commission; 2018b; NGFS; 2018), climate change plays no prominent role in financial theory and analysis. Diaz-Rainey et al. (2017) highlight this problem by showing that climate finance is a minor topic in the finance literature, as the top three financial journals did not publish any articles on this topic between 1998 and 2015. Only very few articles appeared in other leading finance and business journals[7]. Methodological constraints were named as possible explanations by the authors. Indeed, there are several analytical and conceptual difficulties in combining the two areas of research, as already discussed in the previous sections.

Next to macroeconomic analysis, financial market analysis needs to be extended as well. Roukny et al. (2018) and Battiston et al. (2012, 2016) show how the financial crisis of 2008 revealed that increasing interconnectedness and risk sharing in the financial system has led to systemic risks. The authors discuss how multiple equilibria can result from network effects. As a response to the financial crisis, accounting rules and financial regulation have become more *forward-looking*[8]. The stress-test of the European Banking Authority (EBA), applied to the largest banks in the Euro Area, requires financial institutions to calculate "expected" losses in the near future (based on different macroeconomic scenarios), as opposed to reporting already incurred losses. However, environmental and social factors are still missing as additional risk factors in financial risk models.

In 2015, Mark Carney, Governor of the Bank of England, started the debate on the role of central banks and supervisors with his speech "Breaking the tragedy of the horizon" (Carney;

[7] Linnenluecke et al. (2016) provide an overview of emerging topics in the transdisciplinary literature on environmental finance. The main topics identified are regulatory impacts, calculating potential asset impairment, adaptation finance, managing increased volatility and the valuation of opportunities.

[8] The term "forward-looking" has been used in monetary policy and in accounting (IFRS9 explicitly refers to forward-looking information)

2015)[9]. Prior to that, central banks have successfully defended their argument that climate change is not within their mandate. After his speech, Carney initiated the task force on climate-related financial disclosure (TCFD) in December 2015, which was later supported by the Financial Stability Board (FSB). The TCFD distinguishes two types of *climate-related risks* that can have an effect on valuation. On the one hand, there are *physical risks*, resulting from climate change, which are equivalent to economic "damages" from climate change at the macroeconomic level. On the other hand, there are *transition risks* which result from policy or market adjustments. Transition risks can be negative (in declining markets) or positive (in growing markets). In December 2017, the Network for Greening the Financial System (NGFS) was founded by eight central banks and supervisors (NGFS; 2018). Its first report states that:

> "NGFS Members acknowledge that climate-related risks are a source of financial risk. It is therefore within the mandates of Central Banks and Supervisors to ensure the financial system is resilient to these risks." (NGFS; 2018)

Analysing climate-related risks and opportunities in financial markets requires several theoretical advancements in integrating climate policy analysis and financial market analysis. This dissertation provides methodological suggestions on how to integrate climate scenarios in financial analyses.

1.2 Research questions and conceptual framework

As discussed in the previous section, complying with the Paris Agreement (staying within the temperature limit of 1.5-2°C above pre-industrial levels (UNFCCC; 2015)) will require a substantial shift of investments from high-carbon to low-carbon technologies. Further development of the economic models currently used, is required to exploit the full potential of such a transformation.

Against this background, the overall research question of this dissertation can be summarized as follows:

> *Under which conditions can ambitious climate policy lead to positive macroeconomic effects and what are the potential risks and opportunities of climate policy for financial-market actors?*

The following sub-questions were derived and are addressed in different chapters of this dissertation:

1. *Under which conditions can macroeconomic benefits of ambitious climate policy outweigh its costs?*

[9] Carney argued that climate change is beyond the horizon of financial decision makers but once it starts to materialize, it will lead to substantial readjustments in asset prices, which by itself poses a threat to the stability of the financial system. Hence, he put forward that climate-related financial disclosure can "break the tragedy of the horizon" by improving investors understanding of tomorrow's risks and prevent sudden asset price adjustments.

2. *How do financial markets react to climate policy signals? In which ways do companies benefit from such signals?*
3. *What is the exposure (absolute and relative) of the financial market to potential transition risks? Which financial actors and asset classes show the largest exposure to such risks?*
4. *How can transition risks be integrated in risk management, and hence in asset prices and interest rates?*

Each of the four research papers contributes to the overall research question and will focus on one sub-question. Figure 1.1 provides a structural overview of the overall context of this dissertation and highlights the focus of the four papers (Chapter 2-5) within this context.

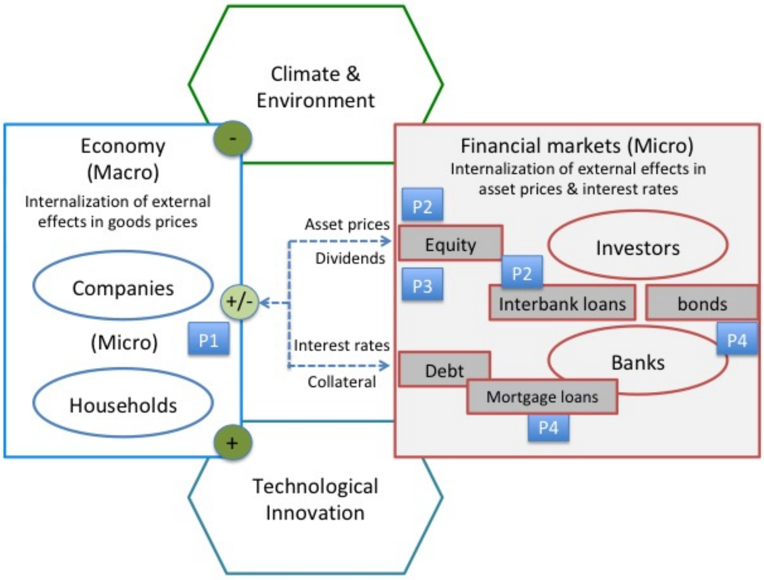

Figure 1.1: Overview of the theoretical context for the different papers gathered in this dissertation.

To illustrate this: Macroeconomic models consist of two main actors, companies and households, who maximize their profit and utility. So far, macroeconomic models of climate change mainly integrated climate change as a negative external effect from economic production (indicated by a minus sign in Figure 1.1). To mitigate this effect, a price for carbon emissions is introduced to internalize the negative externality into the price of goods. Some models also include technological innovation as a positive external effect of production, by reducing the costs for products (indicated by a plus sign). However, the positive spillover effect of technological innovation depends endogenously on the level of production and investments, which is usually not taken into account.

Financial markets play a major role for climate policy by providing the financial resources required to make the necessary investments, but are not included explicitly in macroeconomic models applied for climate change analysis (indicated by a dashed line). Financial markets consist of two additional types of economic actors, investors and banks. Banks provide loans to companies and households at a certain interest rate. Investors (pension funds, investment funds, insurances and other financial institutions) provide equity to companies or buy bonds from non-financial or financial corporations or from public bodies such as the government or development banks. As opposed to goods markets, the internalization of external effects (climate change and technological innovation) into prices in financial markets, i.e. asset prices and interest rates, is less explicit so far (indicated by a dashed line).

The first paper[10] (P1 in Figure 1.1) integrates three elements into a macroeconomic analysis: ambitious climate targets (negative effect), endogenous technological innovation (positive effect), as well as an investment program and adaptive expectations (enabling/amplifying effect). The second, third and fourth papers are concerned with the role of financial markets and the internalization of external effects into asset prices and interest rates. The second paper[11] (P2) investigates whether climate policy announcements, by changing investors' expectations, lead to positive or negative effects on asset prices and therefore on equity holdings. The third paper[12] (P3) operationalizes climate policy as a risk factor in equity markets. Financial exposures to economic sectors with high transition risks are identified and a climate stress-test is applied to equity holdings. Indirect effects are taken into account via the interbank loan market, which can amplify the negative shock through network effects. The fourth paper[13] (P4) operationalizes climate policy as a risk factor in the analysis of credit risk. Mortgage loans are used as an example, due to their large share in banks' loan books and due to the large share of buildings in energy consumption.

Table 1.1 provides an overview of the theoretical and policy context as well as the methodological approach of each research paper (Chapter 2-5). The subsequent sections will discuss the theoretical background, the policy context and the applied methods in more detail.

[10] "The role of sustainable investment in climate policy" (Schütze et al.; 2017)

[11] "Stock market reactions to international climate negotiations" submitted to the Journal of Sustainable Finance and Investment

[12] "A climate stress-test of the financial system" (Battiston et al.; 2017)

[13] "Transition risks and opportunities in residential mortgages" submitted to the Journal of Environmental Economics and Management

Table 1.1: Overview of the theoretical and policy context and the methodological approach for each paper.

	Chapter 2 (Paper 1)	Chapter 3 (Paper 2)	Chapter 4 (Paper 3)	Chapter 5 (Paper 4)
Theory				
Neg. Externalities	•	•	•	•
Pos. Externalities	•	•	•	•
Asym. Information			•	•
Expectation Dynamics	•		•	•
Policy				
Climate Policy	•	•	•	•
Fiscal Policy	•			
Financial Regulation			•	•
Scale				
Global level		•		
EU level	•		•	•
National level				•
Methodology				
General Equilibrium Analysis	•			
Event-Study		•		
Network Analysis			•	
Risk Assessment (VaR, ECL)			•	•

1.3 Theoretical foundation

> "The most important difference between economics and the natural sciences is perhaps the fact that decisions of economic agents today depend upon their expectations or beliefs about the future."
>
> *Cars Hommes (2013), p.5*

Climate change and market inefficiency

According to microeconomic theory, there are several reasons that can lead to inefficient allocations of resources, thus justifying a need for market intervention (Pindyck and Rubinfeld; 2004; Benassy-Quere et al.; 2010): external effects, asymmetric information, market power and public goods. This dissertation discusses climate change in light of external effects and asymmetric information.

Environmental damages are the classical examples of negative external effects, wherein producers cause additional costs to society, which are not included in the market price. The usual policy response is either to introduce standards (also called command-and-control policies) or to introduce a price for the externality (via a tax or a trading system). Climate change is a special case, since it is an intertemporal externality, where the costs will only occur in the future in the form of economic damages from climate change. Additionally, the damages will affect some countries more than others, unrelated to how much they have contributed to the emissions.

However, there are also positive externalities, such as spillover effects from research and development, where the investment benefits society as a whole, e.g. in the form of lower prices and increased employment. A common solution is to incentivize the positive external effect by subsidizing research and development (R&D). This theory was put forward as the "induced innovation hypothesis" by Porter (1991) and Porter and der Linde (1995), claiming that environmental regulation in one country can lead to higher competitiveness of its firms because it forces firms to innovate more than their competitors. Similarly, Zenghelis (2011) describes the market failure in climate mitigation as a result from positive spillover effects from R&D which leads to underinvestment. Acemoglu et al. (2012) combined the two externalities and showed that there is a price effect and a market size effect. A combination of taxing high-carbon goods and subsidizing R&D in low-carbon goods (and sufficient substitutability between the two) would trigger "directed technical change" and lead to a positive outcome.

Next to external effects, asymmetric information can be another source of market inefficiency. There are numerous examples of asymmetric information problems in economics, such as for the market for second-hand goods, the job market and the credit market. Akerlof (1970) describes the asymmetric information problem for the market for second-hand cars ("market for lemons") where the buyer is unable to judge the quality of the car, leading to a fall of average quality and, therefore, its price. Spence (1973) describes a problem wherein a potential employee has more information about his qualification than the employer, thus leading the employer to offer an average wage, which is unattractive to more qualified employees. Similarly, for financial markets, Stiglitz and Weiss (1987) show that when the creditor (bank) has less information than the debtor, pricing the risk (via the interest rate) will be inaccurate and the quality of debtors will deteriorate. The typical policy response to asymmetric information (in different markets) is to provide market-relevant information (aggregate statistics) and to improve company-specific information (via reporting standards).

Similarly, Campiglio (2016) argues that next to political uncertainties surrounding the future implementation of a carbon price (leading to heterogeneous expectations), market failures in the credit market can reduce credit creation for low-carbon investments even if these investments are profitable. Carney (2015) suggests that sudden changes in climate action (what he calls "an abrupt resolution of the tragedy of the horizons") can lead to financial stability risks through sudden repricing of assets. His suggested remedy is to improved the disclosure of information about the carbon intensity of investments. This frames transition risks as a problem of information asymmetry, in addition to an externality.

Financial markets and expectations

In finance, the rational expectations hypothesis (REH) is highly debated. While most finance scholars seem to agree that temporary differences in prices are removed by arbitrage[14], there is less agreement that price levels are always correct[15]. Weitzel and Rosenkranz (2016) provide an overview of the finance literature on rationality, expectations and strategic behavior as well as their impact on market outcomes. There are different theories which explain how bubbles can occur even if rational expectations prevail (Stracca; 2004). Market prices can deviate from their fundamental value for different reasons: due to inefficient markets (as discussed in the previous section), limited arbitrage (e.g. due to liquidity constraints) or the expectations of market participants. According to the "greater fool theory" (De Long et al.; 1990), for example, it is rational to believe that other actors will make mistakes, which justifies buying an overvalued asset as long as the probability of being able to sell it to someone else is high enough.

Hommes (2013) describes the economy as a highly nonlinear expectation feedback system and notes that the advantage of the rational expectations hypothesis is that it leads to perfect consistency between beliefs and realizations. An alternative theory is the concept of bounded rationality introduced by Simon (1955). In cases where information is limited or where computation is too complex or too costly, economic actors apply rules of thumb to simplify the decision. Adaptive learning, for example, where agents extrapolate from past data and update their beliefs based on new data, leads to a co-evolution of expectations and realizations (Hommes; 2013). However, simpler behavioral rules can also lead to biases or mistakes. Even if expectations are found to be rational, expectations are not necessarily homogeneous among different actors. If uncertainty is high and objective probabilities are unknown, actors might apply different (rational) decision strategies. This leads to strategic uncertainty, wherein actors do not have full information about the expectations and decisions of other actors (Weitzel and Rosenkranz; 2016).

These different theories on expectation formation and behavioral rules are highly relevant to sustainable finance as well. Linnenluecke et al. (2016) suggest that observed transaction prices are a weighted average of the probability of the different climate scenarios times the potential loss under these scenarios. Hence, market prices of high-carbon investments will decrease faster, the more investors believe that ambitious climate policy will be implemented. Similarly, Thomä and Chenet (2017) discuss why financial actors do not consider transition risks to the necessary extent. The models applied are based on modern portfolio theory, which assumes perfectly rational agents and normal probability distributions. The 1.5 - 2°C scenarios are at the lower end of the distribution

[14]Because non-rational actors are driven out of the market in the short-term.

[15]Meaning that the price is equal to the fundamental value, the present value of all future cashflows.

of all possible climate scenarios and are therefore less likely to occur than a middle-of-the road scenario (around 3°C). Mielke and Steudle (2018) describe the climate policy challenge as a "stag hunt", where a Pareto superior outcome can be reached if the majority of investors invest in climate mitigation. However, faced with uncertainty about other investors' choices, individual investors often choose the Pareto inferior outcome (with the risk dominant payoff). Coordination among investors can help in selecting the Pareto superior outcome, where higher investments in green technologies lead to higher overall returns.

These theoretical approaches can help in understanding how financial markets promote (or hinder) investments into a sustainability transition. Chapter 2 (first paper) analyses the combined effect of internalizing negative and positive external effects (through a carbon price and an investment subsidy), and of introducing adaptive expectations of investment decisions. Chapter 3 (second paper) investigates how international climate negotiations change (aggregate) expectations of investors on future cashflows of high- and low-carbon companies. Chapter 4 and 5 (third and fourth paper) make proposals on how to internalize potential positive and negative effects of climate policy in asset valuation. These proposals aim to reduce the information asymmetry and to synchronize (aggregate) expectations towards a low-carbon pathway.

1.4 Policy context

> "With better information as a foundation, we can build a virtuous circle of better understanding of tomorrow's risks, better pricing for investors, better decisions by policymakers and a smoother transition to a lower-carbon economy"
>
> *Mark Carney (2015)*

The primary aim of climate policy is to reduce the negative externality resulting from GHG emissions. The policy approach has shifted from pure command-and-control type of policies (standards or bans of certain products and services) to more market-based policies (such as a carbon tax or a trading system for emission certificates). In sectors where carbon pricing has not been introduced yet (transport, buildings, etc.), performance standards are usually chosen to control emission levels. Examples are energy performance standards for buildings and appliances and emission standards for vehicles. Additionally, countries have introduced research subsidies and investment subsidies for new technologies to increase technological innovation and market uptake. Geels et al. (2014) calls for a broader mix of policy options: phasing in tighter regulations, bans or subsidy removals, complemented by the re-training of personnel and redevelopment programs for disadvantaged regions as well as the support of green business coalitions. Furthermore, phasing out existing systems can create more space for niche innovation. Polzin et al. (2019) investigate the effectiveness of renewable energy policies. The international comparison shows that the most effective policy in promoting renewable energy investments is the feed-in-tariff (FiT)[16], mainly because it reduces investment risk and increases returns at the same time. All of these policy proposals aim at reducing the negative environmental externality and increasing the positive externality from innovation and ensuring a smooth transition process.

The purpose of financial market regulation is to ensure the resilience and efficiency of the financial system. On the one hand, financial regulation should prevent a downward spiral from a financial crisis to an economic crisis and vice versa, by ensuring capital and liquidity buffers (EBA; 2018). The stress-test of the European Banking Authority (EBA), for example, tests how the equity of banks is affected by an adverse macroeconomic shock. On the other hand, financial regulation should make financial markets more efficient and transparent by providing reporting standards (such as the IFRS9 (European Commission; 2016)). The role of financial regulation in climate mitigation has only recently started to attract attention. Carney (2015) suggested that improved disclosure of information about the carbon intensity of investments, such that changes in climate action can be anticipated and integrated into asset pricing by financial market actors. Campiglio et al. (2018) discuss different potential roles of central banks and financial regulators in a low-carbon transition, ranging from research activities regarding modeling challenges, disclosing climate-related risks to applying ESG criteria to managed assets. Furthermore, Campiglio et al. (2018) provide a critical assessment of different financial policy options which are already implemented in some emerging economies, such as reserve requirements, capital requirements, liquidity requirements, and lending quotas for certain sectors. By developing early warning indicators for climate-related risks in the financial sector, these policies can help prevent sudden financial losses stemming from asset price adjustments due to policy changes.

To reduce the current investment gap in renewable energy and energy efficiency and to develop early warning indicators for climate-related risks in the financial sector, a better integration of climate policy and financial regulation is needed. Different suggestions of integrating climate policy with investment subsidies and financial regulation are taken up in this dissertation. Chapter 2 (first paper) analyses the macroeconomic outcomes of a green fiscal stimulus, in form of an investment subsidy, combined with a more ambitious climate policy target at the EU level (50% reduction of greenhouse gas emissions by 2030). Chapter 4 and 5 (third and fourth paper) estimate potential effects of climate policy on risk assessments, providing a starting point for climate-related stress-tests and other financial regulation such as capital requirements.

[16] A feed-in-tariff is a policy which ensures guaranteed access to the electricity grid and a guaranteed price per unit of electricity for a certain timespan, such as 20 years.

1.5 Methodology

> "The tools and methods employed should be in the service not only of the probable and the possible but especially of the preferred futures, of what could be and should be."
>
> *Helga Nowotny (2016), p.30*

This dissertation aims at contributing to a deeper understanding of the effects of climate policy on financial markets and at supporting a smooth transition to a sustainable economy. Therefore, the methods employed in this dissertation are a combination of macroeconomic analyses and financial analyses.

In Chapter 2 (first paper), a computable general equilibrium (CGE) model of the European economy, which is used for the macroeconomic assessment of EU climate policy targets, is employed. The model is an exogenous growth model, where technological progress does not depend on internal factors. Climate policy represents an additional constraint to the optimization, where the shadow price for carbon emissions increases the costs for producing carbon-intensive goods and therefore reduces the negative externality of climate change. To include the positive externality from innovation, technological progress is partially endogenized by a mechanism that increases technological progress with increased levels of production in a certain sector. Additionally, myopic expectations are replaced by adaptive expectations. In this way, investors can adapt their level of investments based on investments in the previous periods. Furthermore, an investment program is introduced as an additional policy measure, thus offering the possibility to compare the macroeconomic effect of different combinations of mechanisms and policies and to identify potential synergies.

The second part of this dissertation addresses questions at the level of financial markets and utilizes different types of financial analyses. Chapter 3 (second paper) applies an event study to find empirical evidence for the effect of climate policy announcements, in particular international climate negotiations, on stock prices. Event studies are used to evaluate the effect of new information on market prices. The method defines abnormal price returns as deviation of actual returns from expected returns. To derive expected returns, an estimation window of one year before each climate negotiation was used. The official last day of the climate negotiations was chosen as the event day. The event window includes one day before the event and four days after the event, to include potential early responses as well as delayed responses by market participants. In order to find evidence for transition risks and opportunities identified by investors, the method is applied to a set of high-carbon and a set of low-carbon companies.

Chapter 4 (third paper) performs a climate stress-test of the financial system in the Euro Area.

It uses a network analysis to investigate the potential financial implications of a hypothetical climate policy shock on high-carbon companies. In a first step, the holdings of different financial actors in sectors exposed to transition risks are quantified. The analysis goes beyond the fossil-fuel sector, by identifying additional sectors according to their energy-intensity, hence including the energy producers as well as the energy consumers into the analysis. Five climate-policy-relevant sectors - fossil fuel, utilities, energy-intensive industries, transport and housing[17] - are defined. Due to limited data availability at the sector level, the analysis focuses on equity holdings. Additionally, equity holdings in the financial sector are included in the analysis, since these can result in additional indirect risks. Individual shareholders are grouped by type of financial actor, according to the ESA classification[18] - banks, governments, investment funds, insurance and pension funds, individuals, non-financial companies, other credit institutions and other financial services. Additionally, potential indirect losses were estimated by taking into account potential valuation effects on debt obligations in the interbank lending market. In a second step, results from climate policy scenarios[19] are used to derive a distribution of potential shocks to the fossil-fuel sector and utilities. Based on the exposure and the potential shocks from climate policies, a Value-at-Risk (VaR) analysis for an exemplary “green” bank (invested only in renewable energy production) and an exemplary “brown” bank (invested in fossil fuel based energy production) is performed.

Chapter 5 (fourth paper) aims at estimating the increase in expected credit risk due to transition risks. An expected credit loss (ECL) model is extended by transition risk factors, in order to evaluate potential impacts of climate policy on credit risk. The transition risk factors are derived from an increase in energy prices and a performance standard for existing buildings. The increase in energy price is expected to have a negative effect on default rates (probability of default) and the performance standard is expected to reduce the value of energy-intensive houses, increasing the potential loss in case of a default (loss given default). The energy performance certificates (EPCs) are used as the main environmental indicator, which determines the effect on costs and valuation. Based on the potential effect of different climate policies on default rates and valuation, an ECL analysis is performed for an exemplary “green” (providing loans only to energy efficient buildings) and “brown” bank (providing loans mainly to inefficient buildings).

The suggested methodologies build on common risk models to assess potential impacts of climate policy on equity and debt markets. Financial institutions and regulators can use such analyses as an early warning indicator to manage transition risks in their portfolio and the financial market but also to redirect investments towards more low-carbon technologies. Hence, referring back to Nowotny (2016) “The tools and methods employed should be in the service [...] especially

[17] These sectors result from a reclassification of economic activities according to the NACE classification and their GHG emissions. Energy-intensive industries are identified using the list of sectors, exposed to carbon-leakage risks according to European Commission (2014).

[18] European System of National and Regional Accounts

[19] Using the LIMITS database by Kriegler et al. (2013), which provides results of impact assessments of different climate policy pathways in different IAMs.

of the preferred futures".

1.6 Results

The following section provides a summary of the results as well as answers to the research questions raised. The main outcome can be summarized as follows:

- Climate policies can have positive macroeconomic effects: If combined with an investment program and adaptive expectations, ambitious climate policy can trigger an innovation process, leading to positive effects on economic growth and employment.
- Asset prices only partially reflect transition risks and opportunities: There is a stronger recognition of transition risks since 2013 and especially since the Paris Agreement in 2015, as indicated by negative impacts of climate policy on equity prices of high-carbon companies.
- Financial institutions are exposed to potential transition risks: Holdings in energy-intensive industries represent a large part of equity portfolios. Investment funds show the largest exposure in absolute terms and governments in relative terms.
- Sudden asset price adjustments can undermine financial stability: Sudden introductions of ambitious climate policies could lead to sudden asset price adjustments, which can be further amplified through the interbank lending market and equity and bond holdings in financial institutions.
- Interest-rates should better reflect climate policy: Estimating transition risks in mortgage portfolios is important due to their large share in overall loans. Interest rates for mortgage loans should reflect potential value differences between energy-intensive and energy-efficient buildings.

Chapter 2 (first paper) "The role of sustainable investment in climate policy" (Schütze et al.; 2017) utilizes a traditional climate economic model and reveals the problems arising from the structure of these models: increasing sustainable investments leads to a crowding out of consumption or investments in other parts of the economy. The analysis of scenarios combining (a) ambitious climate targets and a respective carbon price with (b) endogenous technical progress, (c) adaptive expectations and (d) an investment program, shows that positive macroeconomic outcomes are possible. Increasing low-carbon investments is key, because it has a positive effect on technical progress and on investors' expectations, strengthening the positive externalities of climate action.

There are two ways of financing investments, equity and debt, which I consider the two main channels through which climate policy can have an impact on financial markets. Chapter 3 and 4 focus on the equity channel, while Chapter 5 focuses on the debt channel.

Chapter 3 (second paper) "Stock market reactions to international climate negotiations" explores stock market responses to international climate negotiations through an event study. The results show that climate negotiations have small, but significant effects on share prices, indicating a general awareness of investors. The climate negotiations before 2013, mainly led to effects on low-carbon companies. Only starting in 2013, and especially in 2015 (Paris Agreement), there is a stronger recognition of a potential negative impact on high-carbon companies. However, the magnitude of the stock price changes after the announcement of the Paris Agreement was still small, possibly due to a lack of policies supporting the target at national and sector level. Financial market reactions can be used as an indicator for the credibility and the potential impact of climate policy decisions.

Chapter 4 (third paper) "A climate stress-test of the financial system" (Battiston et al.; 2017) develops a methodology to assess the potential impact of climate policy on the financial market, including potential amplification effects through financial interrelations. The climate stress-test integrates climate policy scenarios into a Value-at-Risk (VaR) analysis. Results show that the financial exposure to the fossil fuel sector is small, but that the exposure to energy-intensive industries is relatively large. Investment funds show the largest financial exposure to these sectors in absolute terms and governments show the largest exposure relative to their equity holdings. Exposures are heterogeneous within and between different types of financial institutions. By including the interbank lending market and indirect holdings in investment funds into the analysis, the results show that financial interrelations can become an important indirect driver of risk. Hence, increasing overall transparency in the market regarding transition risks can 1) reduce asymmetric information between financial and non-financial companies and within the financial market and 2) reveal potential risks of asset misallocation at an early stage.

Chapter 5 (fourth paper) "Climate risks and opportunities in residential mortgages" investigates how banks can include climate policy scenarios in the risk management of mortgage portfolios. The method integrates increasing energy costs and the introduction of an energy performance standard for existing buildings into an expected credit loss (ECL) calculation. Mortgage loans are an important asset class, since they represent a large share of total assets of banks with long credit lifetimes and they are are responsible for a large share of energy consumption. Results show that more ambitious climate policy leads to an increase in expected credit loss for an exemplary "brown" mortgage portfolio compared to a "green" mortgage portfolio. Early anticipation of potential transition risks is especially important for buildings, due to the large investment needs and the long investment cycles. This analysis can also be applied to assess potential lending opportunities from increased investments into energy efficiency.

Overall, the results show that ambitious and long-term oriented climate policy can in fact lead to positive macroeconomic effects. However, to ensure a smooth adjustment process and to avoid sudden asset revaluations, potential climate policies need to be anticipated and reflected in asset prices and interest rates, more timely and more explicitly.

1.7 Conclusions

A large part of the academic debate around climate change focuses on climate change as a negative external effect. Pricing this negative externality increases the prices of carbon-intensive goods. Hence, the policy debate around climate action mostly focuses on how to minimize the economic costs of climate action. Chapter 2 (first paper), contributes new insights to this policy debate by showing that if ambitious climate policy is combined with investment policy, supporting innovation in low-carbon technologies, it can lead to overall positive macroeconomic outcomes.

Additionally, climate economic models lack the necessary details about financial market dynamics and are therefore ill-equipped to analyse how to finance the necessary low-carbon investments and how changes in climate policy might affect financial markets. Hence, the subsequent part of this dissertation addresses the research gap between climate-change economics and finance. In Chapter 3 (second paper), an empirical analysis of stock markets shows that asset prices, of both high-carbon and low-carbon companies, respond to climate policy announcements. There is a stronger recognition of potential transition risks in high-carbon companies since 2013 and especially since the Paris Agreement in 2015. In Chapter 4 (third paper), a network analysis shows that if sudden asset price adjustments occur, they can be amplified through the interbank lending market, which increases the financial risk. The largest direct financial exposures to transition risks in equity holdings was found to be in energy-intensive industries, as opposed to much smaller exposures in the fossil fuel industry. Chapter 5 (fourth paper) investigates transition risks and opportunities in mortgage loans. This is especially relevant for banks, as mortgages make up a large part of bank loans and have credit periods up to 25 or 30 years. Furthermore, from a climate policy perspective, buildings represent a large share of fossil fuel consumption and require a substantial amount of low-carbon investment.

The overall conclusion of this dissertation is that climate change is not only a question of negative externalities, but also one of positive externalities as well as information asymmetry between the lender and borrower, and expectation dynamics in financial markets. Until now, the potential risks of ambitious climate policy for high-carbon companies and the potential opportunities for low-carbon companies are not fully reflected in interest rates and asset prices.

To reduce the information asymmetry, improved disclosure of carbon- and energy-intensities at the level of individual companies and asset classes, as well as aggregate statistics at the market level, are required to assess and compare portfolios with respect to the political target. Including "adverse climate policy scenarios", next to "adverse macroeconomic scenarios" into forward-looking risk assessments (such as the EBA stress-test) of all asset classes and financial institutions can make the financial system more resilient to transitions risks and help to reinforce ambitious climate policy through changes in investment and lending choices. Aligning expectations towards an ambitious climate target (such as staying below 1.5°C) requires credible and long-term climate policies at the national and sector level, which reduces the uncertainty over the profitability of low-carbon investments.

1.8 Outlook

This dissertation aims at increasing the understanding of the role of financial markets in a sustainability transition by investigating responses of financial markets to climate policy and by suggesting methods for the integration of climate-policy into financial market analysis. The different levels of analyses show that understanding climate change solely as a negative externality fails to address the complexity of the problem. Information asymmetry, expectations and behavioral factors in financial markets have a strong influence on investment decisions and therefore on macroeconomic outcomes as well. I derive three main areas for further research:

1. At microeconomic level, widening the scope of financial analysis to all asset classes, including network effects: Other important asset classes are corporate loans, sovereign bonds and holdings in investment funds.
2. At microeconomic level, deepening the understanding of behavioral rules in financial markets: Two questions seem particularly interesting:
   - Heterogeneous expectations of different types of investors: How do expectations between SRI investors vs. standard investors differ with respect to climate policy and market developments?
   - Full rationality versus bounded rationality: How do forecasting and decision rules change when ESG data, and climate-related information, becomes part of the investment decision?
3. At macroeconomic level, integrating financial market dynamics in macroeconomic modeling: Macroeconomic models need to specify the different types of financial instruments used for different kinds of investments and should allow for heterogeneous expectations and different decision rules of investors.

With a better understanding of the basis for decisions in financial markets one will gain larger capacities to explain macroeconomic outcomes and develop more effective policy measures in order to decrease the investment gap in renewable energy and energy efficiency.

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Chapter 2

The Role of Sustainable Investment in Climate Policy*

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Abstract

Reaching the Sustainable Development Goals requires a fundamental socio-economic transformation accompanied by substantial investment in low-carbon infrastructure. Such a sustainability transition represents a non-marginal change, driven by behavioral factors and systemic interactions. However, typical economic models used to assess a sustainability transition focus on marginal changes around a local optimum, which—by construction—lead to negative effects. Thus, these models do not allow evaluating a sustainability transition that might have substantial positive effects. This paper examines which mechanisms need to be included in a standard computable general equilibrium model to overcome these limitations and to give a more comprehensive view of the effects of climate change mitigation. Simulation results show that, given an ambitious greenhouse gas emission constraint and a price of carbon, positive economic effects are possible if (1) technical progress results (partly) endogenously from the model and (2) a policy intervention triggering an increase of investment is introduced. Additionally, if (3) the investment behavior of firms is influenced by their sales expectations, the effects are amplified. The results provide suggestions for policy-makers, because the outcome indicates that investment-oriented climate policies can lead to more desirable outcomes in economic, social and environmental terms.

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2.1 Introduction

In climate policy debates, a widespread assumption is that effective climate policy comes at substantial initial costs, and that therefore it would be a burden and a risk for producers and consumers alike. This understanding is at least partially attributable to the models behind it, which usually exclude positive effects by construction (Wolf et al.; 2016). These models focus on marginal changes around an equilibrium that is Pareto optimal, except for climate damages in a more or less distant future. However, a sustainability transition typically implies a non-marginal transition from one economic equilibrium to another. Thus, a sustainability science approach differs from the standard economic approach, assuming, e.g., more complex interactions between the macro- and the micro-level (Antal and van den Bergh; 2016).

A concept that relates to the recent macroeconomic discourse, which refers to a transition between different economic equilibria, is the idea of green growth. Jaenicke (2012), Wolf et al. (2016) and Pollin (2015) provide more in-depth discussions on green growth and the green economy. However, only few studies have investigated short-term economic benefits of climate policy (Jaeger et al.; 2011, 2015) or interaction effects between environmental regulation and technical progress (Guo et al.; 2017). Related reports from international institutions such as UNEP (2011); World Economic Forum (2013); Global Commission on the Economy and Climate (2014); OECD (2017) usually do not use the same models as used in macroeconomic climate policy analysis. Green growth is mainly described by narratives rather than by a trajectory that can be assessed with formal models. According to Antal and van den Bergh (2016) a synthesis of sustainability thinking and macroeconomics still needs to be accomplished.

Since most standard economic models exclude the possibility of green growth by construction, there are two possible solutions in terms of economic modelling: Creating new types of models that differ from the usual approach of computable general equilibrium (CGE) models, like, e.g., agent-based models, or changing certain mechanisms in CGE models in order to overcome some of their intrinsic limitations. Without in any way dismissing the former, this paper aims at the latter.

GEM-E3 (Capros et al.; 1999), the model used for this purpose is calibrated to the European economy and has been used for evaluating EU level climate policies numerous times. The current situation in Europe in the aftermath of the financial crisis is characterized by low levels of investment, growth and employment. This makes Europe an interesting case for the investigation of a new type of climate policy (van der Ploeg and Withagen; 2013), focusing on economic benefits and the role of investment. Additionally, these insights can be helpful for the discussion on how to reach the recently agreed international 1.5°C climate target.

Our paper relates to the vast literature and reports on climate policy evaluation providing cost-benefit analyses. The Intergovernmental Panel on Climate Change (2014) suggests that the cost required to mitigate greenhouse gas (GHG) emissions to safe concentration levels (450 parts per million by volume (ppmv)) ranges from 1% to 3.7% of GDP by 2030 (compared to the baseline GDP). The OECD (2008) estimates climate mitigation costs to be approximately 0.5% of GDP by 2030. According to these calculations, timely and globally concerted action would reduce the costs of GHG abatement (Kriegler et al.; 2013). Studies that investigate the reduction of EU level GHG emissions, such as the European Commission Impact Assessment Report (European Commission Staff; 2014) come to similar conclusions. Depending on the policy scenario, the costs of a 40% emission reduction scenario is estimated to lie between 0.1% and 0.45% of GDP by 2030 (compared to the reference scenario).

According to the Impact Assessment Report, the implementation of a carbon price in all sectors and the reuse of the revenues to reduce labour costs would reduce the economic costs of GHG abatement. The reported costs are usually measured by comparing a reference scenario without constraints with a counterfactual scenario that includes a GHG emission target as an additional constraint to the optimization. In this way, the outcome can only be as good as, or worse than, the reference scenario. Rosen (2016) and Rosen and Guenther (2016) provide a more detailed review of the analytical approaches and assumptions used in the Fifth Climate Assessment (AR5) of the Intergovernmental Panel on Climate Change (2014) and their shortcomings.

Some models of climate policy (see e.g. Stern (2007)) include the future benefits from avoiding climate damages and air pollution, where the proper discount rate of avoided future costs is a decisive parameter and is therefore often debated. Potential short-term economic benefits, such as increased technical progress, international competitiveness, a positive investment climate or other feedback effects are usually not examined. However, when investigating fast decarbonization possibilities, which becomes ever more important with a 1.5°C climate target, the impact of large amounts of investment on innovation and spillover effects should not be neglected. A key question is whether GHG mitigation can bring about economic benefits, even when costs of climate change (damages) in the future are not taken into account. Wolf et al. (2016) provides a comprehensive overview of different modelling approaches that address positive economic effects and the mechanisms they depend on.

This paper will investigate three mechanisms which are considered important for positive effects of climate mitigation:

1. Several studies argue that the transition to a low-carbon economy requires large additional investment, e.g. UNEP and IEA estimate the required additional investment at global scale to be $0.5 trillion annually by 2020 and $1 trillion annually by 2030, in order to reach the target of staying below 2°C global warming (IEA; 2014). This number would increase for a 1.5°C target. However, academic literature on the effects of green investment programs is scarce. To address this research gap, we introduce an investment program and investigate its effects.

2. technical progress is often regarded as a key mechanism for reducing abatement costs. Wing

(2006) notes that computational models used to evaluate the costs and benefits of climate policy often treat technical progress as exogenous and invariant to climate policy, and therefore disregard the feedback effects involved. There is a variety of approaches for the endogenization of technical progress, from the original hypothesis on induced technical change (ITC) by Hicks (1932) to directed technical change for climate change mitigation by Acemoglu et al. (2012). Most commonly used approaches are the stock of knowledge approach (see e.g., Popp (2004)) and the learning-by-doing approach (see e.g., Grübler and Messner (1998); Grubb et al. (1995)). We introduce a simple learning-by-doing mechanism based on production levels.

3. As pointed out by Wing (2006), the endogenization of technical progress via learning-by-doing gives rise to multiple equilibria. With more than one possible equilibrium, the question of equilibrium selection arises, which causes problems in a general equilibrium framework. This problem can be described as a coordination problem (see e.g., Bryant (1983); Cooper and John (1988)). To address this, we introduce a mechanism of adaptive expectations, in which investment decisions of firms are influenced by sales expectations in the specific sector.

Although there are numerous studies on the effects of endogenous technical progress by various scholars (see Wing (2006) for an overview), it usually has not been studied in combination with other model changes or policies, such as adaptive expectations or an investment program. We want to test whether an investment program combined with changes in the model mechanisms can trigger a shift from economic costs to benefits within the given model framework.

This paper is organized as follows: In Section 2.2, we first describe the standard CGE model and the default features of the modelling framework. Second, we describe the model mechanisms considered crucial in determining the overall economic impact of GHG mitigation, and especially key mechanisms for sustainable investment. Third, we provide a description of different scenarios, which are characterized by different combinations of policies and model changes. Section 2.3 compares the results of these scenarios and Section 2.4 summarizes the findings.

2.2 Materials and methods

The objective of this work is to discuss crucial mechanisms for a more comprehensive economic evaluation of climate policies that foster investment.

2.2.1 Landscape

There are different modelling approaches, such as macro-econometric, computable general equilibrium or systems-dynamics, which are used to assess the economic impacts of alternative climate policies.

Computable general equilibrium (CGE) models are the most commonly used tools for the assessment of climate policy, since they simultaneously capture the interrelation of all markets and agents while allowing for the integration of alternative policy scenarios. All scenarios in these models represent an optimal allocation of resources under different types of constraints. By construction, the reference scenario represents a long-run equilibrium where the economy grows at a steady rate. Hence, all other scenarios lead to sub-optimal solutions within the given analytical framework.

CGE models, however, may fall short on realism as they do not capture market imperfections. However, several extensions to the classical Arrow-Debreu-type (Arrow and Debreu; 1954) of general equilibrium models have been made, to make them more realistic. Such extensions are involuntary unemployment in the labour market (Boeters and Savard; 2011), oligopolistic competition and monopolies (Balistreri and Rutherford; 2013) and endogenous productivity (Tarr; 2013). This paper addresses additional mechanisms that are expected to play an important role for climate policy.

2.2.2 The GEM-E3 model

This section provides an overview of the core structure and key mechanisms of the model used.

Model description

For the purpose of this paper, a well-established computable general equilibrium (CGE) model, GEM-E3, is used. This description is based on the detailed model description of GEM-E3, which can be found in the GEM-E3 reference manual (Capros et al.; 1999) and the GEM-E3 model documentation (Capros et al.; 2013). The model has been applied for policy analyses and impact assessments of climate policy, such as the Impact Assessment Report of the European Commission (European Commission Staff; 2014).

The GEM-E3 model is a macroeconomic recursive-dynamic CGE model with multiple regions and sectors. It consists of a CGE core and an environmental module. Different versions of the model can differ regarding their characteristics, such as varied closure rules and institutional regimes. The environmental module includes emission permits, energy efficiency standards and several policy options for allocating emission permits and for using the generated revenues. Labour, (total factor) productivity and expectations on sectoral growth rates are the main determinants of economic growth.

The main characteristics of the model are:

- **Firms:** Firms operate under perfect competition and use a nested production function, including capital, labour, energy and materials. Firms are characterized by myopic expectations.
- **Households:** Representative households (one for each country and region) maximize a utility function to determine their demand for goods and services. The household can buy durable

(equipment) goods, non-durable (consumable) goods, and services. The use of durable goods requires some amounts of non-durable goods.

- **Markets:** Firms optimize their profits and households optimize their utility, determining supply and demand for goods and services. Equilibrium prices are derived in the market, by ensuring that supply equals demand. Consumption and investment are allocated using transition matrices.
- **Technology:** Technical progress is exogenously represented in the production function. In each time step, the producer can change its production inputs depending on changes in prices of labour, capital and all intermediate goods and services. The electricity sector is more detailed, differentiating between different technologies producing electricity.
- **Externalities:** Greenhouse gas emissions are included as an environmental externality by introducing an additional constraint on the system. The emission constraint produces a shadow price for the emissions. Firms can invest in pollution abatement capital, which reduces emissions per unit of output, and hence its costs. This version of the model does not include damages to the environment and the economy in the future.
- **Output:** Projections are made in 5-year intervals and include macroeconomic output (investment, capital, consumption, employment, balance of payments, input-output-tables, and others) as well as output related to energy and the environment (energy use and supply, greenhouse gas emissions, pollution permits, pollution abatement capital).

Appendix 2.A provides a short technical description of GEM-E3-M50, the version of the model used for this paper, as also presented in Jaeger et al. (2015).

Investment and related mechanisms

The hypothesis to be tested in this paper, is that investment is a key mechanism for producing positive economic effects of climate policy. In order to test this hypothesis, it is necessary to determine the variables that are inputs to and outputs of investment from the investment function in GEM-E3 (as shown in Formula (2.6) below):

1. Inputs to investment: The investment demand is endogenously specified using Tobins'Q (Tobin; 1969), by comparing the market price of capital with its replacement cost. In the current implementation, investment depends on: the optimal demand for capital (given by the production function and elasticities), the depreciation rate (technologically determined), the interest rate (arising from financial market dynamics which are outside the scope of the model), the unit cost of investment, expectations on sectoral growth (exogenously defined), as well as a calibrated scale parameter. We derived two main possibilities of influencing the investment decision:

- To change the unit cost of investment via an investment subsidy
- To endogenize expectation dynamics, such that investors learn from their past experience.

2. Outputs of investment:

- Technical progress is exogenous in the model at hand. In the real-world, however, investment has an influence on technical progress - therefore this mechanism will be addressed.
- Investment influences the size of the capital stock and through that production and employment. Its effect is the substitution of labour with capital and between different types of capital - leading to higher unemployment and crowding-out of investment as a first-round effect (which is then offset through higher production levels as a second-round effect). This is an issue we will investigate in the simulation results.

The key mechanisms which will be investigated further in Section 2.2.3 are: the effects of an investment subsidy, expectation dynamics and technical progress.

GHG emissions constraint

A standard way of introducing climate targets is in the form of a policy that puts a cap on total emissions allowed, hence an additional constraint is added to the optimization problem. In this case, we have chosen a more ambitious climate target than the one agreed in the European Union (40% by 2030 compared to 1990), namely 50% (the respective scenario is called M50 only, as described in Section 2.2.4). Simulations for the Impact Assessment Report (European Commission Staff; 2014) have shown that applying a 40% GHG emission reduction target leads to small negative effects on GDP between 0.1% and 0.45% by 2030 (compared to the reference scenario).

To give a structured overview of the model changes and expected outcomes, we formulate a number of propositions. Proposition 0 is used in combination with the model extensions but is based on an existing mechanism in the model. *Proposition 0: The introduction of an emission cap in the form of an additional constraint to the optimization problem, will lead to a worse economic outcome.*

2.2.3 Relevant mechanisms and related model extensions

This section describes the model changes implemented to account for the mechanisms described in Section 2.2.2 . The propositions are used to structure the model changes and the expected results based on the mechanisms of general equilibrium models in general and the GEM-E3 model in particular.

Investment program

A key goal of this paper is to evaluate the effects of a considerable increase in low-carbon investment (public or private) in addition to the introduction of a GHG emission cap.

Greening the economy is the target of a number of green recovery proposals (e.g., Bowen et al. (2009); Edenhofer and Stern (2009); Zenghelis (2011); Beyerle and Fricke (2014)), notably the Green New Deal proposed by the European Green Party (e.g., Schepelmann et al. (2009)) and The New Climate Economy Report (Global Commission on the Economy and Climate; 2014). They highlight the large scale and long-term benefits, such as "building the foundations of sound, sustainable and strong growth in the future" (Bowen et al.; 2009). Two channels through which public expenditures can be geared towards a green economy are proposed by UNEP's Green Economy Report: redirecting public investment and greening public procurement (UNEP; 2011). Further, increasing the leverage effect of public investment on private investment is being discussed at different levels, national, EU and international. UNEP's Green Economy Report suggests government actions that set conditions for private investment: to phase out fossil fuel subsidies, to reform existing incentives and provide new incentives, and to strengthen market-based mechanisms (UNEP; 2011).

The World Economic Forum (2013) concludes that 80% of investment will have to come from private sources. Zenghelis (2011), Zenghelis (2012) and Romani et al. (2011) analyse the possibility of stimulating additional net private sector investment in detail. Finding historically low investment levels in most OECD countries, the authors see a "lack of confidence to invest rather than a lack of liquidity" (Romani et al.; 2011) and argue that credible long-term green growth policies provide opportunities for restoring confidence and leveraging additional investment (Zenghelis; 2012). Similarly, the Green Economy Report calls for the private sectors' "understanding and sizing the true opportunity represented by green economy transitions across a number of key sectors" (UNEP; 2011).

A key assumption of CGE models, however, is full employment of resources. Under this assumption, any new investment project will reduce investment elsewhere. This crowding-out effect is a key distinction between optimizing and non-optimizing models. If increasing investment levels improves the economic situation, this can either point to the fact that there is another possible equilibrium point, which actors cannot foresee or cannot coordinate on. Or it points to the fact that there are market imperfections in place that lead to a non-optimal outcome in the current situation.

To represent this mechanism in the model, a green investment program was introduced. For the purpose of this paper, the investment program was modelled as a change in policy. The value-added tax (VAT) is increased and the resulting additional revenues are used to subsidise investment. It is important to note that, what we want to investigate is the effect of the investment program and not how the additional investment is funded. The way it is implemented is comparable to other reallocation policies, such as the introduction of a price on carbon or a cap on the maximum amount of carbon emissions. Therefore, it can be expected that it leads to a crowding-out effect.

The required additional VAT is calculated such that the government revenues are increased by 10% compared to the reference case plus the GHG emission constraint (the scenario M50only). Hence, the new VAT revenues are determined by:

$$\text{VATrevenues}^{Cf} = \text{VATrevenues}^{M50only} \times 1.1 \tag{2.1}$$

where "*Ref*" denotes the reference scenario, "*M50only*" the 50% GHG emission reduction scenario and "*Cf*" denotes the counterfactual scenarios, meaning the "*M50only*" scenario with additional model changes.

The subsidy per unit of investment, P_{Sub}^{INV}, is calculated such that the new investment is equal to the M50only investment plus the additional value-added tax (VAT) revenues:

$$INV^{Cf} = INV^{M50only} + \text{VATadditionalRevenues}^{Cf} \quad \text{and} \tag{2.2}$$

$$P_{INV}^{Cf} = P_{INV}^{M50only}\left(1 + (P_{Sub}^{INV})^{Cf}\right), \tag{2.3}$$

with P_{Sub}^{INV} being a negative value.

Proposition 1 *In a standard CGE model, such as GEM-E3, an investment program leads to an outcome that is worse than the scenario it is based on (M50only), because it reallocates resources away from the optimal allocation.*

Proposition 2 *If the reference scenario is the optimal scenario by assumption, an investment program will always lead to crowding-out of consumption by investment (and of investment in one sector by investment in another) in the short-run.*

Learning by doing

CGE models, apart from few exceptions which will be described below, represent technical progress exogenously. However, the technical progress of clean technologies is key for a transition to a low-carbon economy. A considerable increase in low-carbon investment will increase the production level of these sectors. This will increase technical progress for these products through product and process innovation. An exogenous rate of technical progress does not take this feedback effect into account when higher levels of investment are applied.

Wing (2006) differentiates four ways of introducing technical progress endogenously, two of which are used less often: (1) price-induced input augmentation and (2) backstop-technologies; and two of which are more popular: (3) the stock of knowledge approach and (4) the learning-by-doing approach.

Price-induced input augmentation is not used very often, due to difficulties in specifying a function that describes the relation between relative input prices and the augmentation of different inputs. Backstop-technologies are regarded as a semi-endogenous approach, which allows for radical technical change by introducing a new production technique. The new technique will be employed in response to an increase in prices, which in turn is dependent on other variables, mostly exogenous.

The stock of knowledge approach results from the new economic growth literature, where knowledge is represented as a kind of capital, the stock of knowledge (H), which grows with R&D investment, depreciates over time and follows an innovation process (transformation function)—which includes the efficiency of innovation, diminishing returns to R&D and spillover effects. However, the problem is the lack of disaggregated data on R&D and the calibration of initial knowledge stocks. The central argument is that climate policy does not increase R&D in general but that there is a trade-off between innovation (accumulation of knowledge) in different sectors. Popp (2004) and related papers implement a stock of knowledge approach into the DICE model. Furthermore, Acemoglu and colleagues (Acemoglu et al.; 2012) use a stock of knowledge approach as well and find that a combination of carbon taxes and (temporary) research subsidies is sufficient to redirect technological development towards clean technologies through investment.

In the learning-by-doing (LBD) approach, the key parameter is the learning rate which depends on experience in a given sector. See Arrow (1962) for a discussion on which economic variables are a good proxy for experience. Bottom-up models favor the LBD approach and mostly use cumulative capacity or cumulative production levels as a proxy for experience. Grubb et al. (1995) use cumulative abatement as a proxy. There is a rich literature on learning and experience curves, which started with a study by Wright (1936) who introduced the concept of "learning curves", measuring learning-by-doing as labour cost reduction in relation to cumulative output. He found a constant percentage of unit labour cost reduction per doubling of cumulative output in airframe manufacturing. Later on, the concept was extended to "experience curves", by including different learning effects through R&D, production scale, cost of capital, etc. and by investigating total product costs instead of labour costs. Nagy et al. (2010) compare three different "laws" of technical progress (time, production levels and cumulative production) for a large set of technologies and find that all three show very similar development paths for a large set of technologies. However, it is not straightforward to transfer these micro-level learning curves to the macroeconomic level.

The goal here is not to build on the vast amount of literature on technical progress by providing deeper insights into the forces that drive it. Instead, we start from the point that technical progress is present and is linked to the "experience" in a sector. Hence, exogenous learning parameters which do not change in response to policy induced changes in sectoral compositions, miss an important part of the feedback effects triggered by climate policy.

In the model used, technical progress or total factor productivity $TFP_{i,j,t}$ is determined by calibrating the model to exogenously given GDP growth rates. This is done because the purpose of the model is not to predict growth but to assume that under business as usual the official growth rate predictions (e.g., by DG ECFIN (European Commission; 2012) in the EU) will be realized in the reference case.

In our approach we have semi-endogenised TFP in order to reflect learning by doing effects from higher production levels. The equation below describes the computation of TFP. It remains a calibrated parameter but an additional factor is added that depends on the production level:

$$TFP^{Cf}_{i,j,t} = TFP^{Ref}_{i,j,t} \cdot \frac{Q^{Cf}_{i,t-1}}{Q^{Ref}_{i,t-1}} \tag{2.4}$$

where "i" denotes the sector, "j" denotes the region and"t" denotes the time. $Q_{i,t-1}$ is the sum of the sectoral outputs over all regions j, i.e., $Q_{i,t-1} = \sum_j Q_{i,j,t-1}$ because spill-over effects between different regions are important for technical progress. The correction factor $Q^{Cf}_{i,t-1}/Q^{Ref}_{i,t-1}$ shows that technical progress in a given sector increases when the production in that sector increases. This means that TFP stays the same in the reference case (as production does not change). However, different levels of production in the counterfactual scenarios lead to different levels of TFP.

The review by Wing (2006) showed that a common way to prevent implausible market share dynamics in LBD approaches is to include upper bounds. In this paper we introduced an upper bound on the correction factor. Furthermore, for simplicity we assume that shrinking sectors do not "unlearn" immediately in response to reductions in demand. Hence, to prevent unreasonable dynamics, the correction factor is limited to a range from 1 to 3., i.e.,

$$TFP^{Ref}_{i,j,t} \leq TFP^{Cf}_{i,j,t} \leq 3 \cdot TFP^{Ref}_{i,j,t}. \tag{2.5}$$

Proposition 3 *The partial endogenization of learning-by-doing leads to an improvement of GDP as compared to M50only, due to its effect on productivity.*

Proposition 4 *The combination of learning-by-doing with an investment program leads to an improvement of GDP, because the investment program triggers a stronger learning-by-doing effect.*

Expectations

The before mentioned literature suggests that technical progress creates positive externalities in the form of spillover effects, which can lead to underinvestment in these technologies. There are two main reasons for this: (1) the social benefit of innovation is higher than the private benefit of the individual investors (2) the benefit is often beyond the investment horizon of the individual.

Often, investors do not take into account their individual contribution to overall technical progress (because this depends on the behavior of others). Instead, they take it as given and collectively invest below the social optimum. Zenghelis (2011) describes climate change as a market failure emerging from uncoordinated actions of individuals that leads to a collectively inferior outcome. Such a mechanism of expectation dynamics has already been investigated in Jaeger et al. (2011) and Jaeger et al. (2015). If several producers invest more into their productive capital, they will experience higher overall technical progress. If this experience is taken into account in investment decisions in the next period, this can lead to positive expectation dynamics.

Investment connects two time steps in a model. Expectations about future prices, policies and demand are crucial in determining the return on investment (which is subject to uncertainty) and therefore, the investment decision. The latter then drives the optimal allocation of capital leading to the optimal outcome.

In the model used, time is modelled in a recursive dynamic way and agents have myopic expectations. Investment is described by the following function:

$$INVV_{i,t} = A1_{i,t} \cdot K_{i,t} \cdot \left(\left(\frac{PK_{i,t}}{PINV_{i,t} \cdot (r_t + d_{i,t})} \right)^A + STGR_{i,t} + d_{i,t} \right). \tag{2.6}$$

where $A1$ is a calibrated scale parameter; K is the optimal demand for capital; PK is the cost of capital; $PINV$ is the cost of investment; d is the rate of depreciation; r is the national interest rate; $STGR$ is an exogenous parameter expressing expectations about sectoral growth. STGR represents the expectations on the future rate of capital return, to ensure that the investment plans are actually realized. Since STGR is an exogenous parameter calibrated to the reference scenario, it does not change with production levels (sales expectations of firms).

However, to include a response to increased rates of investment, this parameter should change endogenously, depending on the economic performance of that sector. For the purpose of better representing expectation dynamics, the following adjustment of STGR was implemented to represent adaptive expectations:

$$STGR^{Cf}_{i,j,t} = STGR^{Ref}_{i,j,t} \cdot \left(\frac{Q^{Cf}_{i,j,t-1}}{Q^{Ref}_{i,j,t-1}} \right)^2. \tag{2.7}$$

Similar to the correction factor described in Section 2.2.3, this represents the fact that sales expectations in a given sector depend on past experience: the larger the change in production level in that sector in a specific country, the higher the sales expectations for the next period and vice versa. The difference to Section 2.2.3 is that output values are differentiated by country and sector, $Q_{i,j,t-1}$, because for expectation dynamics we do not assume large spillover-effects between countries (larger sales in one country do not necessarily lead to higher sales expectations in another country). Furthermore, we assume expectations to be more responsive to increases in production than technical progress, which is why we assume a quadratic relationship.

In sectors with small output levels, the correction factor can lead to large adjustment of the STGR parameter. To take this into account, the correction factor is limited to a range from 0.5 to 3, allowing for negative effects on expectations as well, i.e.,

$$0.5 \cdot STGR^{Ref}_{i,j,t} \leq STGR^{Cf}_{i,j,t} \leq 3 \cdot STGR^{Ref}_{i,j,t}. \tag{2.8}$$

Proposition 5 *The partial endogenization of expectations does not lead to an improvement of GDP as compared to M50only, as it amplifies the negative effects of the emission target through its effect on production levels.*

Proposition 6 *The combination of all three mechanisms (adaptive expectations, learning-by-doing and an investment program) is expected to result in higher levels of GDP as compared to all other scenarios, because the three effects work in the same direction.*

The next section describes the scenarios used for the analysis.

2.2.4 Scenario description

For the purpose of testing the propositions, different scenarios are defined. The geographical focus is Europe, since the low levels of investment make it an interesting case for these specific model changes.

Reference scenario (Ref)

The first step is to define a reference scenario, which represents the optimal growth path in the absence of any imperfections or frictions and assumes a business-as-usual world in terms of policies.

The data used for GEM-E3-M50 for the European Union consists of national accounts data and input-output tables from Eurostat. One underlying assumption of the reference scenario is that the output growth rate is in line with macro-economic projections, in this case 2012 Ageing Report prepared by DG ECFIN (European Commission; 2012). According to this report, the EU28 will have a growth rate of 1.5% over the period 2015–2050 and a decrease in the working age population. The methodology for the calibration of the exogenous parameters is described in more detail in the GEM-E3 model documentation (Capros et al.; 2013). Although the calibration of the reference scenario is not based on the latest data and projections, we do not consider this as problematic. This paper aims at identifying general mechanisms and focuses on the comparison of a reference scenario with counterfactual scenarios.

The different counterfactual scenarios are compared and evaluated against the reference scenario. A counterfactual scenario uses different assumptions (including changes in exogenous variables or policies). If these changes do not affect the reference scenario, the model does not need to be re-calibrated. The aim of the model changes introduced for the purpose of this paper is to keep the calibration of the reference case unchanged, to ensure comparability of results.

Climate policy scenario (M50 only)

All assumptions are identical to the reference scenario for this scenario. Additionally, it includes a constraint on total greenhouse gas emissions. To show the impact of an “extreme” scenario, we chose a more ambitious emission reduction target than the currently agreed target of 40% (compared to 1990). For this scenario, we apply an emissions reduction target of 50% compared to 1990 (approx. 46% reduction from 2005). No changes in climate policies are assumed for non-EU countries. To exclude other reallocation effects, it is assumed that the carbon tax revenues are not reused in the economy for a specific purpose (although this is generally possible within GEM-E3) but they are used instead to improve the public budget.

Variants with model changes

To perform an evaluation of the effects of the mechanisms introduced into the model, several scenarios with different combinations of model changes have been analysed. The scenarios are specified in Table 2.1.

Table 2.1: Scenario description

Abbreviation	Scenario	Description
Ref	Reference	Optimal path, assuming a business-as-usual policy framework
M50 only	M50	50% reduction of GHG emissions compared to 1990
M50 inv	M50 with investment program	Part of the investment required to decarbonize the EU economy is financed by increasing consumption taxes
M50 tl	M50 with technical progress	Learning by doing effects are introduced in the sectors producing both clean energy technologies and other equipment goods
M50 exp	M50 with adaptive expectations	The investment decision of firms is adjusted so as incorporate expectation dynamics, next to myopic expectations
M50 tl+inv		M50 with technical progress and investment program
M50 tl+exp		M50 with technical progress and adaptive expectations
M50 tl+exp+inv		M50 with technical progress, adaptive expectations and investment program

2.3 Results

2.3.1 Macroeconomic aggregates

This section shows the main findings of the simulations. Table 2.2 shows the results of all scenarios compared to the reference scenario in 2030. For GDP, employment, and energy consumption and energy intensity, the results for 2030 are also depicted in Figure 2.1. Appendix 2.B shows the main outcomes of the reference scenario. The combined scenario (M50tl + inv + exp) performs best in all four dimensions.

Table 2.2: Macroeconomic results, all scenarios compared to reference in 2030

	M50only	M50tl	M50exp	M50inv	tl + exp + inv
GDP	−0.56%	−0.22%	−1.04%	−0.24%	+9.73%
Employment	−0.76%	−0.46%	−1.41%	−1.21%	+1.18%
Energy Use	−4.91%	−3.83%	−5.57%	−4.87%	−2.73%

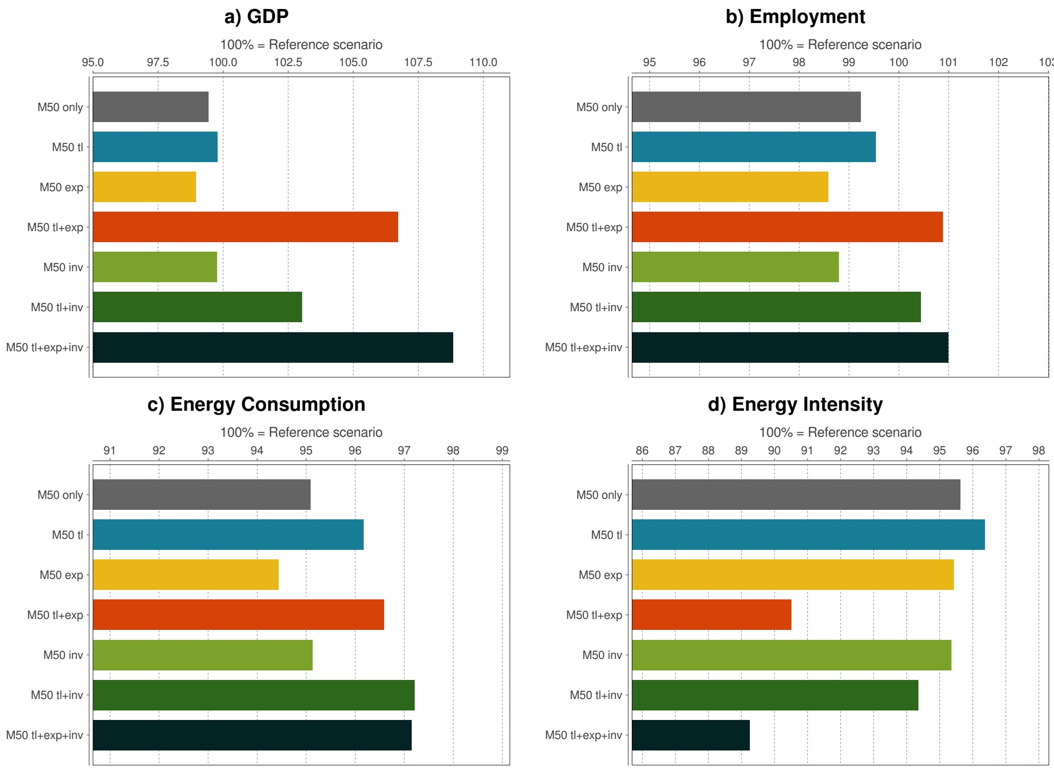

Figure 2.1: Results for GDP and employment, energy consumption and energy intensity in 2030, comparing all counterfactual scenarios with the reference scenario.

We can see that the M50only scenario (with an ambitious climate target, but no model changes applied), shows a decrease in GDP compared to the reference scenario (−0.56% GDP in 2030 compared to reference) due to a 50% GHG emission reduction target. This corresponds with the results of the European Commission Impact Assessment Report on the 2030 climate and energy framework (European Commission Staff; 2014), showing GDP effects between −0.1% and −0.45% in 2030 when comparing a 40% emission reduction scenario with the reference scenario. *This outcome supports Proposition 0.*

M50 combined with the investment program (M50inv) shows slightly improved GDP results if compared to the M50only scenario. *This outcome does not support Proposition 1 if measured in terms of GDP.* However, the proposition can be supported if measured in terms of "welfare", a measure of how well consumer preferences are satisfied. Due to the crowding-out effect, an increase in investment causes a decrease in consumption, which reduces the welfare of the consumer in the short-run.

However, GDP results remain below the reference case, which means that the negative effect of the emission target is only partially offset by the investment program. This means that an ambitious climate target in combination with an investment program leads to lower economic costs than a climate target alone (in terms of loss of GDP as compared to the reference scenario) but does not lead to economic benefits compared to the reference case (but compared to M50only). The investment program leads to a crowding-out effect, hence an increase in investment, and at the same time a decrease in consumption. *This outcome supports Proposition 2.*

M50 combined with only technical progress (M50tl) shows slightly improved GDP results if compared to the M50only scenario. *This outcome supports Proposition 3.* However, GDP results remain below the reference case. This means that the negative effect of the emission target is partially offset, but no positive economic effect can be found.

M50 combined with adaptive expectations (M50exp) leads to lower GDP growth compared to both the M50only scenario and the reference scenario. *This outcome supports Proposition 5.* This means that investors' expectations amplify production levels in a negative way.

The combinations of model changes on the other hand show positive economic effects, despite the GHG emissions constraint. The combination of technical progress and an investment program (M50tl + inv) results in GDP improvements compared to the reference scenario and the M50only scenario in 2030. *This outcome supports Proposition 4.* The combination of technical progress and adaptive expectation (M50tl + exp) results in GDP improvements compared to the reference scenario and the M50only scenario in 2030 as well. This means that positive expectation dynamics can have a similar effect as the investment program.

The combination of investment program, technical progress and adaptive expectations (M50tl + inv + exp) show even higher GDP results. *This outcome supports Proposition 6.*

Regarding employment, the outcome of the M50only scenario is worse than the reference scenario. The same is the case for combinations of M50 and one model change (tl, inv or exp), which shows that these mechanisms alone do not lead to positive effects. Employment levels for M50exp and M50inv are even below M50only. This general conclusion is in line with the European Commission Impact Assessment Report on the 2030 climate and energy framework (European Commission Staff; 2014). However, in the combined scenarios (M50tl + inv, M50tl + exp and M50tl + exp + inv) the employment effect is positive as compared to both the M50only and the reference scenario in 2030.

Total emissions are the same for all scenarios, due to the constraint on GHG emissions. Figure 2.1 shows the energy intensity and energy use in 2030 for all scenarios, which show improvements as compared to the reference case.

The development over time (see Figure 2.2) from 2015 to 2030, shows that the investment program causes a reduction of GDP at first. This can be explained by the the first round effect where investment is crowding-out consumption and the fact that positive effects from the additional investment are only realized in the next time step, hence after 5 years.

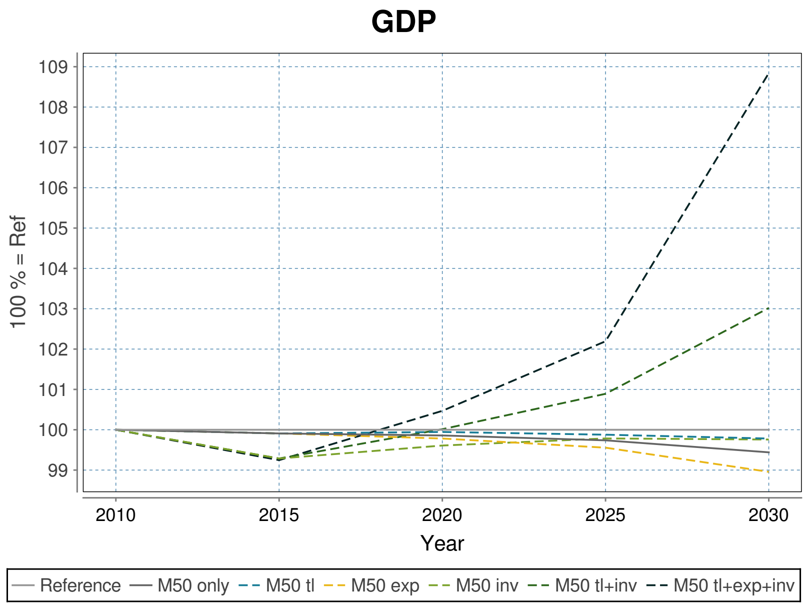

Figure 2.2: Results for GDP over time

2.3.2 Sectoral impacts

The sectoral disaggregation is what distinguishes CGE models from optimal growth models, which are also used for assessments of economic impacts of climate policy. Results at sectoral level can give us insights into crowding-out of investment between sectors. The sectoral dimension is also important for finding out which sectors will contribute most to the transformation in terms of emission reduction (relevant for climate policy) as well as in terms of economic development (important for economic, labour and education policy).

The changes in production levels and emissions of the different sectors are presented in Figure 2.3. The energy sector shows the largest emission reductions (approximately 50% compared to the reference scenario, for every alternative scenario), hence this is the sector that needs to contribute most to the abatement process. The energy-intensive industry will also reduce emission levels considerably. The transport sector is expected to contribute the least to emission reductions. Equipment goods producers will increase emissions, but much less than the increase of the production level. The overall reduction of GHG emissions is 50% in all scenarios, due to the binding constraint on these emissions.

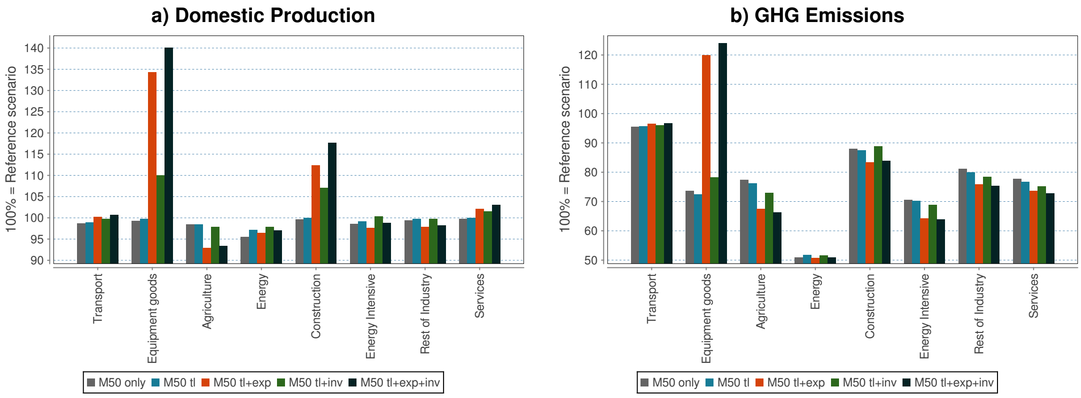

Figure 2.3: Results by sector for production levels and GHG emissions compared to the reference scenario in 2030.

In economic terms, sectors contributing to energy efficiency improvements, such as construction, equipment goods and services will show higher domestic production due to larger investment in these sectors. Also at sectoral level, we can see a crowding-out effect of the investment program from some sectors to others. *This outcome again supports Proposition 2.*

2.4 Discussion

Reaching the Sustainable Development Goals, including climate action and affordable clean energy, requires a fundamental socio-economic transformation accompanied by substantial investment in low-carbon infrastructure. However, there has been little macroeconomic analysis that evaluates the effects of a substantial increase of investment in low-carbon technologies. The usual analyses of climate policy show negative economic effects of emission targets, because they are treated as an additional constraint to the optimization process, e.g., in CGE models and additional feedback effects are not taken into account. However, when evaluating the effects of a large increase of investment for the decarbonization of the economy, assuming no effect on technical progress and investors' expectations does not give a comprehensive picture. Rather, a sustainability transition should be analysed as a non-marginal change of the economic state, driven by behavioral factors and systemic interactions.

This paper identifies key mechanisms that need to be included in a standard computable general equilibrium model to overcome these limitations. These mechanisms are an investment program, technical progress and adaptive expectations. The results of this work highlight the central role of large additional investment and provide a more comprehensive analysis of the effects of climate policy.

The outcomes of the scenarios with single model changes are in line with what can be expected from the literature on macroeconomic climate policy assessment (see e.g., Grübler and Messner (1998); Grubb et al. (1995); Popp (2004)) and from the model properties: Technical progress partially offsets the negative economic effect of introducing an ambitious emission constraint. The introduction of adaptive expectations alone, amplifies the negative effect, because it depresses sales expectations of firms. An investment program leads to crowding-out of consumption with investment and therefore to less efficient resource allocation.

The results of the combined scenarios (M50tl + inv and M50tl + exp, M50 tl + exp + inv), however, add new insights to the literature on the role of technical progress in climate economic models: Technical progress is necessary for positive economic effects of climate policy, but not sufficient. Combining technical progress with an investment program or adaptive expectations leads to positive economic effects. These findings build on Wing (2006), who argued that the endogenization of technical progress gives rise to multiple equilibria. Indeed, the partial endogenization of technical progress introduces the possibility for a different economic growth path. The investment program as well as adaptive expectations introduce the possibility of switching between different economic growth paths.

The results provide suggestions for policy makers aiming for ambitious climate goals. If ambitious climate policy (towards 1.5°C) should bring about more desirable economic outcomes, it should not be implemented in isolation. Instead, green growth policies should be the core of a wider economic program aimed at increasing investment levels and enhancing technical innovation. Green public procurement and green public investment (as proposed in UNEP (2011)) will be an important element, as well as implementing credible long-term green growth policies that restore confidence and leverage additional private investment (Zenghelis; 2012).

We can draw conclusions on the mechanisms that lead to a change in the direction of the economic effects of climate policy. However, drawing conclusions on the magnitude of the effect requires additional empirical validation and sensitivity analysis. Furthermore, generalizing these results to other countries requires more in depth analysis at the (EU) member state level as well as an extension of the analysis to other countries. Additionally, research on the role of the financial market is required in order to address the question of how to finance such an investment program, how potential funding constraints might reduce the positive effect or whether credit-financed investment can reduce the crowding-out effect.

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Appendix 2.A: Short technical description of the GEM-E3-M50 model

This section provides a short technical overview of the GEM-E3-M50 model, as presented in Jaeger et al. (Jaeger et al.; 2015). It provides the general structure of the model in order to better understand the model changes described in the paper. This description is based on the detailed model description of GEM-E3, which can be found in the GEM-E3 reference manual (Capros et al.; 1999) and the GEM-E3 model documentation (Capros et al.; 2013).

Appendix 2.A.1: Firms

Firms maximise their profits, subject to technology constraints:

$$MaxP \times Q - Cost \tag{2.9}$$

$$s.t.Q = CES(K, L, E, M) \tag{2.10}$$

A Constant Elasticity of Substitution (CES) is used as production function. Firms production is modelled via nested production functions so as to explicitly reflect different substitution elasticities among different inputs:

$$Q_i = TFP_i \times \bar{Q}_i \cdot \left(theta_i \times \left(\frac{KLEi}{K\bar{L}E_i}\right)^r + (1 - theta_i) \times \left(\frac{MAi}{M\bar{A}_i}\right)^r\right)^{\frac{1}{r}} \tag{2.11}$$

$$KLE_i = K\bar{L}E_i \times \left(theta1_i \times \left(\frac{KLi}{K\bar{L}_i}\right)^{r1} + (1 - theta1_i) \times \left(\frac{ENi}{E\bar{N}_i}\right)^{r1}\right)^{\frac{1}{r1}} \tag{2.12}$$

$$KL_i = K\bar{L}_i \times \left(theta2_i \times \left(\frac{Ki}{\bar{K}_i}\right)^{r2} + (1 - theta2_i) \times \left(\frac{Li}{\bar{L}_i}\right)^{r2}\right)^{\frac{1}{r2}} \tag{2.13}$$

$$MA_i = \left(\sum_{j=1}^{n} theta3 \times \left(\frac{IOj,i}{I\bar{O}_{j,i}}\right)^{r3}\right)^{\frac{1}{r3}} \tag{2.14}$$

where Q: total output, TFP: Total Factor Productivity, KLE: Capital-Labour-Energy bundle, MA: Material bundle, $theta$: distributional parameters between KLE and MA, r,$r2$ and $r3$: elasticity of substitution parameters, KL: Capital - Labour bundle, EN: Energy bundle, $theta2$: distributional parameter between KL and EN, IO: intermediate inputs, $theta3$: distributional parameter among intermediate inputs.

Appendix 2.A.2: Households

Households maximise their utility, subject to an income constraint:

$$MaxU = LES(C, LJV) \tag{2.15}$$

$$s.t. M = w \cdot L + r \cdot K + foreignTransfers \tag{2.16}$$

where U: Utility represented by a Linear Expenditure System function, C: Consumption, LJV: Leisure. Households follow a two step decision process. At first they allocate their resources among consumption/labour supply and savings and then they allocate aggregate consumption over different consumption purposes.

$$C = ch \cdot \frac{bh}{P} \cdot (M - P \cdot ch - Savings) \tag{2.17}$$

where ch: subsistence minima, bh: consumption share parameter

Appendix 2.A.3: Government consumption

Government consumption (GC) is set exogenously (gcexo), GC = gcexo.

Appendix 2.A.4: Investment

The model is recursive dynamic over time, meaning that multiple (static) equilibria are linked over time with a stock-flow-relationship of capital and investment. Agents have myopic expectations with respect to prices, meaning that the set of decision parameters is constant over time. Endogenously specified investment is determined using Tobins'Q (i.e., by comparing the market price of capital with its replacement cost). The motion equation of the capital stock is:

$$K_t = (1 - d) \times K_{t-1} + INVV_t \tag{2.18}$$

Firms in the current year decide on their optimal capital stock by comparing the rate of return on capital to its replacement cost.

$$INVV_{i,t} = A1_{i,t} \times K_{i,t} \times \left(\left(\frac{PK_{i,t}}{PINV_{i,t} \times (r_t + d_{i,t})} \right)^{A} + STGR_{i,t} + d_{i,t} \right). \tag{2.19}$$

where $A1$ is a calibrated scale parameter; K is the optimal demand for capital; $PINV$ is the unit cost of investment; d is the depreciation rate; r is the national interest rate and $STGR$ is the (exogenous) expectation on sectoral growth.

Appendix 2.A.5: Labour supply

The model does not assume full employment of labour. It incorporates the following labour supply curve that inversely relates wages[w] with unemployment rate [unrt]:

$$w_{j,t}(unrt_{j,t}) = a_{j,t} + \frac{b_{j,t}}{Unrt_{j,t}^{\eta_{j,t}^{Ref}}}. \tag{2.20}$$

Appendix 2.A.6: GHG emissions

Energy related CO_2 emissions are calculated by applying the appropriate emission factors to fossil fuel burning.

$$EMCO2_{ff,i} = e_f CO2_{ff} \times AER_{ff,i} \times EN_{ff,i} \tag{2.21}$$

Process related GHG emissions are linked with the volume of production

$$EMGHG_i = e_f CO2_{ff} \times Q_i \tag{2.22}$$

The imposition of a GHG emission reduction target generates a dual value that increases the user cost of the emitting activity.

$$GHGTARGET \geq EMCO_2 + EMGHG \perp CTAX \tag{2.23}$$

Appendix 2.B: Reference scenario

Table 2.3 shows annual growth rates and Table 2.4 the labour market outcomes from 2015 to 2030 for the reference scenario.

Table 2.3: Macroeconomic annual growth rates of the Reference Scenario.

EU-28	2015–2020	2020–2025	2025–2030
Gross Domestic Product	1.5%	1.6%	1.5%
Investment	1.4%	1.6%	1.5%
Public Consumption	1.6%	1.6%	1.5%
Private Consumption	1.6%	1.7%	1.6%
Exports	2.0%	2.0%	2.1%
Imports	2.3%	2.3%	2.3%
Labour productivity	1.2%	1.6%	1.7%

Table 2.4: Labour Market Outcomes of the Reference Scenario.

EU-28	2015	2020	2025	2030
Employment (in m. persons)	224	227	227	225
Population (in m. persons)	434	436	432	425
Labour Force (in m. persons)	101	102	101	99
Unemployment rate	11%	10%	9%	9%

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Chapter 3

Stock Market Reactions to International Climate Negotiations*

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Abstract

Several studies have shown that investors take environmental regulation into account in their investment decisions. We investigate if international climate negotiations are an effective signal to decarbonize the economy. For that purpose, we analyze short-term market reactions to the outcomes of international climate negotiations, through an event study. We compare the stock price effects on the largest „green“ companies with the largest „brown“ companies globally. We find that international climate negotiations have a signaling effect on global financial markets. Before 2013, climate negotiations mainly had effects on „green“ companies. Only starting in 2013, but especially in 2015 (Paris Agreement), we can find negative effects on „brown“ companies. This indicates that the focus has shifted to the risks for brown companies. Although the Paris Agreement was considered a political milestone, it was less effective as an investment signal. A possible explanation is the mismatch between international targets and national policies.

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3.1 Introduction

Each year an international climate negotiation is held, as a major effort to set more ambitious emission reduction targets and to reach a binding emission reduction agreement between all countries. During the last 10 years of climate negotiations, the Copenhagen summit (COP15 in 2009) became known for having failed to establish a successor to the Kyoto protocol. Six years later, the Paris summit (COP21 in 2015) became known for reaching a landmark climate deal, the Paris Agreement. However, the introduction of a global price on carbon, often argued to be the most effective policy instrument, has not been achieved yet. Subsequently, the lack of adequate policy implementation at international and national levels creates uncertainties for greenhouse-gas-emitting industries and their investors. This raises the question of whether or not these annual negotiations are perceived as effective steps towards a decarbonisation of the global economy. One way of measuring this is by investigating financial market responses to the announcements of the outcome.

While the most important goal for financial managers is the maximization of shareholder value, environmental responsibility (such as greenhouse gas emission reduction) is usually associated with additional costs and few benefits. Porter and der Linde (1995) have argued for a new framing of the environment-competitiveness debate, by introducing the 'induced-innovation hypothesis' which says that environmental awareness can lead to competitive advantages. Indeed, this view is taken up in concepts like the triple bottom line (Glac; 2015; Henriques and Richardson; 2013), corporate social responsibility (CSR)[2] and stakeholder theory[3] (Freeman; 2010). There is a growing literature that finds a neutral or positive effect of CSR activities on valuation and performance (Busch and Hoffmann; 2011) and on reduced stock price crash risk (Wu and Hu; 2019). In 2016, about 1/6 of Assets-under-management (AuM) (USD 22.89 trillion) were managed under responsible investment strategies (Global Sustainable Investment Alliance; 2016), with Europe (52.6%) and the United States (38.1%) representing the largest market shares. Due to their increasing market share, one can expect their decisions to have an influence on market prices.

We start from the premise that international climate policy influences investors' expectations about tighter environmental regulation in different countries, and that investors have information about how individual companies will be effected by it. To investigate if and to what extent climate policy influences investors' expectations on future cash flows (and therefore the valuation) of companies, we perform an analysis based on the event study methodology. Event studies are a common methodology in finance and management research, testing the statistical significance of stock price changes on selected and subsequent days. In the area of sustainability, event studies have been applied to study the effect of environmental performance disclosure (Gupta and Goldar; 2005),

[2] There are different reasons for companies to engage in CSR activities, ranging from internal factors, such as employee satisfaction and customer satisfaction, to external factors, such as legal rules and enforcement mechanisms.

[3] Stakeholder theory argues that managers need to satisfy demands of different stakeholders, which are often competing.

pollution control (McWilliams and Siegel; 1997), sustainability rankings (Lyon and Shimshack; 2015; Murguia and Lence; 2015), sustainable indices (Curran and Moran; 2007; Robinson et al.; 2011), and environmental awards (Klassen and McLaughlin; 1996). Furthermore, event studies have been deployed to study financial-market effects of binding national regulations (Ramiah et al.; 2013) and supra-national regulations (see Koch et al. (2016) and Jong et al. (2014) regarding the EU emission trading system). A meta-analysis by Endrikat (2016) concludes that most event studies focus on a specific country, with the United States typically over-represented. The event-study approach can complement other types of studies on the effectiveness of government intervention, e.g. by investigating their effect on renewable energy deployment and generation (Carley; 2009; Delmas and Montes-Sancho; 2011), investments (Chevallier et al.; 2009) or investors risk perception (Polzin et al.; 2015).

This paper complements the literature by providing an analysis of financial market effects of climate policy events at the international level. Since international climate accords are not legally binding at the country or even the company level, this study provides an indication of the effectiveness of non-binding international climate negotiations. Furthermore, the analysis goes beyond the energy sector and includes companies that use large amounts of fossil fuels in their production processes as well as companies that produce a large share of green products. Hence, we differentiate between high- and low-carbon companies, to find out how these announcements influence companies that will be affected positively, versus companies that will be affected negatively.

The paper is structured as follows. Section 3.2 reviews relevant work and sets the background for the present paper. Section 3.3 describes the selected events and data used. Section 3.4 describes the methods used. Section 3.5 presents and discusses the results and Section 3.6 summarizes the general findings.

3.2 Background and literature review

Estimating the impact of climate and transition risks on individual financial institutions as well as the financial system as a whole has become an increasingly important issue (Dietz et al.; 2016; Battiston et al.; 2017). However, opinions and estimations for a potential size of such a shock are divided. Griffin et al. (2015) concluded that investors recognized the scientific finding that a substantial share of fossil fuel reserves is unburnable under a 2°C target. However, the effect was not as substantial as expected. One of the reasons stated by the authors was that the timing of strict policy implementation is highly uncertain and therefore sudden portfolio adjustments are unlikely.

On the one hand, stricter policy measures at the international level are required to shift investments from high-carbon to low-carbon activities. On the other hand, investors need to have access to information regarding which companies are engaging in low-carbon activities, taking them into account in investment decisions.

The environmental finance literature addresses both of these points. One strand of the literature is investigating if signalling sustainability leadership has a positive effect on shareholder value, either via self-disclosure (e.g. via sustainability reports and environmental disclosure (Gupta and Goldar; 2005)) or via external parties in sustainability rankings (Lyon and Shimshack; 2015; Murguia and Lence; 2015), sustainable indexes (Curran and Moran; 2007; Robinson et al.; 2011), or environmental awards (Klassen and McLaughlin; 1996). At the global level, Robinson et al. (2011) investigated abnormal returns for firms that where added to the Dow Jones Sustainability Index (DJSI), a global sustainability benchmark. Additions to the index are seen as a signal that a company has reached a certain level of social and environmental performance. Another global analysis by Murguia and Lence (2015) investigates the influence of the 2010 Newsweek "Green Global 100" ranking, listing the largest 100 green companies globally. They find that the release of the ranking changed relative prices, and that the top 50 companies (mainly non-heavy industry) reacted more strongly to the ranking release. Furthermore, stronger reactions were reported for non-US-traded stocks, possibly because they had not been included in the Newsweek US ranking from 2009 or because most non-US-traded companies were European, which are often subject to stronger environmental regulation. The paper by Gupta and Goldar (2005) examined the stock market effect of environmental ratings from the leading environmental NGO in India on stock prices of Indian companies. They find that weak environmental performance by dirty industries is penalised by negative abnormal returns (as in the paper and pulp industry) and conclude that environmental ratings can increase market pressure especially in emerging market economies were standards and enforcement mechanisms are not as strong.

Another strand of the environmental finance literature investigates how policy changes affect listed stocks. The paper by Ramiah et al. (2013) investigates 19 announcements of environmental regulation on listed equities in Australia between 2005 and 2011[4]. The authors find that more than half of the sectors were affected by the policy announcements (14 out of 35 industries were not affected). 29% of sectors experienced negative abnormal returns, 20% experienced positive abnormal returns. They find that the wealth of shareholders in the electricity sector (in Australia) did not change, which indicates that the biggest polluters are not affected by the green policies. This was explained by the ability to pass on the increased costs to consumers. The oil, gas, real estate and general industrial sectors experienced negative abnormal returns. By analysing systematic risk they find that green policies create uncertainty in the market. Similarly, Koch et al. (2016) investigated the responsiveness of the CO2 price in the EU emission trading system (EU-ETS) to policy events, looking at short-term policy interventions (ETS reform decisions) and decisions regarding the long-term trajectory (2020 and 2030 policy packages).

[4]Using data on 1770 individual stock prices from data stream, the ASX200 index as a proxy for the market, and the 10-year bond yield as proxy for the risk-free rate. The Datastream classification is utilised to construct industry portfolios (45 industries).

The existing event-study literature related to sustainability and finance provides evidence that investors take environmental and climate-related news into account, finding effects due to environmental ratings and rankings and due to changes in environmental regulation at the national level. However, a meta-analysis by Endrikat (2016) concludes that most event studies focus on a specific country, with the United States being over-represented. So far, only Mukanjari and Sterner (2018) investigate the effect of international climate policy events, namely the effects of the Paris Agreement and the US presidential election in 2016 on energy sector firms.

This paper complements the literature by extending the scope to a series of international climate negotiations and by including not only energy companies but high-carbon companies as well as low-carbon companies.

3.3 Events and data

This section first explains which events were analysed and second, which financial data was used to perform the analysis.

3.3.1 Events

The literature on environmental finance suggests that stock markets react to changes in environmental regulation, leading to positive valuation effects for companies with a positive environmental rating. Despite their non-binding nature, international climate negotiations, the Conferences of the Parties (COP), are among the most important international efforts to reduce carbon emissions. These negotiations and resulting accords set the agenda for the national implementation of climate and environmental policy. Therefore, we expect that climate negotiations which resulted in an international agreement on ambitious emission reductions will lead to negative effects for high-carbon companies (as it would decrease future demand and increase costs) and positive effects for low-carbon companies (via increased revenue expectations) and vice versa.

We examine a series of international climate negotiations, including all climate negotiations between 2009 and 2016, which aimed to establish a successor of the Kyoto Protocol. The Kyoto Protocol, signed in 1997, was the first international treaty aiming to reduce greenhouse gas concentration in the atmosphere. Its first commitment period lasted until 2012. Our analysis starts with the 15th Conference of the Parties (COP15 in 2009) in Copenhagen, because it was set out to establish a post-Kyoto agreement but failed to do so. This was regarded a major set back in international climate negotiations. At COP17, held in Durban in 2011, the Parties agreed to establish a legally binding treaty by 2015, which secured the Kyoto Protocol but diminished the hope for immediate and serious action (Helm; 2012). At COP18, held in Doha in 2012, the Parties agreed on a second commitment period until 2020, called the Doha Amendment to the Kyoto Protocol (Böhringer; 2014). Finally, the 21st Conference of the Parties (COP21), held in

December 2015 in Paris, resulted in the Paris Agreement. The Paris Agreement is regarded a historic deal, as it contained the commitment of all participating countries to "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C [...]" (UNFCCC; 2015, Article 2.1.a).

We performed a financial news search on the terms "climate accord", "climate agreement" and "COP AND climate" and found high media coverage of the climate negotiations on the one hand and the US presidential election in 2016 and the US announcement of the withdrawal from the Paris Agreement in June 2017 on the other hand. The results of the news analysis can be found in Appendix 3.A.

Therefore, we included these two events as additional political events, as they shaped a large part of the international debate on climate change during the last years. The US election in November 2016 created uncertainty about the survival of the Paris Agreement and clearly had an influence on the 22nd Conference of the Parties in Marrakesh (COP22), that followed shortly after the US election. This was followed by the "rose garden speech" in June, 2017, where the US president officially announced the intention of the US government to withdraw from the Paris Agreement. Although, according to the Paris Agreement the withdrawal can only come into effect in 2020, it reduced the credibility of the agreement.

Table 3.1 contains a list of all events, their respective dates, as well as the main political outcome of the event and the stock price effect we expect from this outcome.

3.3.2 Data

To obtain the abnormal returns for high-carbon ("brown" companies hereafter) and low-carbon companies ("green" companies hereafter), we prepared two lists of companies and retrieved historical daily stock data. We obtained our list of green companies from the Clean200 (Heaps et al.; 2016), a ranking of the largest 200 publicly-traded companies worldwide with the largest share of revenues from clean energy. This list was released for the first time on August 16th, 2016 by "As you sow" and Corporate Knights[5]. The ranking uses Bloomberg Data on company size (by market-cap) and the share of "green" revenues, which is an estimate on the share of activities from renewable energy, energy smart technologies, carbon capture and storage (CCS), and carbon markets[6]. To be considered for the ranking, companies need to have a market capitalization of at least 1 billion and a minimum of 10% in green revenue. This ranking was used, because a high share of green revenue indicates that the company would directly benefit from an increase in demand for these products.

We obtained our list of brown companies from the Global 500 from the CDP Global 500 Report, which is published by CDP on an annual basis. The companies were sorted by their scope 1 CO2

[5]Since the first release, several updates have been published. However, the list of the Clean200 remains quite stable. For that reason, they are not considered in the analysis.

[6]Bloomberg divides companies into "main driver" (50-100% of value), considerable (25-49%), moderate (10-24%) and minor (below 10%)

Table 3.1: Selected events, including their dates, the main political outcomes and the expected price effects on green and brown companies. (–) stands for negative, (– –) for very negative (+) for positive and (+ +) for very positive.

Selected event	Date	Main outcome	Expected price effect green	brown
COP15 (Copenhagen)	2009-12-18	Failed to establish a post-Kyoto agreement	(– –)	(++)
COP16 (Cancun)	2010-12-10	Agreement on extension of Kyoto Protocol and on establishing a "Green Climate Fund"	(+)	(–)
COP17 (Durban)	2011-12-09	Agreement on establishing a legally binding treaty but delayed talks until 2015	(–)	(+)
COP18 (Doha)	2012-12-07	Amendment to Kyoto Protocol (EU, AUS, etc.). Agreement to extend Kyoto until 2020	(+)	(–)
COP19 (Warsaw)	2013-11-25	Package to keep climate negotiations on track	no effect expected	
COP20 (Lima)	2014-12-12	Joint emission reduction announcement by US and China	(+)	(–)
COP21 (Paris)	2015-12-14	Paris Agreement as landmark deal	(++)	(– –)
COP22 (Marrakesh)	2016-11-21	No specific outcome reached	no effect expected	
US pres. election	2016-11-08	Announcement to revive the coal industry	(–)	(+)
US withdrawal	2017-06-01	US announcement to step out of Paris Agreement	(–)	(+)

emissions, as reported to CDP[7] and top 200 companies in the list were selected. This approach was chosen, because we expect the companies with the highest emissions to be strongly effected by more ambitious climate policy.

Due to the observation that the set of green companies had a much larger share of companies in emerging markets, we enriched both sets with this additional information: whether a company comes from an emerging or developed market. The classification of the IMF was used. In the set of green companies, 86 are from emerging markets (versus 97 from developed countries). In the set of brown companies, only 24 companies are from emerging markets (versus 162 from developed countries). The list of companies can be found in Appendix 3.B.

Financial data on stock prices and indexes was obtained from Google Finance. Stock market data that was not available from Google Finance was obtained from Yahoo Finance.

We gathered data for non-adjusted daily closing prices for each company and the relevant market indices for the sample period. The data span the period from December 18th, 2008 until

[7] Scope 1 emissions are direct emissions from the operations of the respective company. Indirect emissions from upstream and downstream activities in the supply chain of that company are included in scope 2 and scope 3 emissions.

June 15th, 2017, covering a one year estimation window before the first event, COP15 in December 2009, until the last event, the US withdrawal from the Paris Agreement in June 2017. More details on the estimation and event windows can be found in Section 3.4. The first set included 187 green companies, while the second one 186 brown companies. 13 companies were omitted from the green set and 14 from the brown set due to incomplete or missing data. For individual events, additional companies had to be dropped when stock price data was missing during the event window. The number of companies analysed for each event is reported in Section 3.5.

3.4 Methods

This section will first describe the general methodology of event studies and second, the two types of analysis used, which are based on the event study approach.

3.4.1 Event study

According to early work by Fama (1991), event studies rely on the efficient market hypothesis (EMH), assuming that new information is priced in immediately. Although, the EMH has been challenged by behavioral finance (Shleifer; 2000), event studies have a clear advantage. They take a forward-looking perspective, as stock prices entail investors' evaluations of the expected future performance of companies (as opposed to the backward-looking perspective of accounting-based approaches). And, as shown by Griffin et al. (2015) the event study methodology can also be utilized to investigate "lagged" responses, as opposed to "rational" responses.

The event study method tries to capture the impact of (one or more) external events on stock prices. It requires a measure of abnormal price return, in other words, the actual return minus the expected return of the stock. MacKinlay (1997) provides an overview on the use of event studies and different methodologies applied in economics and finance and McWilliams and Siegel (1997) discuss theoretical and research design issues in event studies applied in management research.

The event study requires an estimation window and an event window. The estimation window is used to estimate the slope and intercept of the market model and to determine the abnormal return in the event window. Because most climate agreements were made during the weekend after the official last day of the negotiations, which is not a trading day, we chose the official last day as the event day (day 0). The estimation window starts 365 calender days (usually about 245 trading days) before the event and ends 10 calender days before the event day. The event window starts one trading day before the event (day -1), to include possible reactions to early announcements before the finalization of the agreement. And the event window ends four trading days after the event (day 4), to include possible lagged responses. For COP21 in Paris this means that the event day is Friday, 2015-12-11. The event window lasts from 2015-12-10 to 2015-12-17 and the estimation window lasts from 2014-12-11 until 2015-12-01.

The event study procedure starts by calculating the abnormal returns for company i and day τ:

$$AR_i(\tau) = R_i(\tau) - E[R_i(\tau)] \tag{3.1}$$

where $R_i(\tau)$ denotes the actual daily return of the stock, $E[R_i(\tau)]$ denotes the expected normal (daily) return and $AR_i(\tau)$ the abnormal return.

The model used to determine the expected normal returns in this work is the market model: it assumes a linear relation between the overall market return and the return of the stock (Ranco et al.; 2015; Gabrovšek et al.; 2017). The market model is estimated by using the return of the individual stock and the return of the stock market index, during the estimation window:

$$E[R_i(\tau)] = \hat{\alpha}_i + \hat{\beta}_i R_{index}(\tau) \ , \tag{3.2}$$

where $R_{index}(\tau)$ denotes the daily return of a stock market index on day τ.

It is worth noting that since companies used in this analysis are traded on different stock exchanges, the market model is calculated by using the stock market index of the country that the company's headquarter is located in. The information about the country of the headquarter of each company is listed in Tables 3.4 to 3.5 in Appendix 3.B.

After calculating the abnormal price returns for each of the n companies, there are two possibilities for further calculations. The first one is to calculate the cumulative abnormal return (CAR) from time τ_1 to τ_2 for one company:

$$CAR_i(\tau_1, \tau_2) = \sum_{\tau=\tau_1}^{\tau_2} AR_i(\tau) \ . \tag{3.3}$$

The second possibility is to aggregate the AR values for all companies in the set and calculate an average cumulative abnormal return ($\overline{CAR}$) from time τ_1 to τ_2:

$$\overline{AR}(\tau) = (1/n) \sum_{i=1}^{n} AR_i(\tau) \ , \tag{3.4}$$

$$\overline{CAR}(\tau_1, \tau_2) = \sum_{\tau=\tau_1}^{\tau_2} \overline{AR}(\tau) \ . \tag{3.5}$$

For example, the values of $\overline{CAR}(-1, -1)$ up to $\overline{CAR}(-1, 4)$ are reported in Section 3.5 for a set of green and a set of brown companies.

According to the definition of the event window, the value of τ_1 in Eq. 3.5 is set to one day prior to the event day and τ_2 to four working days after the event day.

3.4.2 Portfolio-based approach in the presence of cross-sectional correlation

In this analysis, we want to investigate the influence of a specific event day on the stock prices of several companies, which is called event-day clustering. In this case, the average (cumulative) abnormal returns of several companies corresponds to an equally-weighted portfolio: a portfolio where every company's price return is weighted the same.

In other words, the portfolio-based approach tests if the stock prices of a set of companies significantly increases or decreases due to the influence of one event. This type of analysis differs from the standard event study analysis (Ranco et al.; 2015; Gabrovšek et al.; 2017). In the presence of event-day clustering, it is known that cross-sectional correlation of the returns appear, which requires different treatment during the statistical inference (Kolari and Pynnönen; 2010). The statistical test used to infer if the average CAR value for a set of companies is significantly (positively or negatively) affected by this event is an adaptation of the t-test.

The statistical significance is calculated by using the standardized version of the abnormal returns, i.e. standardized abnormal returns (SAR). For company i and day τ it is calculated as:

$$SAR_i(\tau) = \frac{AR_i(\tau)}{\sqrt{\frac{1}{T_1 - T_0 - 1} \sum_{t=T_0+1}^{T_1} AR_i(t)^2}} \,, \tag{3.6}$$

where T_0 and T_1 are the start and end day of the estimation window, respectively. The abnormal returns in the denominator denote the residuals of the market model regression over the estimation window.

The statistical analysis is then performed using the following steps:

- The standardized cumulative abnormal return is calculated: $SCAR_i(\tau_1, \tau_2) = \sum_{\tau=\tau_1}^{\tau_2} SAR_i(\tau)$ where τ_1 is set to T_1, the start of the event window.
- The Patell t statistic on day τ is calculated: $t_P(\tau) = \overline{A}_\tau \sqrt{\frac{n(m-p-3)}{m-p-1}}$, where $\overline{A}_\tau$ is the average $SCAR$ value for all companies on day τ, m is the length of the estimation window and p is the number of estimated parameters in the market model (Patell; 1976).
- The adjusted Patell t statistic on day τ is calculated: $t_{AP}(\tau) = \frac{t_P(\tau)}{\sqrt{1+(n-1)\overline{r}}}$, where $\overline{r}$ is the average of the sample correlations of estimation-period residuals (Kolari and Pynnönen; 2010).
- A two-tailed t-test (at 1%, 5% and 10% significance level) is used with the t_{AP} value.

3.5 Results and discussion

In this section, we first report our findings for the stock market effects of different international climate negotiations. And second, we report stock market effects of two related events.

3.5.1 Reactions to international climate negotiations

Using an equally-weighted portfolio analysis, we investigate the differences between the stock price changes of a set of green and a set of brown companies for a series of climate negotiations. The analysis includes all climate negotiations from Copenhagen (COP15) to Marrakesh (COP22). We find that, despite their non-binding nature, some international climate negotiations have a small but significant effect on stock prices in the expected directions.

Table 3.2 and Figures 3.1 and 3.2 show the Average Cumulative Abnormal Returns ($\overline{CAR}$) over different event windows, along with significance results which show which of the $\overline{CAR}$ are significantly different from zero.

Table 3.2: Average Cumulative Abnormal Returns ($\overline{CAR}$) to international climate negotiations for a set of green and brown companies over a specific event window. Statistical significance is denoted at the 0.1 level by *, at 0.05 level by ** and at 0.01 level by ***, and is calculated according to the adjusted Patell t-test which in turn uses standardized versions of the abnormal returns.

Event	Date	Subset	Num. Comp.	$\overline{CAR}$ $(-1,-1)$	$\overline{CAR}$ $(-1,0)$	$\overline{CAR}$ $(-1,1)$	$\overline{CAR}$ $(-1,2)$	$\overline{CAR}$ $(-1,3)$	$\overline{CAR}$ $(-1,4)$
COP15	2009-12-18	GREEN	93	-0.0046	-0.0129	-0.0133	-0.0151	-0.0148	-0.0172
(Copenhagen)	2009-12-18	BROWN	140	-0.0013	-0.0024	-0.0042	-0.0042	-0.0036	-0.0051
COP16	2010-12-10	GREEN	115	-0.0026	0.0008	0.0024	0.0061 **	0.0082 **	0.0089 **
(Cancun)	2010-12-10	BROWN	137	-0.0003	0.0004	-0.0005	-0.0007	-0.0014	0.0013 **
COP17	2011-12-09	GREEN	116	-0.0007	0.0012	-0.0005	-0.0073**	-0.0157***	-0.0208***
(Durban)	2011-12-09	BROWN	140	-0.0005	0.0007	-0.0006	-0.0050	-0.0024	-0.0009
COP18	2012-12-07	GREEN	116	0.0026	0.0044	0.0119 ***	0.0165 ***	0.0152 ***	0.0164 ***
(Doha)	2012-12-07	BROWN	142	-0.0009	0.0015	0.0019	0.0009	0.0044	0.0028
COP19	2013-11-25	GREEN	116	-0.0021	-0.0011	-0.0025	-0.0008	-0.0015	-0.0001
(Warsaw)	2013-11-25	BROWN	142	-0.0002	-0.0001	-0.0009	-0.0006*	-0.0027**	-0.0033***
COP20	2014-12-12	GREEN	116	0.0010	0.0001	0.0016	-0.0029	-0.0108**	-0.0098
(Lima)	2014-12-12	BROWN	143	-0.0005	-0.0032	-0.0070**	-0.0092**	-0.0024	0.0017 **
COP21	2015-12-14	GREEN	116	-0.0030	-0.0028	-0.0046	-0.0018	0.0043	0.0040
(Paris)	2015-12-14	BROWN	143	0.0009	-0.0020	-0.0038	-0.0065	-0.0091**	-0.0140***
COP22	2016-11-21	GREEN	115	-0.0006	0.0005	-0.0030	-0.0043	-0.0037	-0.0060
(Marrakesh)	2016-11-21	BROWN	143	-0.0006	-0.0027	0.0009	0.0010	-0.0007	-0.0005

We compare the results with the expected effect, as reported in Table 3.1 and focus on the effects after the event (day 1 to day 4). Unlike expected, the climate negotiations in Copenhagen (COP15), which failed to establish a post-Kyoto Agreement, had no significant effect on the green or brown companies. COP16 in Cancun, where an extension of the first commitment period of the Kyoto protocol was agreed upon, had a positive effect on green companies on day 2, 3 and 4 after the event day (0.9% on day 4). COP17 in Durban, where it was decided to delay further discussions on a binding treaty until 2015, had a significantly negative effect on green companies on day 2, 3 and 4 (-2% on day 4). COP18 in Doha, where an agreement on a second commitment period of the Kyoto protocol was reached, had a positive and significant effect on green companies from day 1 to day 4 (1.6% on day 4). Unlike expected, for COP16 - COP18 we found no significant effects on brown companies (except for day 4 in Cancun).

COP19 in Warsaw, which agreed on a package to keep climate negotiations on track, had a small negative effect on brown companies on day 2, 3 and 4 (-0.3% on day 4). COP20 in Lima, which resulted in an agreement that all countries would declare their Intended Nationally Determined Contributions (INDCs) in Paris in 2015, had a mixed effect. It showed small but significant negative effects on brown companies on day 1, 2 and 4. The climate negotiations in Paris (COP21) were the first to have a significant negative effect on brown companies above 1% (-1.4% on day 4). The outcome of the climate negotiations in Marrakesh in 2016 (COP22), which lead to no surprising outcome, had no significant effect on prices of both set of companies. Unlike expected, for COP19 - COP22 we found no significant effects on green companies (except for day 3 in Lima).

The effect of the first four events (COP15-18) was small but significant for green companies and mostly insignificant for brown companies. It seems that financial markets had focused on the potential new market opportunities from an international climate deal. Starting in 2013, the effect on green companies for the four subsequent events (COP19-22) was mainly insignificant. For brown companies, however, Warsaw (COP19) and Lima (COP20), but especially the Paris Agreement (COP21) resulted in negative effects. This result indicates that the focus shifted to potential transition risks for high-carbon companies. For COP21, especially, we also see a stronger divergence between the two sets of companies.

Overall the magnitude of the effect is not higher than in previous climate negotiations, although COP21 established a landmark climate deal, which also received large news coverage. Indeed, these results are in line with the findings of Mukanjari and Sterner (2018), who find only a moderate effect of the Paris Agreement.

We performed an additional analysis, where the green and brown companies were divided into companies from developed and emerging markets. The results are reported in Appendix 3.C. Overall, the results show that the effect on companies from emerging markets (green and brown) turn out to be stronger than for developed markets, especially for green companies. We found no effects on brown companies from developed economies from COP15 (in 2009) to COP18 (in 2012). However, in 2013, this started to change. After COP19 (2013) we find very small but significant negative effects (0.26%) on these companies. COP21 (2015) for the first time shows negative cumulative abnormal returns in brown companies from developed economies above 1.5%.

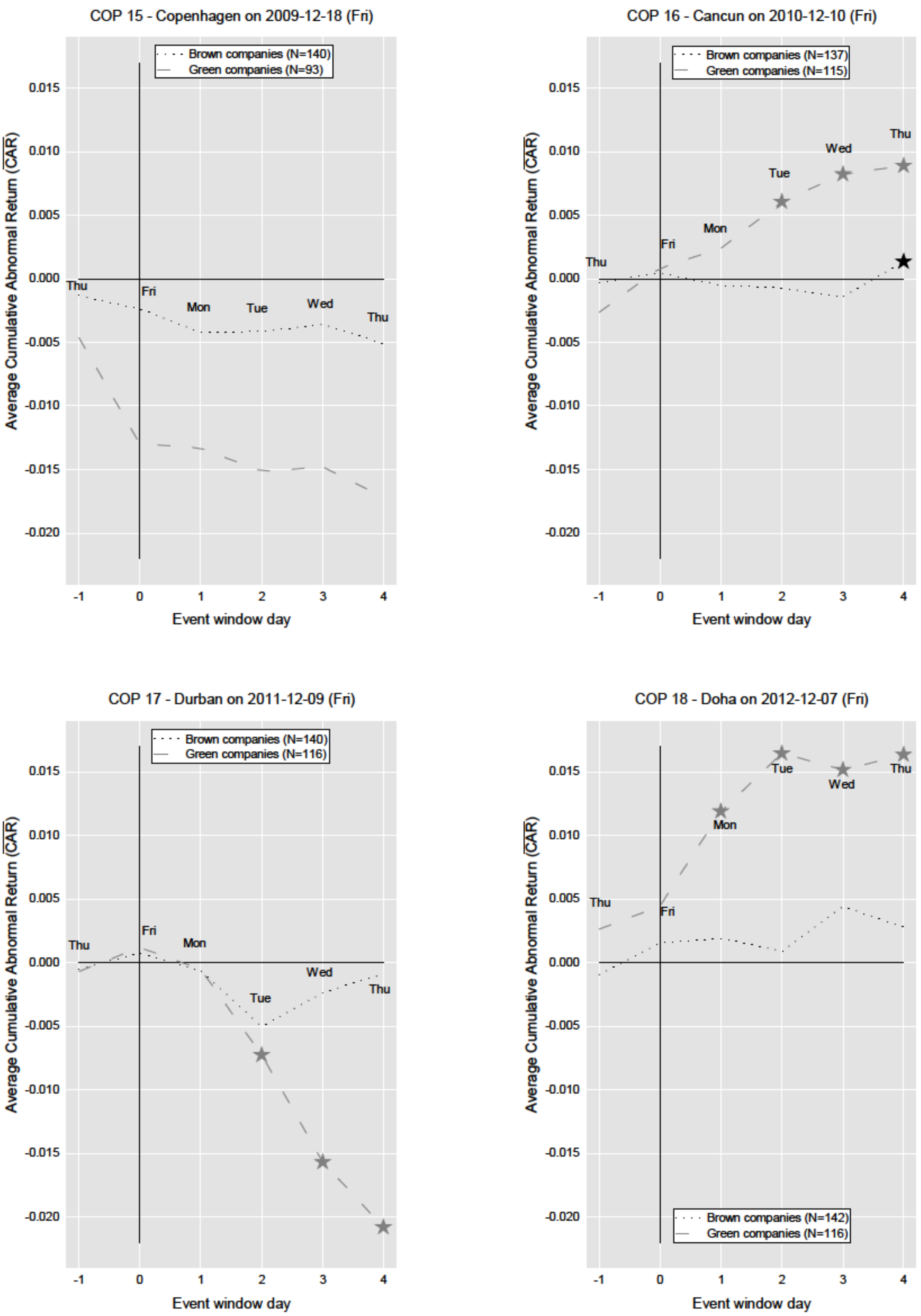

Figure 3.1: Average Cumulative Abnormal Returns ($\overline{CAR}$) for a set of green and a set of brown companies for COP15 (top right), COP16 (top left), COP17 (bottom right) and COP18 (bottom left). Statistical significance at the 0.1 level is denoted by an asterisk, and is calculated according to the adjusted Patell t-test which in turn uses standardized versions of the abnormal returns.

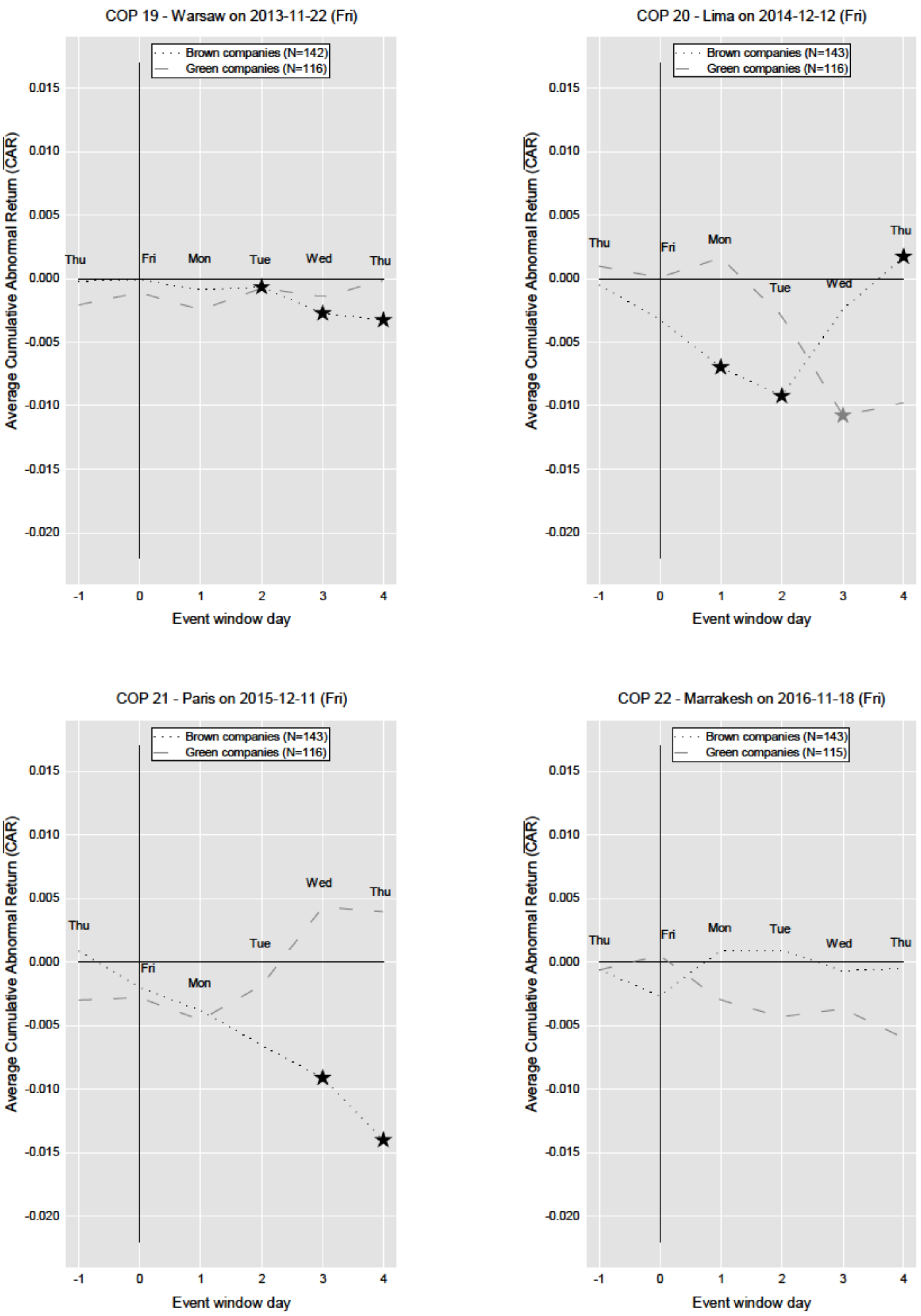

Figure 3.2: Average Cumulative Abnormal Returns ($\overline{CAR}$) of a set of green and a set of brown companies for COP19 (top right), COP20 (top left), COP21 (bottom left) and COP22 (bottom right). Statistical significance at the 0.1 level is denoted by an asterisk, and is calculated according to the adjusted Patell t-test which in turn uses standardized versions of the abnormal returns.

The stronger effect on green companies in the earlier years might be due to the fact that the market uptake of green companies is more dependent on ambitious climate policy. Furthermore, the negative effects on brown companies, especially from developed economies starting in 2013, might indicate that investors started to realize the potential losses in market demand or potential stranded assets of fossil fuel companies and became more sensitive to risks than to gains. As Griffin et al. (2015) reported, it was only in 2012 and 2013 that the financial press picked up the news that a substantial share of proven fossil fuel reserves could become stranded. An additional reason might be that the number of investors using exclusion criteria as their main responsible investment strategy is growing, especially in the EU and the US.

3.5.2 Related political events

Two related political events in the US were included in the analysis, due to their influence on international climate policy negotiations as well as the large news coverage they received. Table 3.3 and Figure 3.3 show the Average Cumulative Abnormal Returns ($\overline{CAR}$), along with significance results which show which of the $\overline{CAR}$s are different from zero.

Table 3.3: Average Cumulative Abnormal Returns ($\overline{CAR}$) for brown and green companies, during US election and the US withdrawal from the Paris Agreement (COP21). Statistical significance is denoted at the 0.1 level by *, at 0.05 level by ** and at 0.01 level by ***, and is calculated according to the adjusted Patell t-test, which uses a standardized versions of the abnormal returns.

Event	Date	Subset	Num. Comp.	$\overline{CAR}$ $(-1,-1)$	$\overline{CAR}$ $(-1,0)$	$\overline{CAR}$ $(-1,1)$	$\overline{CAR}$ $(-1,2)$	$\overline{CAR}$ $(-1,3)$	$\overline{CAR}$ $(-1,4)$
2016 US election	2016-11-08	GREEN	116	0.0005	0.0001	-0.0068**	-0.0035	-0.0021	0.0000
	2016-11-08	BROWN	143	0.0012	0.0014	0.0026	-0.0010*	-0.0033*	-0.0065***
US withdrawal from COP21	2017-06-01	GREEN	85	0.0019	0.0031*	0.0016	0.0001	0.0009	-0.0011
	2017-06-01	BROWN	143	-0.0025	-0.0031	-0.0046	-0.0065	-0.0034	-0.0080

The 2016 presidential election in the US came with a promise to revive the coal industry in the US and decreased the likelihood of more ambitious climate policy. In line with our expectations, the effect of the US presidential elections on green companies was negative at first, however returning to zero on day 4. When companies are divided into companies from developed and emerging markets (as reported in Appendix 3.C) we find that the negative effect on companies prevails for green companies from emerging economies. Contrary to our expectations, the US presidential elections had a negative and significant effects on brown companies, especially on day 4 (-0.65 %) and especially for brown companies from developed countries.

On June 1, 2017, the US president announced its intention to withdraw from the Paris Agreement. Although, according to the Paris Agreement, the withdrawal would only come into effect in 2020 at the earliest, it increases the uncertainty of the future viability of the agreement. The announcement

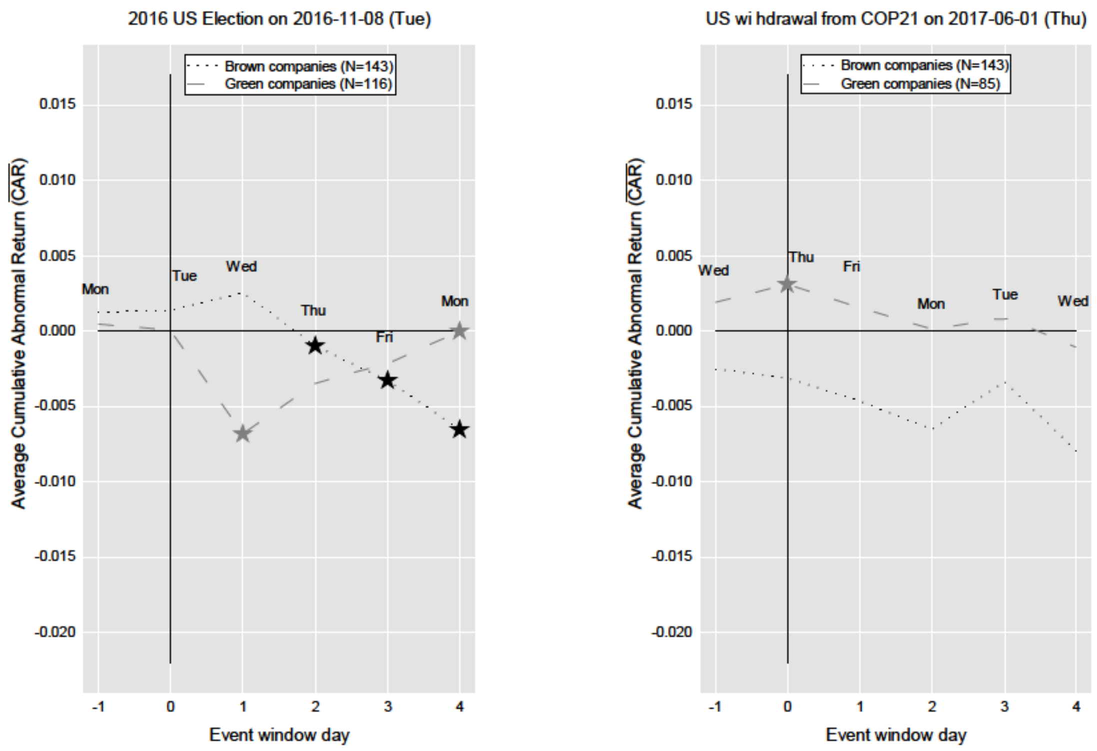

Figure 3.3: Average Cumulative Abnormal Returns ($\overline{CAR}$) of a set of green and a set of brown companies for the US election in 2016 (left) and the US withdrawal from the Paris agreement (right). Statistical significance at the 0.1 level is denoted by an asterisk, and is calculated according to the adjusted Patell t-test which in turn uses standardized versions of the abnormal returns.

had no significant effect on both sets of companies. The stock prices of the brown companies decreased (see Figure 3.3 right) but remained insignificant. This result indicates that either the withdrawal was already foreseen after the election (and therefore priced in already) or that the withdrawal was considered neither credible nor effective. This might be due to the fact that a withdrawal would only come into effect in 2020 at the earliest. However, when the green and brown companies are divided into companies from developed and emerging markets (as reported in Appendix 3.C we can find a negative effect on green and brown companies from emerging economies.

Both, the presidential election and the US withdrawal from the Paris Agreement had a stronger effect on companies from emerging economies. This indicates that companies from emerging economies are more dependent on international climate agreements. The negative effect on brown companies might be explained by the large share of non-US business of large-cap firms, coinciding with Wagner et al. (2017) who found negative effects for companies with large non-US sales (and positive effects for companies with large US-based sales), as well as with Mukanjari and Sterner (2018) who find that globally fossil fuel companies did not benefit from the US presidential elections despite the promise to revive the coal industry.

3.6 Conclusion

In this paper, we investigated the stock market effects of a series of climate negotiation at global scale, differentiating between high-carbon and low-carbon companies, in an event study.

We provide evidence that international climate negotiations can have a signaling effect on global financial markets. Results show that climate negotiations which facilitate the transition to a low-carbon economy lead to either significant positive wealth effects for green companies, with 0.9% and 1.6% abnormal returns for green companies after the post-Kyoto negotiations in Cancun and Doha respectively (but insignificant effects on brown companies), or to significant negative wealth effects for brown companies, with -1.4% of abnormal returns for brown companies after the Paris Agreement (but insignificant effects on green companies). We find that over time, financial market actors seem to have shifted from focusing on market opportunities for green companies (positive and negative effects on green companies until 2012, depending on the event) to focusing on including potential carbon risks in the valuation of brown companies (negative effects on brown companies after 2012). A possible reason might be that investors became more concerned about potential losses in market demand or potential stranded assets of fossil fuel companies, making them more sensitive to these risks than before.

However, overall the average effects are small. Although the Paris Agreement was considered a milestone in climate policy, its effect on stock markets did not reflect that to the same extent, as abnormal returns were not substantially higher than for earlier events. We conclude that investors do not seem to expect large direct impacts on cash flows. In order to become more credible, international commitments need to be complemented by (national) implementation strategies, which have predictable cashflow effects on companies.

The main implication for energy and climate policy is that the influence on cashflows of companies (and therefore their valuation) should be taken into account in the design and ex-ante evaluation of energy and climate policies. In order to reach the goal of "Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development." (UNFCCC; 2015, Article 2.1.c), energy and climate policies also need to be evaluated based on their influence on financial market decisions.

Furthermore, the event study methodology can be applied for ex-post evaluation of the effectiveness of different energy and climate policies in making finance flows consistent with the Paris Agreement. In future work, analyzing additional climate policy related events at the international level (such as the UN Climate Summit in New York or the One Planet Summit in Paris) and the national level could provide more detailed results and increase applicability in a global context. Moreover, applying the same methodology to a larger set of companies and differentiating effects by country or sector can lead to better insights into the distribution of effects. Knowing which countries and industries are most vulnerable to sudden changes in climate policy will become more relevant for financial risk analysis in the future.

Acknowledgements

We are grateful to Carlo Jaeger, Utz Weitzel and Jonas Teitge for their advice and suggestions, as well as to the participants of the 2017 "Conference on Finance and Sustainability" in Zurich and the 2018 "ISEFI" conference in Paris for useful comments. All authors acknowledge financial support from the H2020 FET project DOLFINS (grant no. 640772). Darko Aleksovski and Igor Mozetič also acknowledge support from the Slovenian Research Agency (research core funding no. P2-103).

Appendix 3.A: COP and US-related climate events in online news

To check for the importance and the interest in the climate negotiations (COPs) in online news, we performed an extensive news search. We used the NewsStream web portal Kralj Novak et al. (2015); Sluban et al. (2018) where financial news from about 200 worldwide English news and blogs sites are collected. The news acquisition started in October 2011, so we miss the first two COPs (Copenhagen and Cancun) included in the paper. We used a version of the NewsStream portal which allows for a free-text search of archived news and filtering of only environmental news. The web portal is accessible at http://simpol.ijs.si/Home/NewsSearch.

Figure 3.4 shows the results of a search query with the terms "climate accord" and "climate agreement". All the COP events are visible in the peaks of the news volume. Especially the Paris Agreement in December 2015 stands out. Moreover, the announcement of the withdrawal of the US from the Paris agreement shows 4 times the news volume as compared to the Paris Agreement itself.

Figure 3.5 shows the result of a query "COP and climate". All the COP events are visible in the peaks of the news volume. In addition, the peaks occur at the three State of the Union Addresses by president Obama, and climate protests in New York in 2014.

Figure 3.6 shows the result of a query "Trump and climate". The two peaks correspond to the results of the 2016 US presidential election and the US withdrawal from the Paris Agreement.

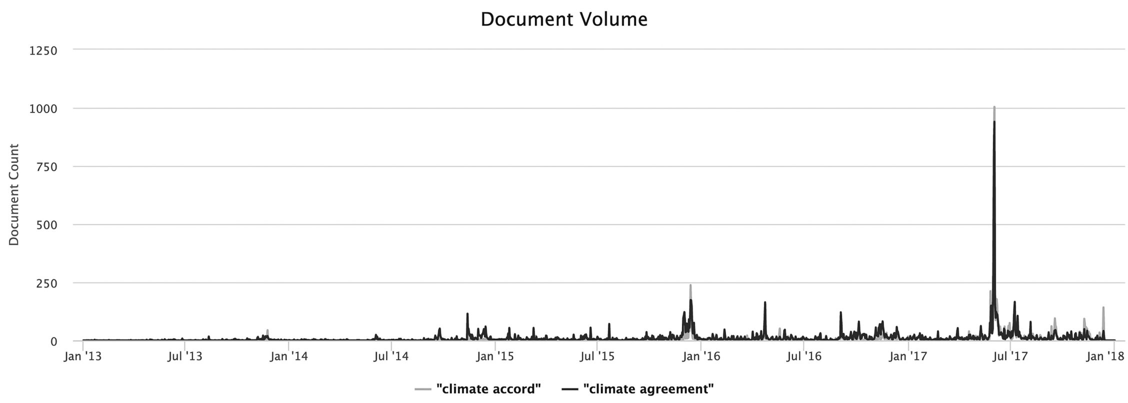

Figure 3.4: Daily volume of online news with terms "climate accord" and "climate agreement". The two largest peaks correspond to the Paris Agreement and the announcement of the withdrawal of the US from the Paris Agreement.

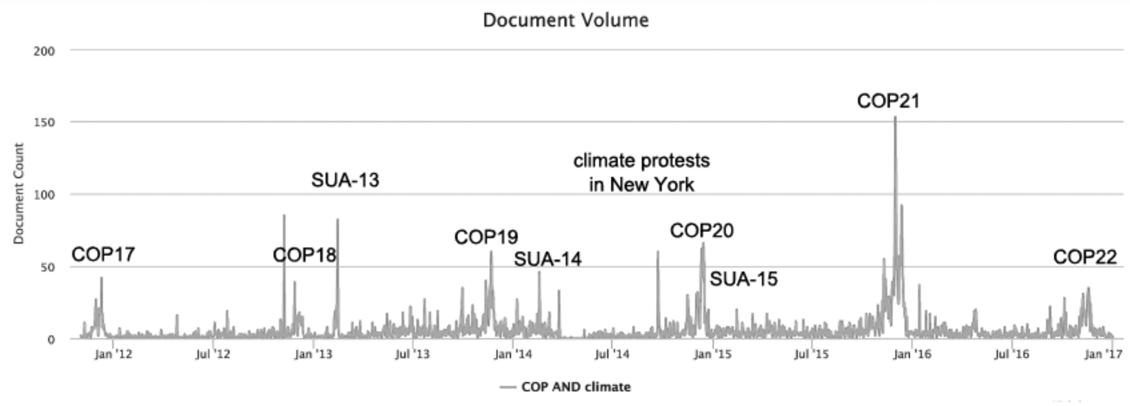

Figure 3.5: Daily volume of online news with terms "COP" and "climate". Peaks correspond to the COP conferences where COP21 (Paris) dominates. SUA labels indicate State of the Union Addresses delivered by president Obama.

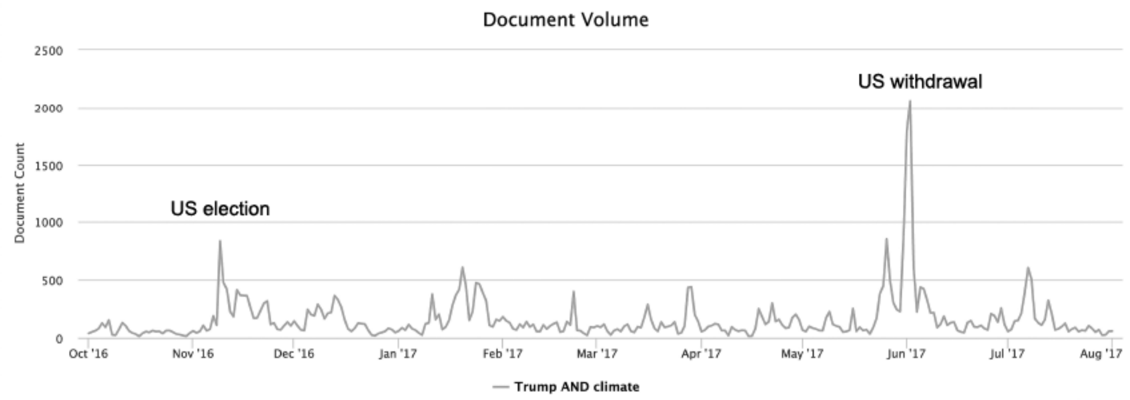

Figure 3.6: Daily volume of online news with terms "Trump" and "climate". The two peaks indicate announcements of the 2016 US presidential election results, and the US withdrawal from the Paris Agreement.

Appendix 3.B: Green and brown companies

This appendix lists the companies used in the analysis. Table 3.4 lists the set of green companies, and Table 3.5 lists the set of brown companies. For each company there is the country of its registration, the stock exchange where it is listed, whether it is considered emerging or developed economy, and its main sector.

Table 3.4: List of 187 green companies. There are 90 companies from emerging economies, and 97 companies from developed economies.

#	Company Name	Country	Stock Exch.	Emer.	Sector
1	CSR LTD	Australia	Australia	n	Materials
2	ANDRITZ AG	Austria	Vienna	n	Industrials
3	UMICORE	Belgium	Brussels	n	Materials
4	CPFL ENERGIAS RE	Brazil	SaoPaulo	y	Utilities
5	SAO MARTINHO	Brazil	SaoPaulo	y	Cons.Stap.
6	WEG SA	Brazil	SaoPaulo	y	Industrials
7	BOMBARDIER INC-B	Canada	Toronto	n	Industrials
8	BROOKFIELD RENEW	Canada	Toronto	n	Utilities
9	INNERGEX RENEWAB	Canada	Toronto	n	Utilities
10	NEW FLYER INDUST	Canada	Toronto	n	Industrials
11	TRANSALTA RENEWA	Canada	Toronto	n	Utilities
12	ARCPLUS GROUP-A	China	Shanghai	y	Materials
13	BAONENGYUAN-A	China	Shenzhen	y	Utilities
14	BEIJING JINGYU-A	China	Shanghai	y	Info.Tech.
15	BEIJING NEW BU-A	China	Shenzhen	y	Industrials
16	BEIJING SIFANG-A	China	Shanghai	y	Industrials
17	BYD CO LTD-H	China	HongKong	y	Cons.Disc.
18	CECEP WIND POW-A	China	Shanghai	y	Utilities
19	CHINA BAOAN-A	China	Shenzhen	y	Industrials
20	CHINA LONGYUAN-H	China	HongKong	y	Utilities
21	CHINA NORTHERN-A	China	Shanghai	y	Materials
22	CHINA SHIPBUIL-A GRP	China	Shanghai	y	Cons.Disc.
23	CHINA XD ELEC-A	China	Shanghai	y	Industrials
24	COFCO BIOCHEM -A	China	Shenzhen	y	Materials
25	CSG HOLDING CO-B	China	Shenzhen	y	Materials
26	DO-FLUORIDE-A	China	Shenzhen	y	Materials
27	DONGFANG ELECT-A	China	Shanghai	y	Industrials
28	EGING PHOTOVOL-A	China	Shanghai	y	Info.Tech.

Continued on next page

Table 3.4 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
29	FAR EAST SMART-A	China	Shanghai	y	Industrials
30	FOSHAN ELEC-B	China	Shenzhen	y	Industrials
31	GUANGDONG CHAN-A	China	Shenzhen	y	Cons.Disc.
32	GUANGDONG EAST-A	China	Shenzhen	y	Info.Tech.
33	HANGZHOU FIRST-A	China	Shanghai	y	Info.Tech.
34	HAREON SOLAR T-A	China	Shanghai	y	Info.Tech.
35	HENGDIAN DMEGC-A	China	Shenzhen	y	Info.Tech.
36	HONGFA TECHNOL-A	China	Shanghai	y	Industrials
37	HUANENG RENEWA-H	China	HongKong	y	Utilities
38	HUAYI ELECTRIC-A	China	Shanghai	y	Industrials
39	HUNAN CORUN NE-A	China	Shanghai	y	Industrials
40	JIANGSU SUNRAI-A	China	Shanghai	y	Industrials
41	KAIDI ECOLOGIC-A	China	Shenzhen	y	Utilities
42	NARI TECHNOLOG-A	China	Shanghai	y	Industrials
43	NINGBO SANXING-A	China	Shanghai	y	Industrials
44	QINGDAO TGOOD-A	China	Shenzhen	y	Industrials
45	RISEN ENERGY-A	China	Shenzhen	y	Info.Tech.
46	RONGXIN POWER -A	China	Shenzhen	y	Industrials
47	SANAN OPTOELEC-A	China	Shanghai	y	Info.Tech.
48	SHANGHAI AEROS-A	China	Shanghai	y	Info.Tech.
49	SHENZHEN CLOU-A	China	Shenzhen	y	Industrials
50	SHENZHEN DESAY-A	China	Shenzhen	y	Industrials
51	SHENZHEN HEMEI-A	China	Shenzhen	y	Info.Tech.
52	SHENZHEN JIAWE-A	China	Shenzhen	y	Info.Tech.
53	SHENZHEN KAIFA-A	China	Shenzhen	y	Info.Tech.
54	SIEYUAN ELECTR-A	China	Shenzhen	y	Industrials
55	SINOVEL WIND-A	China	Shanghai	y	Industrials
56	SUNGROW POWER -A	China	Shenzhen	y	Industrials
57	SUZHOU DONGSHA-A	China	Shenzhen	y	Industrials
58	TBEA CO LTD-A	China	Shanghai	y	Industrials
59	TELLHOW SCI-TE-A	China	Shanghai	y	Industrials
60	TITAN WIND-A	China	Shenzhen	y	Industrials
61	TONGYU HEAVY-A	China	Shenzhen	y	Industrials
62	XIAN LONGI SIL-A	China	Shanghai	y	Info.Tech.
63	XIANGTAN ELEC-A	China	Shanghai	y	Industrials
64	XINJIANG GOLD-A	China	Shenzhen	y	Industrials

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Table 3.4 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
65	XJ ELECTRIC-A	China	Shenzhen	y	Industrials
66	ZHEJIANG CHINT-A	China	Shanghai	y	Industrials
67	ZHEJIANG DUN'A-A	China	Shenzhen	y	Industrials
68	ZHEJIANG NARAD-A	China	Shenzhen	y	Industrials
69	ZHEJIANG YANKO-A	China	Shanghai	y	Industrials
70	ZHONGLI SCIENC-A	China	Shenzhen	y	Industrials
71	ZHONGTIAN TECH-A	China	Shanghai	y	Industrials
72	ZHONGTONG BUS-A	China	Shenzhen	y	Industrials
73	ZHUZHOU KIBING-A	China	Shanghai	y	Industrials
74	NOVOZYMES-B SHS	Denmark	Copenhagen	n	Materials
75	ROCKWOOL INTL-B	Denmark	Copenhagen	n	Industrials
76	VESTAS WIND SYST	Denmark	Copenhagen	n	Industrials
77	VALMET OYJ	Finland	Helsinki	n	Industrials
78	SCHNEIDER ELECTR	France	Paris	n	Industrials
79	HELLA KGAA HUECK	Germany	Xetra	n	Cons.Disc.
80	INFINEON TECH	Germany	Xetra	n	Info.Tech.
81	NORDEX SE	Germany	Xetra	n	Industrials
82	OSRAM LICHT AG	Germany	Xetra	n	Industrials
83	SIEMENS AG-REG	Germany	Xetra	n	Industrials
84	SMA SOLAR TECHNO	Germany	Xetra	n	Info.Tech.
85	SUEDZUCKER AG	Germany	Xetra	n	Cons.Stap.
86	WACKER CHEMIE AG	Germany	Xetra	n	Materials
87	ATLANTICA YIELD	UK	NASDAQ	n	Utilities
88	DIALOG SEMICOND	UK	Xetra	n	Info.Tech.
89	CHINA AGRI-INDUS	Hong Kong	HongKong	y	Cons.Stap.
90	CHINA EVERBR INT	Hong Kong	HongKong	y	Industrials
91	CHINA HIGH-SPEED	Hong Kong	HongKong	y	Industrials
92	GCL-POLY ENERGY	Hong Kong	HongKong	y	Info.Tech.
93	XINYI GLASS	Hong Kong	HongKong	y	Cons.Disc.
94	XINYI SOLAR HLDS	Hong Kong	HongKong	y	Info.Tech.
95	BHARAT HEAVY ELE	India	India	y	Industrials
96	EXIDE INDUS LTD	India	India	y	Cons.Disc.
97	HAVELLS INDIA	India	India	y	Industrials
98	IDFC LTD	India	India	y	Financials
99	SUZLON ENERGY	India	India	y	Industrials
100	TATA CHEMICALS	India	India	y	Materials

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Table 3.4 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
101	THERMAX LTD	India	India	y	Industrials
102	EATON CORP PLC	Ireland	NewYork	n	Industrials
103	KINGSPAN GROUP	Ireland	London	n	Industrials
104	PRYSMIAN SPA	Italy	Italy	n	Industrials
105	AZBIL CORP	Japan	Tokyo	n	Info.Tech.
106	DIC CORP	Japan	Tokyo	n	Materials
107	EBARA CORP	Japan	Tokyo	n	Industrials
108	GS YUASA CORP	Japan	Tokyo	n	Industrials
109	HITACHI CAPITAL	Japan	Tokyo	n	Financials
110	HITACHI HIGH TEC	Japan	Tokyo	n	Info.Tech.
111	KINDEN CORP	Japan	Tokyo	n	Industrials
112	KYOCERA CORP	Japan	Tokyo	n	Info.Tech.
113	KYOWA EXEO CORP	Japan	Tokyo	n	Industrials
114	NIDEC CORP	Japan	Tokyo	n	Industrials
115	NISSIN ELECTRIC	Japan	Tokyo	n	Industrials
116	PANASONIC CORP	Japan	Tokyo	n	Cons.Disc.
117	ROHM CO LTD	Japan	Tokyo	n	Info.Tech.
118	SHARP CORP	Japan	Tokyo	n	Cons.Disc.
119	SHIN-ETSU CHEM	Japan	Tokyo	n	Materials
120	STANLEY ELEC CO	Japan	Tokyo	n	Cons.Disc.
121	SUMCO CORP	Japan	Tokyo	n	Info.Tech.
122	SUMITOMO FOREST	Japan	Tokyo	n	Cons.Disc.
123	TOKUYAMA CORP	Japan	Tokyo	n	Materials
124	TOYOTA MOTOR	Japan	Tokyo	n	Cons.Disc.
125	DOOSAN HEAVY	Korea	Korea	y	Industrials
126	HANWHA CHEM CORP	Korea	Korea	y	Materials
127	HYOSUNG CORP	Korea	Korea	y	Materials
128	LS CORP	Korea	Korea	y	Industrials
129	OCI CO LTD	Korea	Korea	y	Materials
130	SAMSUNG SDI CO	Korea	Korea	y	Info.Tech.
131	ARCADIS NV	Netherlands	Amsterdam	n	Industrials
132	ASM INTL NV	Netherlands	Amsterdam	n	Info.Tech.
133	KONINKLIJKE PHIL	Netherlands	Amsterdam	n	Industrials
134	NXP SEMICONDUCTO	Netherlands	NASDAQ	n	Info.Tech.
135	EDP RENOVAVEIS S	Spain	Lisbon	n	Utilities
136	GAMESA	Spain	Spain	n	Industrials

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Table 3.4 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
137	JM AB	Sweden	Stockholm	n	Cons.Disc.
138	NIBE INDUSTRIE-B	Sweden	Stockholm	n	Industrials
139	SVENSKA CELL-B	Sweden	Stockholm	n	Cons.Stap.
140	SWECO AB-B	Sweden	Stockholm	n	Industrials
141	ABB LTD-REG	Switzerland	Stockholm	n	Industrials
142	OC OERLIKON CORP	Switzerland	Zurich	n	Industrials
143	SCHWEITER TEC-BR	Switzerland	Zurich	n	Industrials
144	TE CONNECTIVITY	Switzerland	NewYork	n	Info.Tech.
145	DELTA ELECT INC	Taiwan	Taiwan	y	Info.Tech.
146	SIMPLO TECHNOLOG	Taiwan	Taiwan	y	Info.Tech.
147	TECO ELEC & MACH	Taiwan	Taiwan	y	Industrials
148	DELTA ELEC THAI	Thailand	Bangkok	y	Info.Tech.
149	ENERGY ABSOLUTE	Thailand	Bangkok	y	Energy
150	TOFAS	Turkey	Istanbul	y	Cons.Disc.
151	ACUITY BRANDS	USA	NewYork	n	Industrials
152	ANALOG DEVICES	USA	NASDAQ	n	Info.Tech.
153	ANDERSONS INC	USA	NASDAQ	n	Cons.Stap.
154	APOGEE ENTERPR	USA	NASDAQ	n	Industrials
155	APPLIED MATERIAL	USA	NASDAQ	n	Info.Tech.
156	BORGWARNER INC	USA	NewYork	n	Cons.Disc.
157	COMFORT SYSTEMS	USA	NewYork	n	Industrials
158	COVANTA HOLDING	USA	NewYork	n	Industrials
159	CREE INC	USA	NASDAQ	n	Info.Tech.
160	EMCOR GROUP INC	USA	NewYork	n	Industrials
161	EMERSON ELEC CO	USA	NewYork	n	Industrials
162	ESCO TECH INC	USA	NewYork	n	Industrials
163	FIRST SOLAR INC	USA	NASDAQ	n	Info.Tech.
164	GENTHERM INC	USA	NASDAQ	n	Cons.Disc.
165	GIBRALTAR INDUST	USA	NASDAQ	n	Industrials
166	HANWHA Q CEL-ADR	USA	NASDAQ	n	Info.Tech.
167	HEXCEL CORP	USA	NewYork	n	Industrials
168	ITRON INC	USA	NASDAQ	n	Info.Tech.
169	JOHNSON CONTROLS	USA	NewYork	n	Cons.Disc.
170	MONOLITHIC POWER	USA	NASDAQ	n	Info.Tech.
171	NEXTERA ENERGY P	USA	NewYork	n	Utilities
172	ORMAT TECHNOLOGI	USA	NewYork	n	Utilities

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Table 3.4 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
173	OWENS CORNING	USA	NewYork	n	Industrials
174	PATTERN ENER	USA	NASDAQ	n	Utilities
175	PERKINELMER INC	USA	NewYork	n	Health Care
176	QUANTA SERVICES	USA	NewYork	n	Industrials
177	REGAL BELOIT COR	USA	NewYork	n	Industrials
178	REPUBLIC SVCS	USA	NewYork	n	Industrials
179	SMITH (A.O.)CORP	USA	NewYork	n	Industrials
180	SUNPOWER CORP	USA	NASDAQ	n	Info.Tech.
181	TERRAFORM POWE-A	USA	NASDAQ	n	Utilities
182	TESLA MOTORS	USA	NASDAQ	n	Cons.Disc.
183	TETRA TECH INC	USA	NASDAQ	n	Industrials
184	TIMKEN CO	USA	NewYork	n	Industrials
185	TRIMBLE NAVIG	USA	NASDAQ	n	Info.Tech.
186	UNIVERSAL DISPLA	USA	NASDAQ	n	Info.Tech.
187	WOODWARD INC	USA	NASDAQ	n	Industrials

Table 3.5: List of 186 brown companies. There are 24 companies from emerging economies, and 162 companies from developed economies.

#	Company Name	Country	Stock Exch.	Emer.	Sector
1	Wesfarmers	Australia	Australia	n	Cons.Stap.
2	Woodside Petroleum	Australia	Australia	n	Energy
3	Woolworths Ltd	Australia	Australia	n	Cons.Stap.
4	Ambev Cia de Beb. das Am.	Brazil	SaoPaulo	y	Cons.Stap.
5	Petroleo Brasil. SA Petrobras	Brazil	SaoPaulo	y	Energy
6	Vale	Brazil	SaoPaulo	y	Materials
7	Barrick Gold Corp	Canada	Toronto	n	Materials
8	Canadian National Railway	Canada	Toronto	n	Industrials
9	Canadian Natural Res. Ltd	Canada	Toronto	n	Energy
10	Cenovus Energy	Canada	Toronto	n	Energy
11	Enbridge	Canada	Toronto	n	Energy
12	Goldcorp	Canada	Toronto	n	Materials
13	Husky Energy	Canada	Toronto	n	Energy
14	Imperial Oil	Canada	Toronto	n	Energy
15	Manulife Financial Corp	Canada	Toronto	n	Financials

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Table 3.5 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
16	Potash Corp of Saskatchewan	Canada	Toronto	n	Materials
17	Suncor Energy	Canada	Toronto	n	Energy
18	Teck Resources Ltd	Canada	Toronto	n	Materials
19	TransCanada Corp	Canada	Toronto	n	Energy
20	Air Liquide	France	Paris	n	Materials
21	Carrefour	France	Paris	n	Cons.Stap.
22	Danone	France	Paris	n	Cons.Stap.
23	EDF	France	Paris	n	Utilities
24	GDF Suez	France	Paris	n	Utilities
25	Orange	France	Paris	n	Telecom.
26	Pernod Ricard	France	Paris	n	Cons.Stap.
27	Saint-Gobain	France	Paris	n	Industrials
28	SANOFI	France	Paris	n	Health Care
29	Total	France	Paris	n	Energy
30	Vinci	France	Paris	n	Industrials
31	BASF SE	Germany	Xetra	n	Materials
32	Bayer AG	Germany	Xetra	n	Health Care
33	BMW AG	Germany	Xetra	n	Cons.Disc.
34	Continental AG	Germany	Xetra	n	Cons.Disc.
35	Daimler AG	Germany	Xetra	n	Cons.Disc.
36	Deutsche Post AG	Germany	Xetra	n	Industrials
37	Deutsche Telekom AG	Germany	Xetra	n	Telecom.
38	E.ON SE	Germany	Xetra	n	Utilities
39	Linde AG	Germany	Xetra	n	Materials
40	RWE AG	Germany	Xetra	n	Utilities
41	SAP AG	Germany	Xetra	n	Info.Tech.
42	Volkswagen AG	Germany	Xetra	n	Cons.Disc.
43	CLP Holdings Ltd	Hong Kong	HongKong	y	Utilities
44	Power Assets Holdings Ltd	Hong Kong	HongKong	y	Utilities
45	ITC Ltd	India	India	y	Cons.Stap.
46	Larsen Toubro	India	India	y	Industrials
47	ENEL SpA	Italy	Italy	n	Utilities
48	Eni SpA	Italy	Italy	n	Energy
49	Canon	Japan	Tokyo	n	Info.Tech.
50	Honda Motor	Japan	Tokyo	n	Cons.Disc.
51	Inpex Corp	Japan	Tokyo	n	Energy

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Table 3.5 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
52	Mitsubishi Electric Corp	Japan	Tokyo	n	Info.Tech.
53	Nippon Telegraph/phone Corp	Japan	Tokyo	n	Telecom.
54	Nissan Motor	Japan	Tokyo	n	Cons.Disc.
55	Seven I Holdings	Japan	Tokyo	n	Cons.Stap.
56	Shin-Etsu Chemical	Japan	Tokyo	n	Materials
57	Takeda Pharmaceutical Ltd	Japan	Tokyo	n	Health Care
58	Arcelor Mittal	Luxembourg	Amsterdam	n	Materials
59	Fresnillo Plc	Mexico	Mexico	y	Materials
60	Industrias Penoles	Mexico	Mexico	y	Materials
61	Wal Mart de Mexico	Mexico	Mexico	y	Cons.Stap.
62	Airbus Group	Netherlands	Paris	n	Industrials
63	Heineken NV	Netherlands	Amsterdam	n	Cons.Stap.
64	Royal Dutch Shell	Netherlands	Amsterdam	n	Energy
65	Royal Philips	Netherlands	Amsterdam	n	Cons.Disc.
66	Statoil ASA	Norway	NewYork	n	Energy
67	Telenor Group	Norway	Norway	n	Telecom.
68	Gazprom OAO	Russia	Moscow	y	Energy
69	Novatek	Russia	Moscow	y	Energy
70	Kumba Iron Ore	South Africa	SouthAfrica	y	Materials
71	MTN Group	South Africa	SouthAfrica	y	Telecom.
72	Sasol Ltd	South Africa	SouthAfrica	y	Energy
73	Hyundai Motor	South Korea	Korea	y	Cons.Disc.
74	Korea Electric Power Corp	South Korea	Korea	y	Utilities
75	LG Chem	South Korea	Korea	y	Materials
76	POSCO	South Korea	Korea	y	Materials
77	Samsung Electronics	South Korea	Korea	y	Info.Tech.
78	Endesa	Spain	Spain	n	Utilities
79	Gas Natural SDG SA	Spain	Spain	n	Utilities
80	Iberdrola SA	Spain	Spain	n	Utilities
81	Repsol	Spain	Spain	n	Energy
82	Holcim Ltd	Switzerland	Switzerland	n	Materials
83	Nestle	Switzerland	Switzerland	n	Cons.Stap.
84	Novartis	Switzerland	Switzerland	n	Health Care
85	Roche Holding AG	Switzerland	Switzerland	n	Health Care
86	Syngenta Intl AG	Switzerland	NewYork	n	Materials
87	Taiwan Semiconductor Manuf.	Taiwan	Taiwan	y	Info.Tech.

Continued on next page

Table 3.5 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
88	Teva Pharma. Industries Ltd	Israel	TelAviv	y	Health Care
89	PTT	Thailand	Bangkok	y	Energy
90	PTT Explor. Prod. Pub. Co	Thailand	Bangkok	y	Energy
91	Anglo American	UK	London	n	Materials
92	Antofagasta	UK	London	n	Materials
93	Associated British Foods	UK	London	n	Cons.Stap.
94	AstraZeneca	UK	London	n	Health Care
95	BAE Systems	UK	London	n	Industrials
96	BHP Billiton	UK	London	n	Materials
97	BP	UK	London	n	Energy
98	British American Tobacco	UK	London	n	Cons.Stap.
99	BT Group	UK	London	n	Telecom.
100	Carnival Corp	UK	London	n	Cons.Disc.
101	Centrica	UK	London	n	Utilities
102	Diageo Plc	UK	London	n	Cons.Stap.
103	GlaxoSmithKline	UK	London	n	Health Care
104	National Grid	UK	London	n	Utilities
105	Rio Tinto	UK	London	n	Materials
106	Rolls-Royce	UK	London	n	Industrials
107	SSE	UK	London	n	Utilities
108	Tesco	UK	London	n	Cons.Stap.
109	Tullow Oil	UK	London	n	Energy
110	Unilever Plc	UK	London	n	Cons.Stap.
111	Vodafone Group	UK	London	n	Telecom.
112	3M	USA	NewYork	n	Industrials
113	Abbott Laboratories	USA	NewYork	n	Health Care
114	Air Products Chemicals	USA	NewYork	n	Materials
115	Altria Group	USA	NewYork	n	Cons.Stap.
116	American Electric Power	USA	NewYork	n	Utilities
117	Anadarko Petroleum Corp	USA	NewYork	n	Energy
118	Apache Corp	USA	NewYork	n	Energy
119	AT&T	USA	NewYork	n	Telecom.
120	Baker Hughes Inc	USA	NewYork	n	Energy
121	Baxter Intl	USA	NewYork	n	Health Care
122	Boeing	USA	NewYork	n	Industrials
123	Bristol-Myers Squibb	USA	NewYork	n	Health Care

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Table 3.5 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
124	CenturyLink	USA	NewYork	n	Telecom.
125	Chevron Corp	USA	NewYork	n	Energy
126	Colgate Palmolive	USA	NewYork	n	Cons.Stap.
127	ConocoPhillips	USA	NewYork	n	Energy
128	Corning Inc	USA	NewYork	n	Info.Tech.
129	Costco Wholesale Corp	USA	NASDAQ	n	Cons.Stap.
130	CSX Corp	USA	NASDAQ	n	Industrials
131	Cummins	USA	NewYork	n	Industrials
132	CVS Caremark Corp	USA	NewYork	n	Cons.Stap.
133	Deere & Co	USA	NewYork	n	Industrials
134	Devon Energy Corp	USA	NewYork	n	Energy
135	Dow Chemical	USA	NewYork	n	Materials
136	Duke Energy Corp	USA	NewYork	n	Utilities
137	Ecolab	USA	NewYork	n	Materials
138	EI du Pont de Nemours	USA	NewYork	n	Materials
139	Eli Lilly & Co	USA	NewYork	n	Health Care
140	Exelon Corp	USA	NewYork	n	Utilities
141	Exxon Mobil Corp	USA	NewYork	n	Energy
142	FedEx Corp	USA	NewYork	n	Industrials
143	Ford Motor	USA	NewYork	n	Cons.Disc.
144	Freeport-McMoRan Cop/Gold	USA	NewYork	n	Materials
145	General Electric	USA	NewYork	n	Industrials
146	General Mills	USA	NewYork	n	Cons.Stap.
147	General Motors	USA	NewYork	n	Cons.Disc.
148	Halliburton	USA	NewYork	n	Energy
149	Hess Corp	USA	NewYork	n	Energy
150	Hewlett-Packard	USA	NewYork	n	Info.Tech.
151	Honeywell Intl	USA	NewYork	n	Industrials
152	Intel Corp	USA	NASDAQ	n	Info.Tech.
153	IBM	USA	NewYork	n	Info.Tech.
154	Johnson & Johnson	USA	NewYork	n	Health Care
155	Kellogg	USA	NewYork	n	Cons.Stap.
156	Kimberly-Clark Corp	USA	NewYork	n	Cons.Stap.
157	Las Vegas Sands Corp	USA	NewYork	n	Cons.Disc.
158	Lockheed Martin Corp	USA	NewYork	n	Industrials
159	Lowe	USA	NewYork	n	Cons.Disc.

Continued on next page

Table 3.5 – continued from previous page

#	Company Name	Country	Stock Exch.	Emer.	Sector
160	Merck & Co	USA	NewYork	n	Health Care
161	Mondelez Intl Inc	USA	NASDAQ	n	Cons.Stap.
162	Monsanto	USA	NewYork	n	Materials
163	Newmont Mining Corp	USA	NewYork	n	Materials
164	Noble Energy	USA	NewYork	n	Energy
165	Norfolk Southern Corp	USA	NewYork	n	Industrials
166	Occidental Petroleum Corp	USA	NewYork	n	Energy
167	PepsiCo	USA	NewYork	n	Cons.Stap.
168	Pfizer	USA	NewYork	n	Health Care
169	Philip Morris Intl	USA	NewYork	n	Cons.Stap.
170	PPG Industries	USA	NewYork	n	Materials
171	Praxair	USA	NewYork	n	Materials
172	Procter Gamble	USA	NewYork	n	Cons.Stap.
173	Schlumberger Ltd	USA	NewYork	n	Energy
174	Starbucks Corp	USA	NASDAQ	n	Cons.Disc.
175	Sysco Corp	USA	NewYork	n	Cons.Stap.
176	Target Corp	USA	NewYork	n	Cons.Disc.
177	Texas Instruments Inc	USA	NASDAQ	n	Info.Tech.
178	Coca-Cola	USA	NewYork	n	Cons.Stap.
179	The Home Depot	USA	NewYork	n	Cons.Disc.
180	Union Pacific Corp	USA	NewYork	n	Industrials
181	United Technologies Corp	USA	NewYork	n	Industrials
182	UPS	USA	NewYork	n	Industrials
183	Verizon Communications	USA	NewYork	n	Telecom.
184	Wal-Mart Stores	USA	NewYork	n	Cons.Stap.
185	Walt Disney	USA	NewYork	n	Cons.Disc.
186	Yum! Brands	USA	NewYork	n	Cons.Disc.

Appendix 3.C: Results for emerging and developed economies

For the same COP and political events, we investigated differences between companies that are located either in emerging or developed economies. Details on the locations of companies (emerging or developed markets) are in Appendix 3.B.

The results are similar to the results reported in Section 3.5 and can be found in Figures 3.7, 3.8 and 3.9. However, some differences in effects are worth taking into account. The climate negotiations in Cancun (COP16) showed positive effects on green companies from developed countries, while Durban (COP17) showed negative effects on green companies from developed economies, as well as on green and brown companies from emerging markets. After the Doha climate negotiations (COP18), we find positive effects on green companies from emerging and developed economies from day 1 to day 4 after the event. Furthermore, we find positive effects on brown companies from emerging economies on day 3 and 4 after the event. After the climate negotiations in Warsaw (COP19), we find negative effects on brown companies from emerging economies from day 1 to day 4 and negative effects on brown companies from developed economies on day 3 and 4. In Lima (COP20), we find mixed results, on day 1 negative effects on brown companies from emerging and developed companies, which returned to zero on the subsequent days. For green companies from emerging economies we find positive effects on green companies from emerging economies on day 1, however turning negative on day 3. The Paris agreement (COP21) showed negative effects on the brown companies from developed countries on day 2, 3 and 4 and insignificant effects on the other groups of companies. The climate negotiations in Marrakesh (COP22) showed significant price decreases for green companies from emerging markets and increases for brown companies from emerging markets.

For the 2016 US presidential election, we found significantly negative effects for green companies from emerging economies from day 1 until day 4. Furthermore, brown companies from developed economies show significantly negative stock price effects on day 2 to day 4. The US withdrawal from the Paris agreement, on the other hand, had significant negative effects on companies from emerging markets (brown and green).

This indicates that emerging economies were expected to lose from the withdrawal, possibly due to a fear that the US will try to become more energy independent and that imports from abroad (e.g. China, the largest country group within the green companies) might become subject to higher taxes.

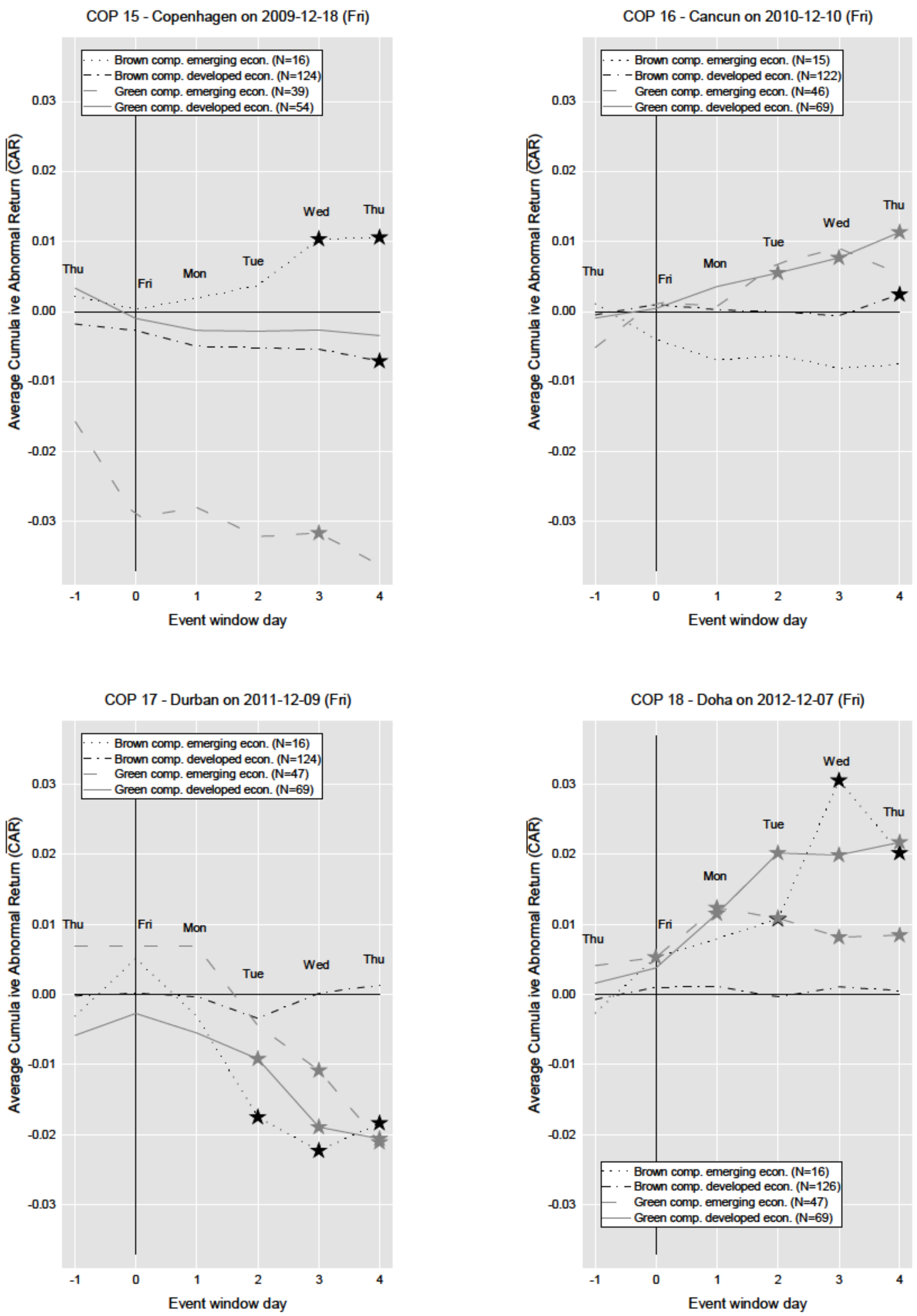


Figure 3.7: Average Cumulative Abnormal Returns ($\overline{CAR}$) for a set of green and a set of brown companies from emerging markets and developed markets for COP15 (top right), COP16 (top left), COP17 (bottom right) and COP18 (bottom left). Statistical significance at the 0.1 level is denoted by an asterisk, and is calculated according to the adjusted Patell t-test which in turn uses standardized versions of the abnormal returns.

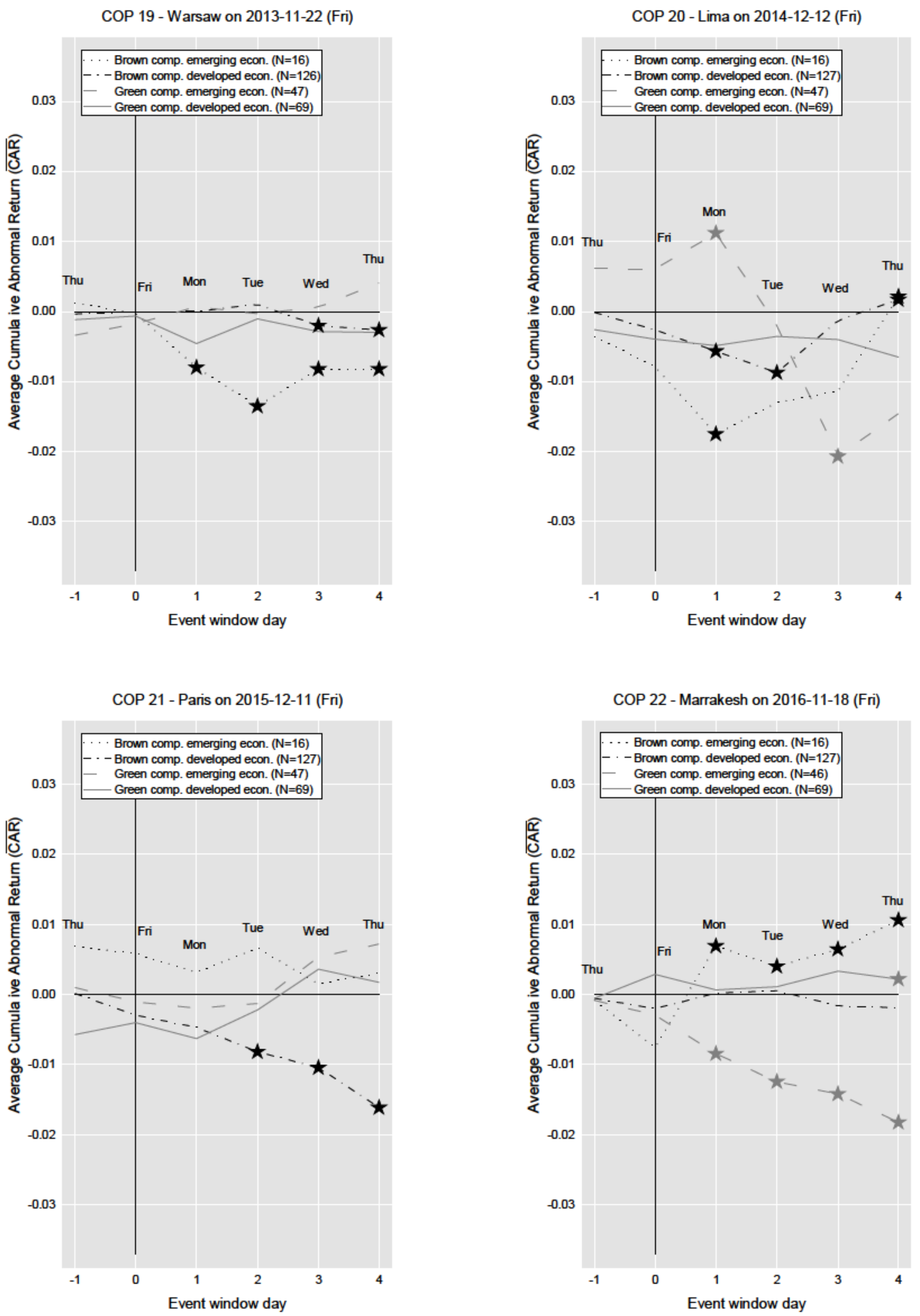
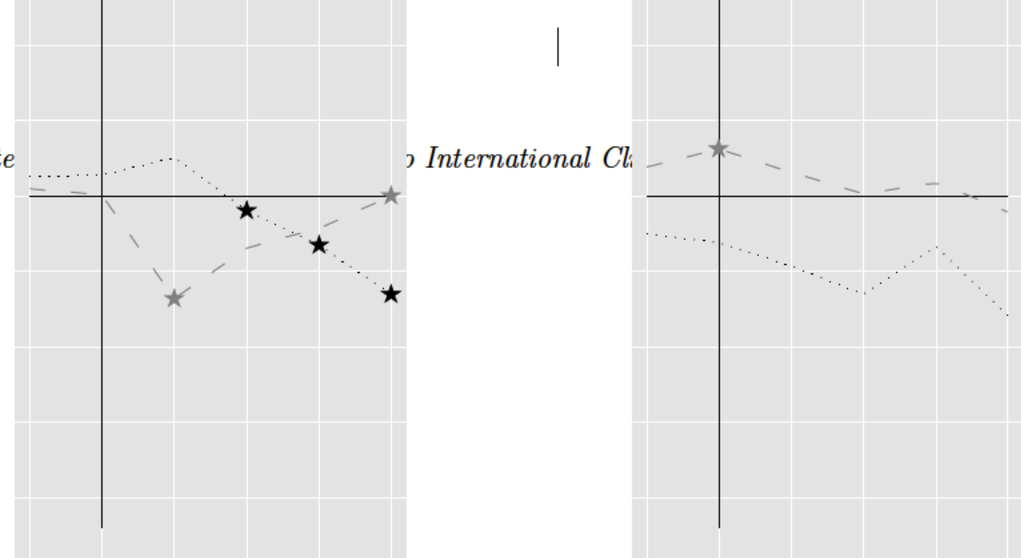


Figure 3.8: Average Cumulative Abnormal Returns ($\overline{CAR}$) of a set of green and a set of brown companies from emerging markets and developed markets for COP19 (top right), COP20 (top left), COP21 (bottom left) and COP22 (bottom right). Statistical significance at the 0.1 level is denoted by an asterisk, and is calculated according to the adjusted Patell t-test which in turn uses standardized versions of the abnormal returns.



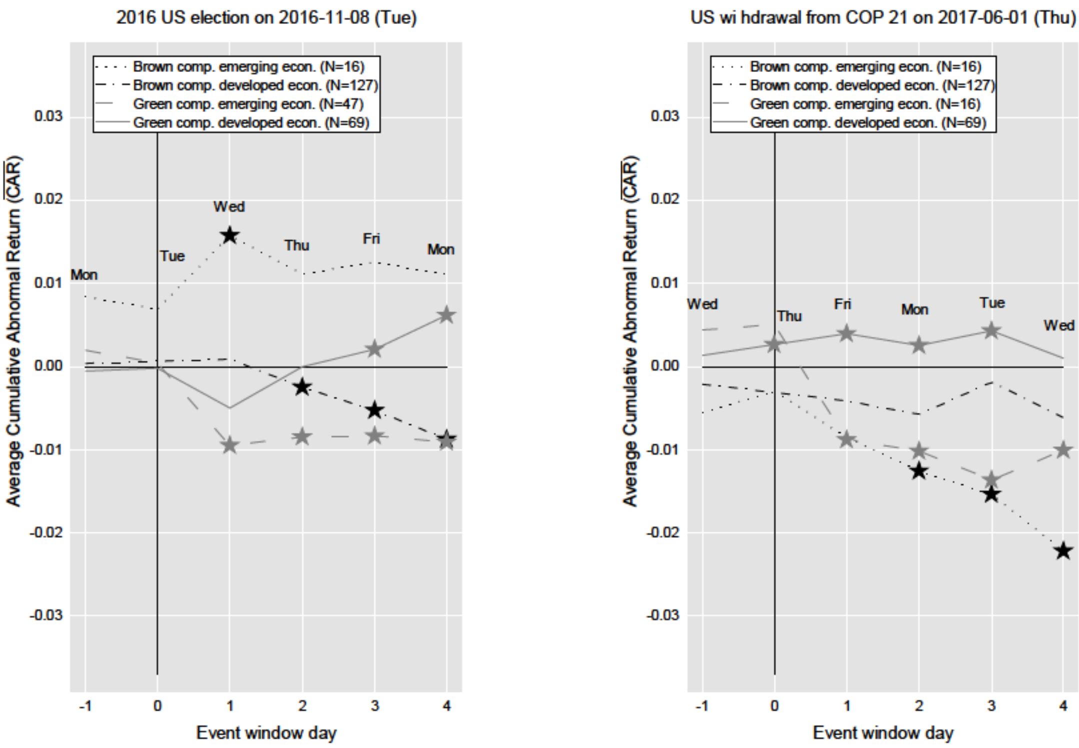


Figure 3.9: Average Cumulative Abnormal Returns ($\overline{CAR}$) of a set of green and a set of brown companies from emerging markets and developed markets for the US election in 2016 (left) and the US withdrawal from the Paris Agreement (right). Statistical significance at the 0.1 level is denoted by an asterisk, and is calculated according to the adjusted Patell t-test which in turn uses standardized versions of the abnormal returns.

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Chapter 4

A Climate Stress-Test of the Financial System*

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Abstract

The urgency of estimating the impact of climate risks on the financial system is increasingly recognised among scholars and practitioners. By adopting a network approach to financial dependencies, we look at how climate policy risk might propagate through the financial system. We develop a network-based climate stress-test methodology and apply it to large Euro Area banks in a "green" and a "brown" scenario. We find that direct and indirect exposures to climate-policy relevant sectors represent a large portion of investors' equity portfolios, especially for investment and pension funds. Additionally, the portion of banks' loan portfolios exposed to these sectors is comparable to banks' capital. Our results suggest that climate policy timing matters. An early and stable policy framework would allow for smooth asset value adjustments and lead to potential net winners and losers. In contrast, a late and abrupt policy framework could have adverse systemic consequences.

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4.1 Introduction

Assessing the impact of climate risks and climate policies on the financial system is currently seen as one of the most urgent and prominent policy issues (Carney; 2015; ESRB Advisory Scientific Committee; 2016). In particular, there is a debate on whether the implementation of climate policies to meet the 2°C target generates systemic risk or, instead, opportunities for low-carbon investments and economic growth. However, data are scarce and there is no consensus on the appropriate methodologies to use to adress this issue. The magnitude of so-called stranded assets of fossil fuel companies (in a 2°C economy) has been estimated to be around 82% of global coal reserves, 49% of global gas reserves and 33% of global oil reserves (McGlade and Ekins; 2015). Moreover, several studies have investigated the role of stranded assets in specific sectors and countries (Meinshausen et al.; 2009; Leaton; 2012; Robins et al.; 2012; Fleischman et al.; 2013; Caldecott and Robins; 2014; World Resource Institute; 2015). By investing in fossil fuel companies, financial institutions hold direct "high-carbon exposures", which for European actors have been estimated to be, relative to their total assets, about 1.3% for banks, 5% for pension funds and 4.4% for insurances (Weyzig et al.; 2014a). One can compute the Value at Risk (VaR) associated with climate shocks (Dietz et al.; 2016) in the context of Integrated Assessment Models (Nordhaus; 1993) in which aggregate financial losses are derived top-down from estimated GDP (gross domestic product) losses due to physical risks resulting from climate change. Yet, assessing the financial risk of climate policies (often referred to as transition risks) requires estimations of the likelihood of the introduction of a specific policy. However, the likelihood that a climate policy is introduced depends on the expectations of the agents on that very likelihood. Thus, the intrinsic uncertainty of the policy cycle undermines the reliability of the probability distributions of asset returns, also due to the presence of fat tails (Nordhaus; 2011). Further, it is now understood that interlinkages among financial institutions can amplify both positive and negative shocks (Battiston et al.; 2013, 2016a, 2016b) and significantly decrease the accuracy of our estimation of default probabilities in an interconnected financial system (Battiston et al.; 2016c). As a result, calculations of expected losses/gains from climate policies carried out with traditional risk analysis methodologies have to be taken with caution. Here, we develop a complementary approach, rooted in complex systems science, and consisting of a network analysis of the exposures of financial actors (May et al.; 2008; Haldane and May; 2011) to all climate-policy relevant sectors of the economy, as well as the exposures among financial actors themselves, across several types of financial instruments. This analysis is meant as a tool to support further investigations of the potential impact and the political feasibility of specific climate policies (Rogelj et al.; 2011; Peters; 2016). To go beyond the mere exposure to the fossil fuels extraction sector, we remap an existing standard classification of economic sectors (NACE Rev2) according to their relevance to climate mitigation policies, and we analyse empirical micro-economic data for shareholders of listed firms in the European Union and in the United States. We find (see Supplementary Table 6[2]) that while direct exposures via equity holdings to the fossil fuel sector are small (4-13% across financial actor types), the combined exposures to climate-policy relevant sectors are large (36-48%) and heterogeneous. In addition, financial actors hold equity exposures to the financial sector (13-25%), implying indirect exposures to climate-policy relevant sectors.

4.2 Results

By targeting the reduction of greenhouse gas (GHG) emissions, climate policies can affect (positively or negatively) revenues and costs of various sectors in the real economy with indirect effects on financial actors holding securities of firms in those sectors. However, the existing classifications of economic sectors such as NACE Rev2 (Eurostat; 2008) or NAICS (United States Census Bureau; 2017) were not designed to estimate financial exposures to climate-policy relevant sectors. Therefore, we define a correspondence between sectors of economic activities at NACE Rev2 4-digit level and five newly defined climate-policy relevant sectors (fossil fuel, utilities, energy-intensive, transport and housing) based on their GHG emissions, their role in the energy supply chain, and the existence in most countries of related climate policy institutions (see Appendix 4.A: Methods and Figure 4.1).

The exposures of financial actors (classified according to the standard European Systems of Accounts, ESA (Eurostat; 2010)) can be decomposed along the main types of financial instruments: equity holdings (e.g. ownership shares including both those tradable on the stock market and those non-tradable), bond holdings (e.g. tradable debt securities) and loans (e.g. non-tradable debt securities). By combining the breakdown of exposures across instruments with the reclassification of securities, we compute the total direct exposure of a given financial actor to each climate-policy relevant sector (see Appendix 4.A: Methods).

[2]Supplementary Information is available as online material: https://media.nature.com/original/nature-assets/nclimate/journal/v7/n4/extref/nclimate3255-s1.pdf

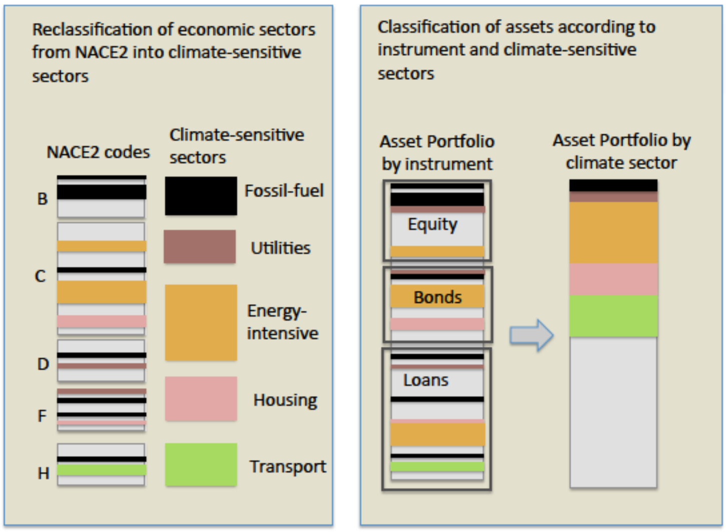

Figure 4.1: Diagram illustrating the reclassification of sectors from NACE Rev2 codes into climate-policy relevant sectors. For more information see the Methods and Supplementary Table 3.

4.2.1 Direct financial exposure through equity holdings

To provide empirical estimates of exposures to climate-policy relevant sectors we apply our methodology to recent available datasets. Despite their relevance for policy purposes, data about securities holdings of financial institutions, in particular to climate-policy relevant sectors, is generally scarce, inconsistent or even undisclosed. Along the three main instrument types mentioned above (equity, bonds and loans), at the level of individual institutions only some data of equity holdings are publicly available.

We thus first analyse a sample obtained from the Bureau Van Dijk Orbis database covering all EU and US listed companies and their disclosed shareholders (14,878 companies and 65,059 shareholders) at the last available year, i.e., 2015. On the bassis of our methodology, we construct the portfolio of each shareholder and we compute its exposure to each climate-policy relevant sector. To gain insights on the magnitude of indirect exposures we further classify equity holdings in companies belonging to the financial sector. We group shareholders by financial actor type to include, besides the institutional financial sectors from the ESA classification (i.e. Banks, Investment Funds, Insurance and Pension Funds) also Individuals, Governments, Non-financial Companies, Other Credit Institutions and Other Financial Services (Table 4.1).

Table 4.1: Absolute (first row, in USD billions) and relative (second row, percentage of aggregate equity portfolio) exposure of each financial actor type in each sector.

	OCIs (955)	GOV (125)	Individuals (33,733)	Banks (798)	IPFs (6,392)	OFSs (3,081)	NFCs (14,851)	IFs (5,124)
Fossil-fuel	31.17	66.17	98.17	173.29	230.21	185.15	377.30	549.85
(767)	6.02%	11.43%	3.77%	6.34%	7.09%	5.33%	8.06%	6.05%
Utilities	19.32	63.58	21.16	77.02	55.53	65.46	93.09	249.32
(216)	3.73%	10.99%	0.81%	2.82%	1.71%	1.88%	1.99%	2.74%
Energy-intensive	172.84	147.53	766.33	708.30	865.87	1019.84	1408.65	2701.69
(3956)	33.40%	25.49%	29.47%	25.92%	26.68%	29.36%	30.08%	29.71%
Housing	13.26	15.88	100.57	59.07	85.28	76.60	146.72	189.36
(797)	2.56%	2.74%	3.87%	2.16%	2.63%	2.21%	3.13%	2.08%
Transport	11.43	18.48	55.38	47.67	54.48	69.96	106.67	173.02
(224)	2.21%	3.19%	2.13%	1.74%	1.68%	2.01%	2.28%	1.90%
Finance	127.01	95.33	419.63	684.72	609.11	669.82	702.44	1532.08
(2659)	24.54%	16.47%	16.14%	25.06%	18.77%	19.29%	15.00%	16.85%
Other	142.44	171.80	1139.53	982.46	1345.08	1386.27	1847.40	3698.41
(6259)	27.53%	29.68%	43.82%	35.95%	41.44%	39.91%	39.46%	40.67%

Figure 4.2 (a) shows the result of the aggregated exposures in terms of equity holdings in listed companies for each financial actor type. The combined shares of equity holdings held by the financial sector (i.e. Investment Funds, Insurance and Pension Funds, Banks, Other Credit Institutions, and Other Financial Services) amounts to about 32.4 trillion US dollars, equivalent to 58.7% of total market capitalization.

The following findings emerge. First, the relative equity portfolio exposures of all financial actor types to the fossil sector are limited (i.e. ranging from 4.4% for Individuals to 12.9% for Governments) (see Supplementary Table 6[3]). Second, their relative equity portfolio exposures to all climate-policy relevant sectors are large (i.e. ranging from 45.2% for Insurance and Pension Funds, to 47.7% for Governments), and mostly accounted for by the energy-intensive sector. Third, since financial actors' exposures to the financial sector itself range from 13% for Industrial Companies up to 25.8% for Other Credit Institutions, they bear additional indirect exposures to climate-policy relevant sectors. Within each financial actor type, the standard deviation of exposures across individuals (see Supplementary Table 6) reflects the level of heterogeneity across individuals' portfolio compositions. Examples of individual equity holdings' compositions are shown in Figure 4.2(b-c) for the twenty largest players among investment funds and banks.

[3]Supplementary Information is available as online material: https://media.nature.com/original/nature-assets/nclimate/journal/v7/n4/extref/nclimate3255-s1.pdf

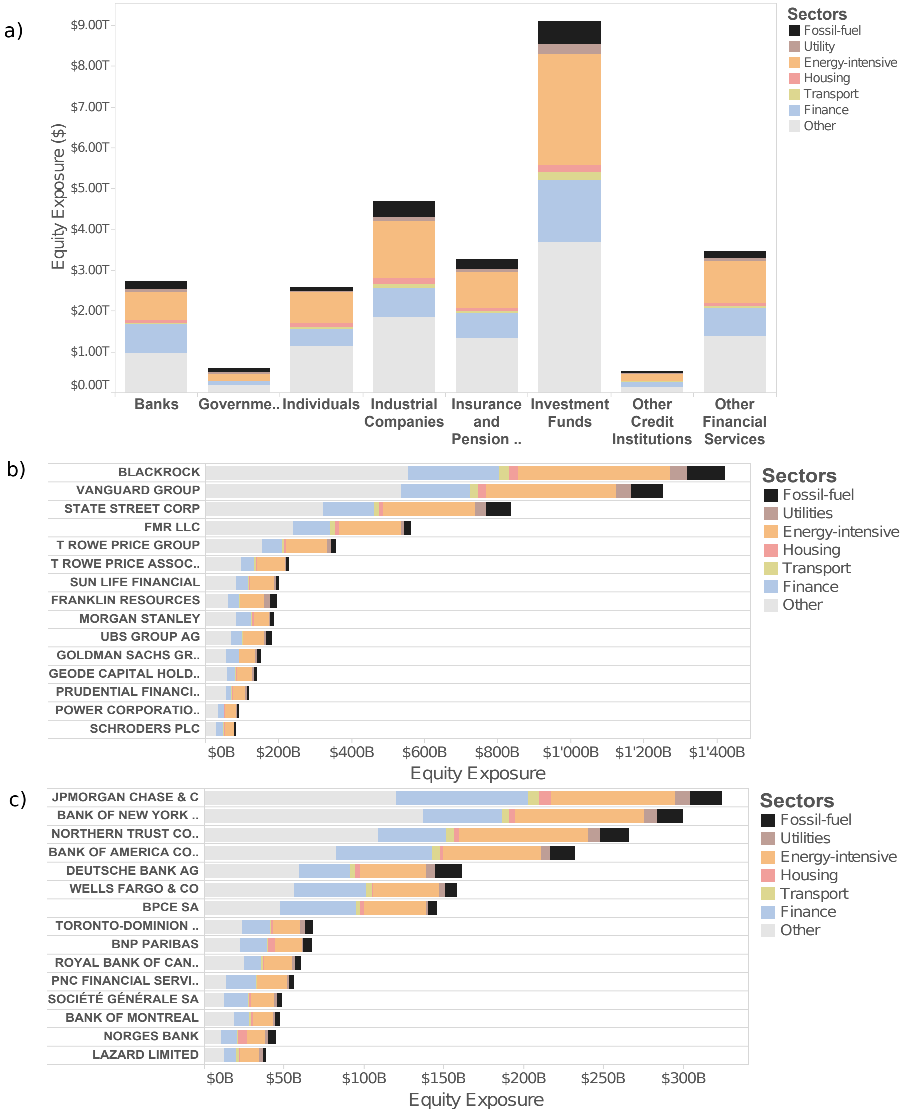

Figure 4.2: Equity holdings in EU and US listed companies in 2015 (data from BvD Orbis). a) Exposures to policy-relevant sectors of aggregate financial actors world-wide. b) Exposures to policy-relevant sectors of selected investment funds world-wide (top 15 by size of equity portfolio in the data). c) Exposures to policy-relevant sectors of selected banks world-wide (top 15 by size of equity portfolio in the data).

4.2.2 Climate stress-testing EU largest banks

Several quantitative estimates exist for the macro-economic impacts of climate change and climate policies (IPCC; 2014; Kriegler et al.; 2013), as well as for the value of stranded assets (Robins et al.; 2012). Accordingly, probabilistic estimates of the climate VaR can be carried out from an aggregate perspective (Dietz et al.; 2016). However, these estimates are too broad to define shock scenarios for individual institutions. At a more granular level, estimates of the value of stranded assets are available in the literature but their sectoral coverage is currently too narrow to inform an analysis of systemic impacts.

To overcome these limitations, we extend the stress-test methodology developed in Battiston et al. (2012) and Battiston et al. (2016d), which allows to disentangle the two main contributions to systemic losses. First round losses are defined as losses in banks' equity due to direct exposures to shocks. Second round losses are defined as indirect losses in banks' equity due to the devaluation of counterparties' debt obligations on the interbank credit market. The magnitude of second-round effects can vary significantly. Traditional methods (based on Eisenberg and Noe (2001)), yielding small second-round effects, are appropriate only under specific market conditions (i.e. full recovery from counterparties' asset liquidation and no mark-to-market valuation of debt obligations). In general, instead, second-round effects can be comparable in magnitude to first-round effects (Battiston et al.; 2012, 2016a, 2016d, 2016e)

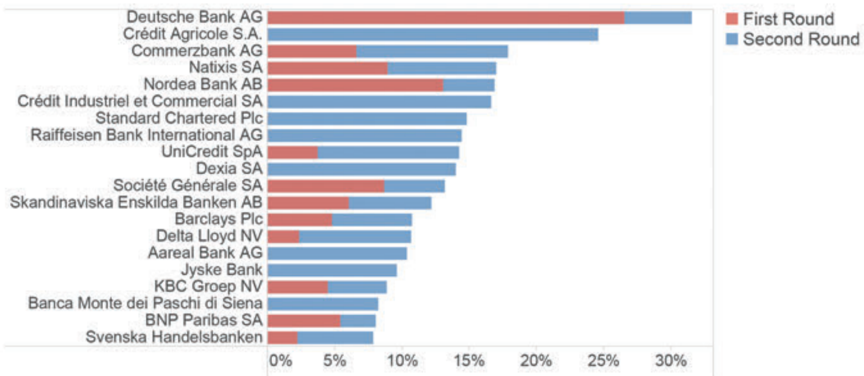

Figure 4.3: First and second round losses in banks' equity for the 20 most-severely affected EU listed banks, under the Fossil-fuel + Utilities 100% shock. Subsidiaries have not been taken into account.

We illustrate how our methodology can be used to conduct a climate stress-test of the banking system based on microeconomic data at the level of individual banks, by carrying out two exercises on the set of the top 50 listed European banks by total assets (see Appendix 4.A: Methods).

In the first exercise we aim to determine an upper-bound on the magnitude of the losses induced by climate policies by considering a set of scenarios in which the whole equity value of the firms in the shocked sector would be lost. We can then compute for each bank the ratio of the exposures to climate-policy relevant sectors over the banks' capital (i.e. banks' equity on the liability side of their balance sheets). Different scenarios consist of different combinations of sectors as indicated in Supplementary Table 8[4], by increasing levels of shocks' severity. For instance, in the second scenario, 100% of the market capitalization of listed firms both in the fossil-fuel sector and in the utilities sector is lost. Figure 4.3 shows the losses as percentage of the banks' capital across the 20 most affected banks as a results of the second scenario from Supplementary Table 8. Red (blue) bars indicate the losses from the first- (second-) round shocks. Notice that some banks have no first-round losses but have important losses at the second-round. None of the largest banks could default solely due to their exposures to climate-policy relevant sectors on the equity market. This result implies that even in a sever scenario, there is no systemic impact, when considering only the equity holdings channel. More refined scenarios, allowing one to compute a VaR for each bank, require one to have distributions of shocks across climate-policy relevant sectors, which are not available in the literature at this stage. As a first step in this direction, in our second exercise, we construct distributions of shocks for the fossil fuel and utility sectors based on the economic impact assessment of climate policies provided by the LIMITS database (Kriegler et al.; 2013) and we consider several scenarios of banks' exposures to climate-policy relevant sectors (see Appendix 4.A: Methods).

In particular, we interpret scenarios (2) and (4) in terms of distributions of losses suffered by a "representative" (average) bank adopting one of two different investment strategies:

- (2) a "green" bank having all its equity holdings in Utilities invested in Renewables-based Utilities and having no equity holdings in the Fossil-Fuel sector,
- (4) a "brown" bank having all its equity holdings in Utilities invested in Fossil-fuel based utilities and keeping its equity holdings in the Fossil-Fuel sector.

Supplementary Table 10[5] reports the main statistics on the global relative equity loss in the banking system. The results of the two exercises are consistent: the system VaR in the brown scenario is less than one percent of the total banks' capital. Supplementary Table 3[6] reports the statistics for the "representative" brown and green bank: depending

[4]Supplementary Information is available as online material: https://media.nature.com/original/nature-assets/nclimate/journal/v7/n4/extref/nclimate3255-s1.pdf

[5]Supplementary Information is available as online material: https://media.nature.com/original/nature-assets/nclimate/journal/v7/n4/extref/nclimate3255-s1.pdf

[6]Supplementary Information is available as online material: https://media.nature.com/original/nature-assets/nclimate/journal/v7/n4/extref/nclimate3255-s1.pdf

on whether their exposure to utilities is mainly concentrated on renewables-based utilities or on fossil-fuel ones and if they are exposed to the fossil-fuel sector, banks might face very different impacts from climate policies. Further, Supplementary Figure 6[7] shows the distribution of first-round losses: the brown bank incurs more losses than the green one, but these losses are small in comparison with the equity of the average bank (i.e. 32 bn USD) and with its total asset (i.e. 604 bn USD). Finally, Figure 4.4(a-b) reports the VaR for the 20 most affected banks both in the brown and in the green scenario.

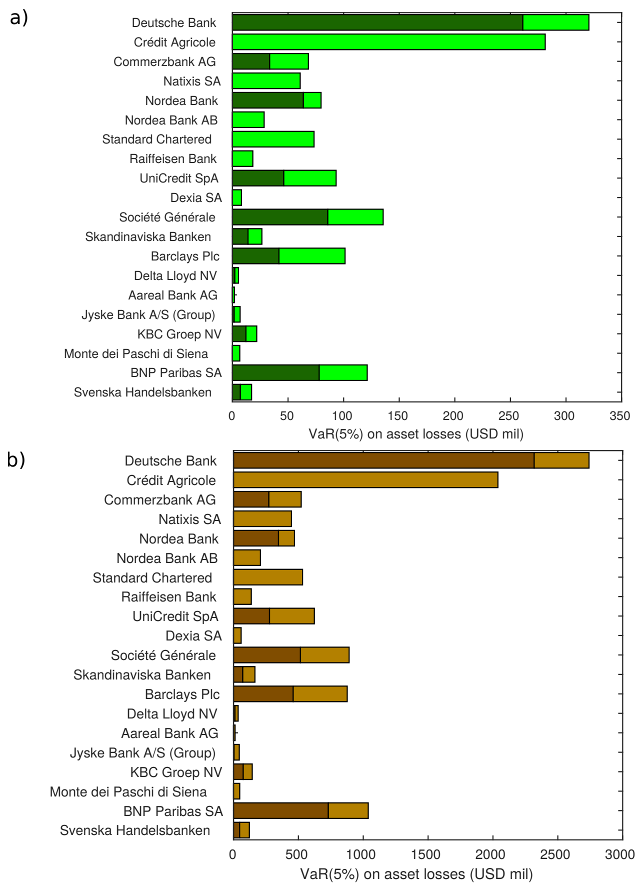

Figure 4.4: Value at Risk at the 5% significance level of the 20 most severly affected EU listed banks in the dataset, under the scenario that they follow the green investment strategy (a) or the brown investment strategy (b). Darker color refers to VaR(5%) computed on the distribution of first round losses only, while lighter color refers to VaR(5%) computed on the sum of first and second round losses

The limited magnitude of banks' losses in this exercise is due to the fact that Euro Area banks bear little equity holdings compared with their balance sheet (about 1.2T EUR i.e.

[7]Supplementary Information is available as online material: https://media.nature.com/original/nature-assets/nclimate/journal/v7/n4/extref/nclimate3255-s1.pdf

3.8% of total assets and 48% of capital), probably due to higher capital requirements for equity holdings (Bank for International Settlements; 2013). However, banks bear larger exposures on loans to non-financial corporations (about 4.8T EUR = 13.8% of total assets and 192% of their capital). Unfortunately, Euro Area banks' loans are only available at 1-digit NACE Rev2 aggregation (European Central Bank; 2017). At this stage, we cannot compute individual exposures of banks to climate-policy relevant sectors via their loans. Sector level data for 2014 from the ECB data warehouse provides the following aggregate estimations for the banks' exposures on loans as a fraction of banks' capital: 11.4% for fossil and utilities; 28% for energy-intensive; 16% for transportation; 73% for housing. We also need to consider banks' loans to households (presumably mostly granted for mortgages), which add a further 208% of exposures in the housing sector as a fraction of capital.

Better disclosure of climate related financial exposures (Financial Stability Board; 2016) would allow one to improve calculations for individual banks. The above considerations suggest that banks would not default solely due to their loan exposures to firms in the fossil-fuel and utilities sectors. However, if climate policies imply higher volatility of loans' values in the energy-intensive and transport sector or in the housing sector and for mortgages, this would translate into volatility of large portions of banks' assets, relative to their capital (16%+28%=44% and 73%+208%=281%, respectively).

4.2.3 Indirect exposures of European financial actors

By cross-matching aggregate balance sheet information for financial actors (from ECB Data Warehouse) with equity holdings (from ORBIS), the following findings emerge for the Euro Area. First, the major direct exposures to climate-policy relevant sectors of investment funds and pension funds are concentrated in equity holdings, while for banks they are concentrated on loans. Interestingly, bond holdings are only a minor channel of direct exposure to climate-policy relevant sectors because outstanding bonds issued by non-financial firms in the Euro Area amount to about 1 trillion Euro, i.e. about only one-fifth of the values of equity shares issued by the same type of firms. Indeed, only less than 7% of bonds are issued by firms in the real sectors, with roughly 40% issued by governments and another 45% issued by financial institutions.

Second, financial actors bear also indirect exposures to climate-policy relevant sectors. For instance, pension funds hold an exposure of about 25% of their total assets in equity shares of investment funds, which in turn have an estimated exposure of about 25% of total assets in equity holdings of climate-policy relevant sectors. Pension funds also hold an exposure of 15% of their total assets in bonds and loans to banks, which, on the basis of the previous section, hold an estimated exposure of about 14% of total assets to climate-policy relevant sectors. In contrast, the direct exposure of pension funds to climate-policy relevant sectors through equity holdings is about 8% of total assets. These findings imply that shocks on the fossil sector and increased volatility on asset values in the other climate-policy relevant sectors could affect non-negligible portions of pension funds' assets through both direct (8.3%) as well as indirect exposures (about 8%).

4.3 Conclusions

By remapping the existing classification of economic activities (NACE Rev2) into newly defined climate-policy relevant sectors, we find that direct and indirect exposures to such sectors represent a large portion of financial actors' equity holdings portfolios (in particular for investment funds and pension funds). Moreover, exposures represent a portion of banks' loan portfolios comparable to banks' capital. Further, we develop a network-based climate stress-test methodology that can be used to derive statistics of losses for individual financial actors, including VaR. We illustrate the methodology on a sample of the top 50 largest EU banks taking into account first and second-round effects of shocks to their equity portfolios.

Our findings suggest that the implementation of climate mitigation policies is key, both in terms of timing and expectations. The extent to which financial exposures will translate into shocks depends on the ability of market participants to anticipate climate policy measures. If climate policies are implemented early on and in a stable and credible framework, market participants are able to smoothly anticipate the effects. In this case there would not be any large shock in asset prices and there would be no systemic risk. In contrast, in a scenario in which the implementation of climate policies is uncertain, delayed and sudden (Weyzig et al.; 2014b; ESRB Advisory Scientific Committee; 2016) (e.g. as a reaction to increased frequency of extreme weather events and to align with the COP21 agreement, market participants would not be able to fully anticipate the impact of policies. In this case, given the large direct and indirect exposures of financial actors to climate policy relevant sectors, this might entail a systemic risk because price adjustments are abrupt and portfolio losses from the fossil-fuel sector and fossil-based utilities do not have the time to be compensated by the increase in value of renewable-based utilities. These two scenarios and their corresponding VaR are illustrated by the loss distributions for a "green" and a "brown" investing strategy in our climate stress-test on EU banks.

Moreover, the fact that financial actors bear large exposures to climate-policy relevant sectors implies that climate mitigation policies could increase volatility on large portions of their portfolios. Climate mitigation policies are commonly thought to have an adverse effect on the value of assets in the fossil-fuel sector Leaton (2012), as well as an adverse effect on the whole economy (see on Climate Change (2015), chapter 6). However, a transition to a low-carbon economy could also have net positive aggregate effects (Wolf et al.; 2016). Overall the effects of climate policies are likely to vary across firms and sectors: e.g., the renewable energy and the energy efficiency sectors are expected to increase massively in market share (see OECD (2011), IEA report 2015; IRENA Annual Review 2016), while real-estate assets can increase or decrease in value, depending on their energy performance (see Supplementary Table 6.7 in on Climate Change (2015)). Further, stock price volatility in climate-policy relevant sectors can increase as a result of: technological innovation (Shiller; 1992; Mazzucato and Semmler; 2002), increased competition (Irvine and Pontiff; 2009) and policy uncertainty (Brogaard and Detzel; 2015). Therefore climate policy could lead to winners and losers (in absolute terms) across financial actors, depending on the composition of their portfolios.

Overall, our network analysis of financial exposures highlights that financial actors' portfolios are both interdependent and largely exposed to the outcome of the climate policy cycle. This implies the possibility of multiple equilibria without a clear way to assign ex-ante probabilities for each equilibrium to occur. Therefore, while climate-related financial information disclosure is crucial for risk evaluation, a stable policy framework is necessary to resolve the multiplicity of possible outcomes. To this end, a network-based, conditional VaR approach represents an advancement in the analysis of climate-policy risks and their implications for the financial sector.

Acknowledgments

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Appendix 4.A: Methods

Identifying climate-policy relevant sectors in the real economy

Many climate policies target the reduction of GHG emissions (in particular non-carbon neutral processes). In order to identify the climate-policy relevant sectors we group economic activities with the following logic. We start from the top sectors by direct GHG emissions according to Eurostat (scope 1 CO_2 equivalent), which includes activities across sectors such as utilities, transports, agriculture, manufacturing and households. We also include the mining sector, although it has small direct emissions according to the scope classification, because all the emissions of the three above sectors derive directly or indirectly from the fossil fuel extraction when accounting from the supply side (Erickson and Lazarus; 2013). We then take into account the so-called carbon leakage risk classification, which according to the EC Directive 2014 (European Commission; 2014) identifies activities (mostly within manufacturing) for which either costs or competitiveness are heavily affected by introduction of a carbon price. It can be easily verified that the traditional NACE2 (but the same holds for NAICS) classification of economic activities is not well-suited for a climate-policy analysis. For instance, some activities classified under B-mining and quarrying, such as "B7.1 - Mining of iron ores" are not so relevant for climate policies. In contrast, some activities classified under C-manufacturing, such as "C19.2 - Manufacture of refined petroleum products" or transport "H49.5 - Transport via pipeline", are more relevant to the fossil fuel sector from the criterion of economic scenarios resulting from climate policies. Furthermore, some activities that pertain to the housing sector from a policy perspective fall into different NACE2 sectors such as F - construction and L - real estate.

All the considered economic activities can be divided into three categories: 1) suppliers of fossil fuels, 2) suppliers of electricity 3) users of either fossil fuels or electricity. We can further divide the third category according to the traditional policy areas: transport, housing and manufacturing. While suppliers of fossil fuels are mostly negatively affected by GHG emission reduction policies, the other categories can be affected positively or negatively depending on the energy source utilized (fossil fuel vs renewable). Based on all the above information we can finally remap all the economic activities from the 4-digit NACE2 classification into the following climate-policy relevant sectors: fossil, utilities, transport, energy-intensive, housing. The complete mapping from NACE Rev.2 4-digits codes is provided in Supplementary Information[8].

Assessing direct exposures of financial actors

Since our goal is to assess the exposure of financial actors to the climate-policy relevant sectors in the real economy, we group financial actors into financial institutional sectors according to the standard ESA classification: banks, investment funds, insurance and pension funds. The exposures of each financial actor can be decomposed along the main types of financial instruments: equity holdings (e.g. ownership shares including both those tradable on the stock market and those non-tradable), bond holdings (e.g. tradable debt securities) and loans (e.g. non-tradable debt securities). More formally, denoting by A_i the total assets of financial actor i, and by $\mathbb{S}$ the set of climate-policy relevant sectors, we can write

$$A_i = \left(\sum_{S \in \mathbb{S}} \sum_{j \in S} \alpha_{ij}^{\text{Equity}} + \alpha_{ij}^{\text{Bond}} + \alpha_{ij}^{\text{Loan}} \right) \; + \; R_i \tag{4.1}$$

where the terms α_{ij}'s denote the monetary values of the exposures of i in the securities associated with economic actors j for the different types of instruments and R_i is a residual accounting for the exposure to other sectors and instruments not considered in our analysis.

Although instrument types have different risk profiles, it is informative to look at the total exposure of financial actors to a given sector across all instruments. For instance, we can compute in this way the full exposure of a given bank to the fossil sector, by summing up all of its equity holdings, bonds and loans exposures to this sector. If we denote by α_{iS} the total exposure of actor i to sector S, we can write $\alpha_{iS} = \sum_{j \in S} \alpha_{ij}^{\text{Equity}} + \alpha_{ij}^{\text{Bond}} + \alpha_{ij}^{\text{Loan}}$.

In addition to the exposures of individual financial actors, we are also interested in the aggregate exposure of an entire financial institutional sector F to a given climate-policy relevant sector, $A_{FS} = \sum_{i \in F} \alpha_{iS}$. Finally, the total direct exposure of the financial system in the totality of climate-policy relevant sectors is $A_{\mathcal{FS}} = \sum_{F \in \mathcal{F}} \sum_{i \in F} \alpha_{iS}$, where $\mathcal{F}$ denotes the set of institutional financial actors.

Assessing indirect exposures of financial actors

A large portion of assets held by financial institutions are in fact securities issued by other financial institutions. For instance, about 40 % of banks' balance sheet in the Euro Area; about 25% of the market capitalization is invested in equity issued by companies in the

[8]Supplementary Information is available as online material: https://media.nature.com/original/nature-assets/nclimate/journal/v7/n4/extref/nclimate3255-s1.pdf

financial sectors; about 40% of the bond market is represented by outstanding obligations issued by financial institutions.

As a result, there is a potential systemic risk that can materialize through the so-called second-round effects (Battiston et al.; 2016b, 2016c). For instance, first-round effects may induce directly the bankruptcy of a financial institution which then defaults on its obligations towards its financial counterparties. Second-round effects refer to financial contagion effects including, but not necessarily further defaults. More generally, the accounting practice of mark-to-market implies that the deterioration of the balance sheet of a financial institution has a negative impact on the market value of its obligations held by its counterparties [9]. More formally, in the breakdown of total assets, we can distinguish the securities issued by firms in the financial sectors (whose values depend on their own assets' values) from those issued by firms in the climate-policy relevant sectors to obtain

$$A_i = \left(\sum_{j \in \mathcal{F}} \alpha_{ij}^{\text{Equity}}(A_j) + \alpha_{ij}^{\text{Bond}}(A_j) + \alpha_{ij}^{\text{Loan}}(A_j) \right) + \left(\sum_{k \in \mathcal{A}/\mathcal{F}} \alpha_{ik}^{\text{Equity}} + \alpha_{ik}^{\text{Bond}} + \alpha_{ik}^{\text{Loan}} \right) + R_i. \tag{4.2}$$

where $\mathcal{A}$ denotes the set of all actors and, again, $\mathcal{F}$ denotes the set of institutional financial actors. The above is a system of coupled equations in the asset values. In the spirit of analysing the short term effects of a deviation in the values from an initial face value of the securities, the terms $\alpha_{ij}^{\text{Instrument}}(A_j)$ can be written as the product $\alpha_{ij}^0 f_{ij}(A_j)$, where α_{ij}^0 represents the face value of the security at the initial time and $f_{ij}(A_j)$ represents the valuation of the security with respect to its face value. While the exact functional form of f_{ij} depends on the instrument type and the pricing model used for the valuation of the security, it is possible nevertheless to infer certain useful properties. Consider for instance a chain of exposure in which the financial actor i holds bond securities issued by the financial actor j, who in turns holds securities issued by a firm k in the climate-policy relevant sector. From the equations above it follows that

$$\frac{\partial A_i(A_j(A_k))}{\partial A_k} = \frac{\partial A_i(A_j)}{\partial A_j} \frac{\partial (A_j)}{\partial A_k} = \alpha_{ij}^0 \alpha_{jk}^0 \frac{\partial f_{ij}}{\partial A_j} \frac{\partial f_{jk}}{\partial A_k}. \tag{4.3}$$

Without loss of generality, in line with widely used pricing models such as those based on the Merton model for the value of debt obligations, the functions f_{ij} are non-decreasing in

[9] Mark-to-market and in particular, Credit Valuation Adjustment (CVA), is recognized as a major mechanism of financial distress propagation. During the 2007/8 financial crisis, it accounted for two thirds of all losses on the financial system (see FSA (2010))

the value of the assets of the issuer j, i.e. $df_{ij}/dA_j \geq 0$, because the ability of the issuer to pay either dividends or interest rates to its creditor generally increases with the issuer's total assets, everything else the same.

It follows that, as long as the terms df_{ij}/dA_j are not too small and comparable across instruments, the indirect exposure to a climate-policy relevant sector along chains of financial actors is determined by the product of the face value of the exposures along the chain, $\alpha^0_{ij}\alpha^0_{jk}$, where each exposure corresponds to the strength of the link between the two nodes. The result can be generalized to longer chains, although we focus on length two in this work. Therefore the problem of identifying the largest indirect exposure of a given path length is mathematically equivalent to graph-theoretical problem of finding the path(s) with the largest product of link weights along the path in a weighted graph.

Distribution of shocks

In order to infer a distribution of shocks on the fossil-fuel and utilities sector we use the LIMITS database (Kriegler et al.; 2013), which provides economic impact assessments of climate policies using a set of economic models and several scenarios that take into account the stringency of climate policy and the timing of its implementation. Results are reported as time-series of forecasted production level for each sub-sector with a five-year interval up to 2050. In particular we analyze the estimated time-series of the share of fossil fuels and renewables in primary and secondary (electricity) energy consumption. Out of the time-series, one can infer a distribution of shocks by considering each change in market share from one period to the next which corresponds to an observation of a shock for the respective sub-sector. Hence one obtains one shock per period per scenario and per model, for a total of 5,421 shocks. From an economic viewpoint, interpreting these shocks on market shares as shocks on equities amounts to make the following simplifying assumptions. First the share of nominal expenses on energy is constant (i.e the demand elasticity of substitution is 1). Second the value of equity in a sub-sector is proportional to total income. Third, market valuation is based on one-period (five years) ahead expectations. The shocks can then be interpreted as the impact on market valuation of a previously unanticipated policy measure. The extent to which these shocks will materialize depends on the ability of agents to anticipate policy measures. The shock scenario we describe in the paper corresponds to a setting in which informational imperfections prevent agents to smoothly adjust their expectations. The alternative scenario emphasized in the conclusion corresponds to a situation where a stable policy framework would allow financial actors to smoothly adjust their expectations. In this case, climate-induced systemic risk would not materialize. Figures SI 6 shows the resulting distribution of variation in asset value for a brown bank (investing in fossil-fuel primary sector and fossil-fuel based utilities) and a green bank (investing in the renewable utilities sector only).

Data

Data on equity holding was obtained through the Bureau Van Dijk Orbis database. We collected a sample covering all EU and US listed companies and their disclosed shareholders with voting rights as of the end of the last available year, i.e. 2014. After some consistency checks we end up with 14,878 companies and 65,059 shareholders. By grouping the exposures by investor we thus reconstruct portions of their equity holding portfolios, within the limitations of the available data. Further details on the dataset and the methodology is provided in Supplementary Information[10]. Data on the balance sheets of the top 50 listed European banks is obtained from Bureau Van Dijk Bankscope database. Data include for each bank its total lending and borrowing to other banks. Exposures of a bank to individual other banks are not publicly available and have been estimated based on existing methodologies (Battiston et al.; 2016d). Data on GHG and CO_2 emissions of sectors have been obtained from Eurostat statistics[11]. Data on financial exposures at the sectoral level have been obtained from the ECB Data Warehouse [12]

Data availability

The data that support the findings of this study are available from Bureau Van Dijk (Orbis database) but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Bureau Van Dijk.

[10] Supplementary Information is available as online material: https://media.nature.com/original/nature-assets/nclimate/journal/v7/n4/extref/nclimate3255-s1.pdf

[11] http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics

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Chapter 5

Transition Risks and Opportunities in Residential Mortgages*

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Abstract

A range of studies has analysed how climate-related risks can impact financial markets, focusing on equity and corporate bond holdings. This article takes a closer look at transition risks and opportunities in residential mortgages. Mortgage loans are important from a financial perspective due to their large share in banks' assets and their long credit lifetime, and from a climate perspective due to their large share in fossil fuel consumption. The analysis combines data on the energy-performance of buildings with financial data on mortgages for Germany and identifies two risk drivers – a carbon price and a performance standard. The scenario analysis shows that expected credit loss can be substantially higher for a "brown" portfolio compared to a "green" portfolio. Taking climate policy into account in risk management and strategy can reduce the transition risk and open up new lending opportunities. Financial regulation can promote such behaviour.

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5.1 Introduction

The importance of climate-related risk analyses has increased over the last years, especially since a speech by the governor of the Bank of England, Mark Carney, in 2015 where he argued that "more needs to be done to develop consistent, comparable, reliable and clear disclosure around the carbon intensity of different assets" (Carney; 2015). This has led to the establishment of the task force on climate-related financial disclosure (TCFD; 2017), which has developed guidelines on how climate-related risks should be accounted for in the governance, risk assessment and strategy of investors. Also banks are increasingly being asked to report on their ESG risks. In 2018, UNEP FI has launched the Principles for Responsible Banking, which aims at introducing and improving reporting standards for banks (UNEP FI; 2018). At EU level, banks and lending activities still play a minor role in the EU Action Plan on Financing Sustainable Growth (European Commission; 2018c). However, as part of the EU banking package of December 2018, the European Parliament and Council commissioned the European Banking Authority (EBA) to prepare a report on the integration of ESG risks into banks' risk management and potentially into the supervisory process (European Parliament; 2018). Additionally, the taxonomy for sustainable activities, as part of the EU Action Plan on Financing Sustainable Growth (European Commission; 2018c), includes a taxonomy for "green" buildings (Technical Export Group on Sustainable Finance; 2019). All of these initiatives aim at decreasing the information asymmetry between an investor and an investee or a lender and a borrower, with respect to climate-related risks.

A growing body of literature aims to assess the potential impact of climate change and climate policy on financial markets (Leaton; 2012; Robins et al.; 2012; Fleischman et al.; 2013; Weyzig et al.; 2014; Dietz et al.; 2016; Battiston et al.; 2017). So far, most analyses have focused on equity markets and corporate bonds in the fossil fuel sector and in energy-intensive industries. Loans on the other hand have received less attention, and especially the subgroup of residential mortgages. This might be due to two reasons. First, disclosure on greenhouse gas emissions usually focuses on emissions from a company's operations (scope 1 and 2 emissions).[2] In the building sector this includes the construction of the building but disregards a large part of greenhouse gas emissions caused during

[2]Scope 1 emissions are direct emissions from the operations of the respective company. Scope 2 emissions include emissions from upstream and downstream activities in the supply chain of that company. Scope 3 emissions appear during the lifetime of the product.

the operation of the building by the tenant (scope 3 emissions). Second, roughly half of residential buildings in the EU are owner-occupied buildings. Hence, the counterparties are individual households, not companies, which makes climate-related reporting harder to check and to enforce.[3]

In light of this, residential mortgages are deemed important for five reasons: First, loans to households to finance buildings make up about 13.8% of the balance sheet of Euro Area banks (ECB; 2019), as much as loans to non-financial corporations all together. Additionally, there are loans to non-financial corporations in real estate and construction using buildings as collateral. Furthermore, insurances and pension funds are exposed to real estate and mortgages via equity holdings in real estate companies, real estate funds and mortgage bonds. During the financial crisis in 2008/09, especially financial institutions with less transparent risk exposures to mortgage-backed securities and related credit default swaps suffered from higher risk premiums (Duca et al.; 2010). Second, like other infrastructure, buildings have long investment cycles and therefore higher risks of locking in carbon emissions for several decades. Owners and investors need time to adapt, especially since mortgages are usually financed over 15-25 years (EMF; 2017). Third, (residential, public and commercial) buildings are responsible for 30% of energy use in Germany (Öko-Institut and Fraunhofer ISE; 2016), the largest part of which is used for space and water heating, with a share of renewable energy for heating and cooling of only 13% in Germany[4] (Eurostat; 2019b). Fourth, according to an analysis of the EU long-term strategy, investment needs for energy demand efficiency (EUR 270-335 bn annually) are higher than for energy supply (EUR 133-246 bn annually) (European Commission; 2018b). Fifth, green mortgage bonds are a growing market, having grown from USD 19 bn in 2016 to USD 45 bn in 2017[5]. However, if green mortgage bonds are only used to reclassify new buildings (with efficiency labels A-B) as opposed to existing buildings (with labels C-H), it might have no influence on investments into energy efficiency and renewable energy in buildings. Investors need to be able to compare the climate risk of all mortgage bonds, not only of green mortgage bonds.

By reviewing climate policies for the building sector in Europe, this paper identifies

[3] For real estate companies and real estate funds, sustainability scores are provided by GRESB (2018), an Environmental-Social-Governance (ESG) benchmark for the real estate sector.

[4] Gas and mineral oil were still the main energy sources, with 44% and 26% of energy use, respectively.

[5] The first green mortgage bond of EUR 500 mln was issued by Obvion (a subsidiary of Rabobank) in 2016. In 2017, the US federal national mortgage association (The multi-family branch of Fannie Mae) contributed the largest bond with a volume of USD 27.6 bn.

different transition scenarios – an increase in energy prices and the introduction of a performance standard for existing buildings. Using Germany as an example, the potential effect of these transition scenarios on a "brown" and a "green" mortgage portfolio is assessed. It integrates data on the energy-performance of buildings into an expected credit loss calculation of a mortgage portfolio. Additionally, it provides a discussion on how banks can align their mortgage portfolio with the Paris Agreement and national policy goals. By including energy efficiency into strategic decisions and product development, one can identify lending and investment opportunities to households and to industries, that benefit from the transition.

This analysis can be useful for banks, who are increasingly being asked to assess and disclose their climate-related risks and their alignment with climate policy goals. Additionally, it can be used by investors at the level of individual securities, e.g. by comparing the transition risk of a green mortgage bond versus a standard mortgage bond. Furthermore, it is important for policy makers, who want to align financial policies with ambitious climate policies.

This paper is organized as follows. Section 5.2 presents background and literature on the topic. Section 5.3 explains the method applied. Section 5.4 explains the data used to construct portfolios and scenarios. Section 5.5 presents the results, which is followed by a discussion and conclusion in Section 5.6 and 5.7.

5.2 Background

5.2.1 Climate targets and policies

The European Union has three targets under the 2030 climate and energy framework (European Commission; 2018a): 40% greenhouse gas emissions reduction target (compared to 1990), 32% renewable energy target and a 32.5% energy efficiency target. To reach these targets, the Energy Performance of Buildings Directive (EPBD) (2018/844/EU) (EU; 2018) provides the policy framework for buildings. It demands mandatory energy performance certificates (EPCs) in advertisements for the rental or sale of a building and minimum performance requirements for new buildings and major renovations of old buildings. Targets are implemented at the national level, mostly through building codes, labels and financial incentives. As part of the EU Action Plan on Financing Sustainable Growth (European Commission; 2018c), a taxonomy for sustainable activities and investments has recently been proposed (Technical Export Group on Sustainable Finance; 2019). The current proposal for green buildings includes new buildings, if they are built as net-zero energy building (NZEB)[6] and if they have an EPC of B or better[7], and building renovations, if they increase the energy performance by at least 30% and if they comply with the building code for major renovations.

In Germany, at the national level, the climate change plan (*Klimaschutzplan 2050*) provides the policy framework (BMUB; 2016). The plan outlined a national target of 80% reduction of greenhouse gas emissions by 2050 (40% by 2030) compared to emissions in 1990. For buildings, the target is a reduction of 80% of primary energy use by 2050 compared to 2008 (and 40% by 2030) and a 50% share of renewable energy for heating and cooling. On the legislative side, Germany introduced a mandatory building code, the Energy Savings Ordinance (*Energieeinsparverordnung*) in 2002, as implementation of the first Energy Performance of Buildings Directive at EU level. This Ordinance complemented the Thermal Insulation Ordinance (*Wärmeschutzverordnung*), which was introduced in 1977. The Energy Certificate for Buildings (*Energieausweis für Gebäude*) was introduced in 2008 and the Heating Act (*EEWärmeG*) in 2009. Financial incentives are provided by the national development bank, KfW, via its "energy-efficient construction and refurbishment program" (IWU and Fraunhofer IFAM; 2018), which offers reduced-rate loans and subsidies for different energy-efficiency measures and renewable energy installations.

As the first country to introduce a feed-in-tariff (FiT) for renewable electricity, Germany tripled its share of renewable electricity in gross electricity consumption within 10 years – from 11.8% in 2006 to 32.2% in 2016 (Eurostat; 2019b, nrg_ind_335a). However, Germany only doubled the share of renewable energy for heating and cooling in the same timeframe – from 7% in 2006 to 13% in 2016 (Eurostat; 2019b, nrg_ind_335a). Studies investigating the effectiveness of renewable energy policies, indeed show that the feed-in-tariff is the most effective policy in promoting renewable energy investments, mainly because it reduces investment risk and increases returns at the same time (Polzin et al.; 2019). Similar studies on the effectiveness of climate policy for energy efficiency and renewable energy for heating are currently missing.

[6] According to the EPBD, all new buildings should be built according to the NZEB standard by 2020. However, there is no common definition of NZEB among European countries.

[7] The criteria will be reviewed and revised, to ensure that the threshold is above the top 15% of the local building stock.

5.2.2 Risk management and strategy development

Weber et al. (2008) find that environmental risks and sustainability criteria are increasingly being incorporated in the credit risk management process (divided into 5 phases: rating, costing, pricing, monitoring, work out) of financial institutions, especially among signatories of the UNEP Principles of Responsible Investment (UN PRI). However, the authors find that especially in the costing stage of the credit risk management process, where expected loss is quantified, only few respondents take environmental credit risk into account.

The stress-test of large European Banks, performed by the EBA, requires banks to assess the impact of two different scenarios on their balance sheet, a baseline and an adverse scenario (EBA; 2018). A major change in the EBA stress-test of 2018 was the introduction of the International Financial Reporting Standard 9 (IFRS9), which was implemented in the EU in 2016 (European Commission; 2016). IFRS9 entails that credit impairment is calculated over the lifetime of the loan (as opposed to only 12 months) and that "expected" credit losses have to be reported (as opposed to "incurred" credit losses). The latter requires banks to include forward-looking macroeconomic variables (EBA; 2018). These changes in the stress-test procedure would allow to include other forward-looking variables, such as socio-ecological variables. However, the integration of climate-related risks in credit risk analysis is still at an early stage. Along these lines, the TCFD recommends to establish a process to identify, assess and manage climate-related risks (TCFD; 2017). The recommendations explicitly contain the use of forward-looking scenarios for the purpose of risk management and for developing strategies to address these risks.

Following the definition of the TCFD (2017), there are transition risks (policy, technology, market and reputation) and physical risks (acute and chronic). Table 5.1 provides examples for these risk categories for buildings in particular. Regarding physical risks, Hirsch et al. (2015) estimate the annual expected loss (AEL) for selected locations in Germany caused by different extreme weather events (flood, hail, storm) at property-level. Using 15 example locations, the authors demonstrate how the tool can be used to better understand the impact of extreme events in the future. The scenario analysis in this paper focuses on transition risks.

Regarding transitions risks, the literature on sustainability in real estate mainly addresses two types of questions: 1) whether sustainable real estate carries lower default risks and 2) whether energy-efficient and sustainable buildings have a higher market value, hence sell at a premium. Most studies are from the US, UK or Australia and focus mainly on commercial real estate. Regarding the first question, the default risk of sustainable real estate, Kaza et al. (2014) find that mortgages on energy-efficient homes (characterized by the Energy Star label) have significantly lower default risks (one-third lower) than other buildings. Similarly, An and Pivo (2018) find lower default rates in commercial mortgage-backed securities (CMBS) for buildings certified as "green" under Energy Star or LEED. Concerning the second question, the valuation of sustainable real estate, Krause and Bitter (2012) identify sustainability as one of three main trends in real estate valuation literature. Warren-Myers (2012) examines the link between sustainability and value from a classical valuation perspective. The study highlights the role of valuers and advisers, and discusses how sustainability can be incorporated by valuation professionals and which measures are most applicable. So far, most studies on valuation effects of sustainability are from the United States, where premiums for Energy star and LEED buildings for commercial real estate in the US were found to be 16-17% higher (Eichholtz et al.; 2010). For Europe, Bio Intelligence Service et al. (2013) found positive effects on the sales price of a one letter improvement of energy efficiency of 8% in Austria, 4.3% in France and 2.8% in Ireland. However, the availability of data at the sector-level needs to be improved. For Germany, Surmann et al. (2015) assess the influence of energy efficiency on the market value of office buildings. Due to the small sample size, no conclusive evidence could be established.

Additionally, to identify lending opportunities from sustainability in the residential mortgage market and to offer dedicated energy efficiency products, it is important to better understand the drivers and barriers of energy efficiency investments. Ameli and Brandt (2015) find that home-owners and high-income households are more likely to invest into energy conservation. Additionally, environmental attitudes play an important role. Comerford et al. (2018) find that the introduction of color-letter grades (A = green, B = yellow, C = orange, D-G = red) on the English Energy Performance Certificate (EPC) motivated vendors to invest in energy efficiency. The authors find that in the period after the adoption of the color-letter grading system in 2007 more houses moved just above the D-grade threshold (the red colour). Hamilton et al. (2016) argue that if lenders include energy performance in mortgage calculations it would have a negative effect on the value of energy-intensive buildings and increase the affordability of more efficient houses. Furthermore, there is evidence that sustainability in the real estate sector is regarded as a positive signal by investors and shareholders. An event study by Ansari et al. (2015) finds that sustainability reporting under the Global Reporting Initiative (GRI) has a positive impact on the value of listed real estate companies in Europe, USA and Australia.

5.3 Method

This paper follows the TCFD recommendations of identifying, assessing and managing climate-related risks. First, to identify climate-related risks, a review of climate policies for the building sector in the EU is provided. Second, to assess the risk, possible transition scenarios are integrated into a credit risk analysis. Third, possible strategies for adjusting the portfolio and identifying opportunities are discussed.

According to (Ganguin and Bilardello; 2004, p.289) "credit scoring [. . .] is an essential tool for pricing debt instruments and for credit risk management", consisting of default risk on the one hand and recovery expectations on the other hand. The credit risk of a mortgage loan can also be divided into these two components, the default risk of the borrower and the valuation of the building (determining the recovery expectation). This paper applies a common framework used by banks and financial regulators to determine credit risk, expected credit loss.

The standard expected credit loss (ECL) is derived as follows:

$$ECL = EAD \times PD \times LGD \tag{5.1}$$

where ECL is the expected credit loss, EAD is the exposure at default, PD is the probability of default and LGD is the loss given default.

Applying this method for climate-related credit risks has been suggested by UNEP FI and OliverWyman (2018). However, the UNEP FI report focused on only one factor of the equation, the probability of default (PD) and does not apply the framework to the real estate sector or to mortgages. The "carbon quick scan tool" (Camphuis et al.; 2018; Hähl et al.; 2019) applied the expected loss model for different asset classes, including mortgages. However, it focuses on a change in loss-given default (LGD) and does not perform an analysis of different scenarios and portfolios. To include different risk drivers, the method used in this paper combines insights from UNEP FI and OliverWyman (2018) and the "carbon quick scan tool" (Camphuis et al.; 2018), by analysing potential effects on the solvency of the borrower and the value of the building. Hence, the analysis is extended in several points. First, different transition scenarios, which can have an impact on the risk factors, are identified. Second, climate-related changes in LGD as well as in PD are included in the analysis. Third, adjustments in the exposure at default (EAD) are made, comparing a "brown" and a "green" mortgage portfolio, to evaluate risk mitigation options and to inform strategic decisions.

As PD and LGD are usually derived from historical data, two analytical challenges need to be kept in mind. First, there is a lack of historical data that combines default rates and valuation with the energy performance of buildings. Second, the energy transition requires a major economic restructuring, which requires forward-looking estimates as well. Providing estimates of climate-related risks requires knowledge of climate change scenarios, potential policy responses, market developments and technological developments. To identify different forward-looking risk factors for buildings, the categorization of the TCFD (2017) is applied. Table 5.1 shows examples for each of the different risk types in the building sector. These potential risks will have an influence on the risk profile of the borrower and the value of the collateral.

Table 5.1: Impact of different climate-related risks on buildings.

Risk category	Type	Example in the building sector
Transition risk	Policy and legal	Increasing carbon price or carbon tax (e.g. Sweden and Switzerland), enhanced performance standards for existing buildings (e.g. the Netherlands and the UK).
	Technology	Substitution of existing products/technologies due to technological innovation.
	Markets	In/decreased costs of raw materials (e.g. concrete, steel, wood, insulation, etc.) In/decreased energy prices (e.g. due to geopolitical changes).
	Reputation	Shift in consumer preferences leading to higher demand for energy-efficient houses (energy-intensive buildings selling at a discount).
Physical risks	Acute	High rebuilding costs due to storms, floods or other extreme weather events.
	Chronic	Increasing insurance premiums in coastal areas and along rivers.

The Expected credit loss including transition risks is derived with the standard formula extended by a climate factor:

$$\textit{Climate ECL} = \textit{EAD} \times (\textit{PD} + \textit{climate PD}) \times (\textit{LGD} + \textit{Climate LGD}) \tag{5.2}$$

where *climate PD* is the additional probability of default due to transition risks and *climate LGD* is the additional loss given default due to transition risks. The mortgage portfolio is divided into different classes depending on their energy performance certificate. The *climate PD* and *climate LGD* are calculated for each class of buildings. The size of the climate factors (*climate LGD* and *climate PD*) depends on the sensitivity of *PD* and *LGD* to the shock. The *climate PD* is estimated using the increase of energy expenses, E, over income, I, times a sensitivity factor. The *climate LGD* is estimated using the required investment, I, as share of the market value of the asset, V, times a sensitivity factor:

$$\textit{Climate PD} = \left(\frac{E}{I}\right) \times \textit{PD sensitivity} \tag{5.3}$$

$$\textit{Climate PD} = \left(\frac{Inv}{V}\right) \times \textit{LGD sensitivity} \tag{5.4}$$

Table 5.2 shows how the different components of the expected credit loss calculation can be influenced by transition scenarios. Since the focus of this paper lies on transition risks in buildings, the energy performance certificate (EPC) is used as the main environmental indicator. Since the introduction of the Energy Performance of Buildings Directive (EPBD), it is the most widely used performance indicator for buildings in Europe. Some performance measures include the construction or major refurbishment of a building (Such as LEED, BREEAM, DGNB[8]). Others focus only on the operation of a building, mainly the energy consumption (such as “Energy Star”[9] in the US or the EPC in the EU) but also the water consumption or waste production. Rogmans and Ghunaim (2016) provide an evaluation framework for different sustainability indicators in the real estate sector. The analysis can be extended by using additional sustainability indicators.

[8]LEED is a certification program for green buildings in the US and internationally, developed by the non-profit U.S. Green Building Council (USGBC). BREEAM is a certification program in the UK, developed by the Building Research Establishment. It has been introduced to other European countries as well. DGNB is a certification program in Germany, developed by the German Sustainable Building Council.

[9]Energy Star is a voluntary labelling program by the EPA in the US. „Leadership in Energy and Environmental Design“.

Table 5.2: Description of how the transition can influence risk factors.

Risk factor	Baseline Scenario	Transition Scenarios
EAD	Given in the short-term by the lending strategy.	Can be changed in the long-term through strategic reallocation of loans.
PD	Influenced by macroeconomic conditions (unemployment level, GDP, interest rates, inflation).	Increase of energy prices (geopolitical) or energy/carbon taxes (market and policy risks), insurance costs (physical risks); revenue decrease (changing consumer preferences lead to lower rents and higher vacancy rates)
LGD	Depends on location and characteristics of the asset, market liquidity etc.	Renovation requirements reduce the market value of the asset, either over time or suddenly (policy risk).

5.4 Data

To perform a scenario analysis, mortgage loans outstanding in Germany are used to provide a first overview of the transition risk in the German mortgage market. This data is then connected to energy and climate scenarios, by using the current distribution of energy labels of buildings and the emission reduction targets for buildings in 2050.

5.4.1 Scenarios

Incentives and price signals for investments in energy efficiency and renewable energy for heating appear insufficient to stimulate the necessary investments, such that the national and EU emission reduction targets will be reached. According to Blazejczak et al. (2014), Dena (2016) and BCG and Prognos (2018), the national target of 80% reduction in primary energy use and a 50% share of renewable energy by 2050 can only be reached if the annual renovation rate is increased from the current 1% to at least 2%.

Several potential transition shocks are conceivable, when comparing policies with other European countries. All countries have introduced a national building code for new buildings, a label for very efficient houses or net zero energy buildings (NZEB) and several incentives for investments into efficiency and renewable energy in buildings. A comparison of CO_2 prices, gas prices, the share of renewable energy and the share of energy-intensive buildings is provided for different European countries in Table 5.3. According to the IEA policy database (IEA; 2019) as well as the Odysee-Murrey database (Odyssee-Mure; 2019) the amount of policy measures differs quite substantially between countries. However, some countries in the Euro Area and the EU have already introduced a CO_2 price (mostly in the form of a carbon tax) for emissions in the sectors not covered by the EU-Emission Trading System (EU-ETS) such as transport and heat (non-ETS sectors). For countries that adopted a CO_2 price, the price varies substantially, where Sweden is at the top rank (World Bank and Ecofys; 2018) with 139 Euro per ton. Sweden also has the highest gas price for households consumers (including all taxes and levies) in the EU (Eurostat; 2019b). Some EU countries have introduced a regulation that prohibits building owners to rent out inefficient houses after a certain year. In the Netherlands this applies for commercial buildings with label D or worse after 2023, and in the UK for all residential buildings with E or worse after 2020. Even in the absence of such regulatory measures, Comerford et al. (2018) found that a colour-letter grade can have an effect on consumer preferences, especially buildings with an energy label E or worse (red colour). Once the share of energy efficient houses increases, a tipping point might be reached and prices of energy-intensive buildings might decrease much faster, especially in areas with high vacancy rates, e.g. some rural areas.

Two main risk drivers can be identified from reviewing European policies on energy efficiency in buildings, an energy-price increase and a performance standard for existing buildings. The energy price used for the baseline scenario of this analysis is based on the current gas prices for household consumers in Germany (EUR 6 ct/kWh in 2018). If the government (at national, EU or international level) would introduce a CO_2 price of 100 Euro/ton (or 180 Euro/ton as recently proposed in Germany for the year 2030) for heating oil and gas, it would lead to an increase of the fuel price by approximately 2.5 ct/kWh (or 4.5 ct/kWh, respectively).[10] Based on the current price of 6 ct/kWh this would lead to an increase to 8.5 ct/kWh (or 10.5 ct/kWh, respectively), which is close to the current price is Sweden. This is in line with forecasts by Öko-Institut and Fraunhofer ISE (2016), which projects an increase of gas and oil prices from 6-7 ct/kWh today to 8-13 ct/kWh in 2030 (average 10.5 ct/kWh) and 9-21 ct/kWh in 2050 (average 15 ct/kWh). Hence, 10.5 ct/kWh is used for the low energy price scenario and 15 ct/kWh is used for the high energy price scenario.

An energy performance standard for existing buildings would lead to a reduction of

[10] Using an average carbon intensity factor of 0.25kg CO_2/kWh for gas and oil and a carbon price of 100 or 180 Euro per ton (0.10 or 0.18 Euro/kg CO_2), results in 2.5 ct/kWh (or 4.5 ct/kWh, respectively). 1 kWh is equal to about 0.1 liter of heating oil.

Table 5.3: Carbon prices and energy prices for heat, share of renewable energy and share of energy-intensive buildings (label D-H). For countries of the Euro Area, plus 3 additional EU countries; the UK, Denmark and Sweden due to the size of their mortgage market. * indicates that the country has already reached its 2020 target.

Country	Carbon price for non-ETS sector (Euro/ton)	Gas price for households (Euro/kWh)	Share of renewable energy: heating & cooling (gross final energy consumption)		Buildings with energy label D-H
Belgium	0	0.054	8.1%	(8.7%)	67%
Germany	0	0.061	13%	(14.8%)	62%
Ireland	25	0.063	6.8%	(9.5%)	48%
Spain	0	0.067	16.8%	(17.3%)	96%
France	55	0.067	21.1%	(16.0%)	65%
Italy	0	0.071	18.9%	(17.4%*)	85%
Netherlands	0	0.082	5.5%	(6.0%)	55%
Austria	0	0.067	33.3%	(33.5%)	n.A.
Portugal	8	0.076	35.1%	(28.5%)	68%
Finland	77	n.A.	53.7%	(38.7%*)	60%
UK	25	0.046	7.0%	(9.3%)	64%
Denmark	29	0.090	41.7%	(32.2%*)	62%
Sweden	139	0.113	68.6%	(53.8%*)	n/a
Source	(World Bank and Ecofys; 2018)	(Eurostat; 2019b)	(Eurostat; 2019b)		(Enerdata; 2016)

the market value for energy-intensive buildings. The value difference is determined by the required investment for renovation to upgrade the building to a better energy performance label (to be able to operate it and to keep it attractive in the future). The renovation costs are adopted from BCG and Prognos (2018), who estimate total costs to be between 285 - 465 Euro/m^2 for multi-family homes and 425 - 590 Euro/m^2 for single family homes. The former is used for the low investment cost scenario and the latter is used for the high investment cost scenario (for energy labels D-H). Similarly, investments financed via the "energy-efficient renovation" program of KfW were in the order of 398 Euro/m^2 on average[11], which is in line with the average of the low investment cost scenario.

[11] Total investments of 10.1 bn Euro for 276,000 residential units in 2016 IWU and Fraunhofer IFAM (2018), which is 36,600 Euro per unit, assuming an average floor space of 92 m^2.

Investment subsidies as well as promoting low-carbon innovation in the building sector would reduce the renovation costs. Hence, depending on the policy approach in a country, this value difference can be lower, mitigating the risk of a value loss. Table 5.4 describes three different theoretical scenarios and their impact on risk factors, which were derived from potential transition shocks.

Table 5.4: Description of the different scenarios resulting from different shocks.

Scenario	Shock cause (and main driver)	Impact on risk factor
Scenario 1	Introduction of a performance standard (policy risk) or change in consumer preferences (reputation risk)	Decline in house prices, leading to higher *LGD* for buildings with label D-H
Scenario 2	Introduction of a carbon price or increase in energy prices (policy or market risk)	Higher operating costs, leading to higher *PD*
Scenario 3	Combination of Scenario 1 and 2	Leading to higher *PD* and *LGD*

5.4.2 Portfolios

Commercial and residential buildings owned by non-financial corporations are usually financed via corporate loans and equity (listed or non-listed) and are therefore usually covered in sector analyses that include the real estate sector (e.g. Battiston et al. (2017)). However, residential buildings owned by individuals (which are often also owner-occupied) are largely financed through private bank loans, and are therefore not covered in most sectoral climate risk analyses.

The “brown” and “green" portfolio used for this scenario analysis combines data of the German building stock and outstanding bank loans for residential buildings in Germany (ECB; 2019) with data on the national distribution of energy labels (Dena; 2018) and national climate policy targets. In 2018, the amount of building-related loans by German banks consisted of EUR 1,229 bn in loans for house purchases and residential buildings by households (ECB; 2019). Compared to the aggregate balance sheet of German banks of EUR 7,880 bn, this amounts to approximately 15.6% of total assets. The share is higher than loans to non-financial corporations, with EUR 1,042 bn (ECB; 2019). The situation is similar for other European countries, as can be seen in Table 5.5. The countries with the largest mortgage loan market in the EU are Germany, France and the UK. The average loan-to-value (LTV) ratio in Germany is 80% (meaning that on average buildings are financed with 20% equity), however, there are also loans which are finance with 100% (EMF; 2017). Only 20% of mortgages are financed with short-term (less than 5 years) or variable interest rates (EMF; 2017), meaning that for 80% of mortgages banks cannot easily adjust interest-rates, even if the default risk increases. The relative size of mortgage loans and their long credit lifetimes make it an important asset class for forward-looking risk analyses.

Table 5.5: Aggregate balance sheet of banks (MFIs) and breakdown of loans to other banks (MFIs), non-financial corporations (NFCs) and households (HH) for house purchases. For countries of the Euro Area, plus 3 additional EU countries; the UK, Denmark and Sweden due to the size of their mortgage market. Source:(ECB; 2019)

Country	Total assets of Banks (MFIs) in Euro	Loans to MFIs in Euro	loans to NFCs in Euro	Loans to HH for house purchases in Euro
Euro Area	***31,393***	***6,724***	***4,423***	***4,339***
Belgium	1,043	209	142	164
Germany	7,880	1,901	1,042	1,229
Ireland	1,042	146	54	76
Spain	2,664	324	473	518
France	9,100	2,554	1,066	1,039
Italy	3,692	562	708	380
Netherlands	2,390	332	378	473
Austria	857	171	178	112
Portugal	394	32	72	95
Finland	648	143	88	98
UK	9,164	544	486	1,381
Denmark	1,075	125	159	294
Sweden	n/a	n/a	n/a	n/a

The building stock in Germany consists of 40.3 million residential building units, of which 18.8 million are single- and dual-family homes and 21.5 million are multi-family homes (Dena; 2018). The average living space per unit is 92 m^2 (3.7 bn m^2 floor space in total). In 2017, 51.7% of the population lived in owner-occupied houses, below the European average of 69.2% (Eurostat; 2019a), half of which have an outstanding loan or mortgage. Approximately 1% of buildings are being renovated each year and about 0.6% are new constructions (245,000 in 2017 (Destatis; 2018)). In 2016, 1 million transactions were made in the property market in Germany, with a value of EUR 237.5bn (AK OGA; 2017). The share of residential property was 72% (727.400 transactions, about 1.8% of residential building units), with a value of EUR 155.7 bn. This means that only about 1/3 of the transactions are new constructions and 2/3 are existing buildings. Hence, given that EUR 1,229 bn constitute the outstanding loans for residential buildings by households for half of the owner-occupied residential building units in Germany (10 million units), this would result in an average outstanding loan of 122,900 Euro/unit. According to (BBSR; 2017, p.13) the average price for single or dual-family houses in Germany in 2016 was 1,545 Euro/m^2, which would result in an average value of approx. 142,000 Euro for 92 m^2 (for most locations the price range is between 1,000 and 2,500 Euro/m^2, but can be up to 8,500 Euro/m^2 in Munich). The average household net-adjusted disposable income (after taxes and transfers) in Germany was USD 34,297, or 30,900 Euro[12], per year in 2016 (OECD; 2019).

For the “brown" portfolio, the distribution of energy performance certificate (EPC) in Germany is obtained from the building report of Dena (2018). According to Dena, the energy consumption per m^2 has improved from 150 kWh/(m^2a) in 2008 (Dena; 2016) to 135 kWh/(m^2a) in 2015 (Dena; 2018). In 2016, 50% of buildings consumed more than 140 kWh/(m^2a), and the least efficient buildings consumed up to 300-400 kWh/(m^2a). The average energy consumption of single- and dual-family homes built before 1978 is between 140-160 kWh/(m^2a) and multi-family homes built before 1978 between 110-140 kWh/(m^2a). The share of buildings in different energy performance categories (label A to H) was estimated from the building report of Dena (2018) and are depicted in Figure 5.1.

For the “green" portfolio, it is assumed that the number of outstanding loans by banks are the same as for the “brown" portfolio, but that the bank integrates energy efficiency goals into the risk management process and its strategic decisions. Over time, this would result in a portfolio with only energy-efficient buildings (label A and B), in line with the climate target for 2050. Such a portfolio is also in line with existing definitions of “green” mortgage bonds[13]. A fully renovated building can reach average values of energy consumption of 50-60 kWh/(m^2a) (Dena; 2016), which means that, theoretically, all renovated buildings can reach energy label B. The description of the portfolios is summarized in Table 5.6 and

[12] Using an annual average exchange rate of 1.11 (1 Euro = 1.11 USD) in 2016, according to the European Central Bank.

[13] e.g. “Muenchener Hypothekenbank eG” in Germany include only buildings with energy label A or B in their green mortgage bonds.

Figure 5.1.

Table 5.6: Description of the two different portfolios.

Brown portfolio (baseline portfolio)	Green portfolio (2050 policy-compatible)
This portfolio uses the current distribution of German residential buildings for different energy classes.	This portfolio is in line with current definitions of green mortgage bonds (and would meet the national target for the average energy consumption of 40 kWh/(m^2a) by 2050).

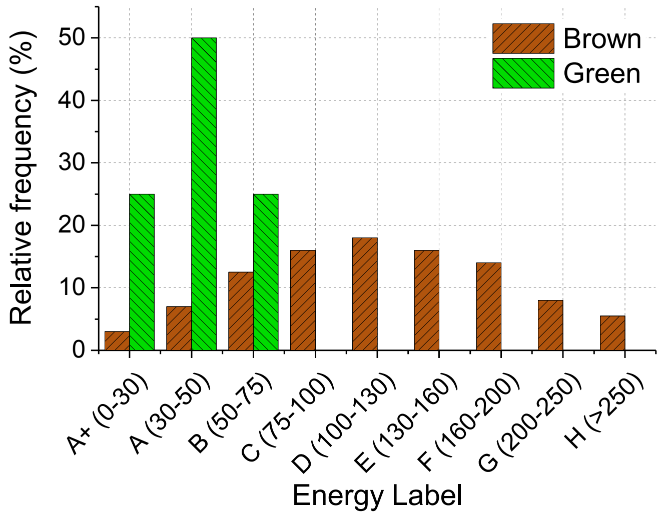

Figure 5.1: Distribution of houses by energy segment for the current ("brown" portfolio and a "green" portfolio.

5.5 Results

5.5.1 Risk assessment: impact of different scenarios

To calculate the valuation shock for Scenario 1, the average renovation costs for each building segment, that might be subject to a performance standard (energy label D-H), is computed as percentage of the average value of a housing unit, as described in Section 3: e.g. buildings with an energy label F (average energy use: 180 kWh/(m^2a); size: 92 m^2), an average value of 142,000 Euro and renovation costs of 375 Euro/m^2 :

$$\frac{(92 \text{ m}^2 \times 375 \text{ Euro/m}^2)}{142,000 \text{ Euro}} = 24.3\% \qquad (5.5)$$

This means that for a house with an average value and an energy label F, the owner would need to invest 24.3% on upgrading the house, which would reduce its market value.

To derive the energy price shock for Scenario 2, the increase in energy costs for each segment (energy label A-H) as a percentage of the average household income is derived, as described in Section 3: e.g. for buildings with an energy label F (average energy use: 180 kWh/(m^2a); size: 92 m^2) and an energy price increase from 6 to 10.5 ct and an average household income in Germany in 2016 (30,900 Euro):

$$\frac{92 \text{ m}^2 \times 180 \text{ kWh}/\left(\text{m}^2\text{a}\right) \times (10.5 \text{ ct} - 6 \text{ ct})}{30,900 \text{ Euro}} = 2.4\% \tag{5.6}$$

This means that a household with an average income and a house with energy label F would need to spend 2.4% of its income on additional energy costs.

The resulting average additional annual energy costs and estimated renovation costs for each energy label are reported in Table 5.7. In Scenario 1, the potential value loss varies between 15.5% and 30.1% (for label C to H) in the low cost scenario and between 24.9% and 38.2% (for label C to H) in the high cost scenario. In Scenario 2, the potential income loss varies between 0.2% and 4.4% (for label A to H) in the low cost scenario and between 0.4% and 8.7% (for label A to H) in the high cost scenario.

Table 5.7: Value and income effect of Scenario 1 and Scenario 2 (with low and high costs) on different building classes (A+ to H)

Energy label *kWh/(m^2a)*		Scenario 1 *Euro (% of value)*		Scenario 2 *Euro / year (% of income)*	
		low	high	low	high
A+	(0-30)	-	-	62 (0.2%)	124 (0.4%)
A	(31-50)	-	-	166 (0.5%)	331 (1.1%)
B	(51-75)	-	-	259 (0.8%)	518 (1.7%)
C	(76-100)	22,080 (15.5%)	35,305 (24.9%)	362 (1.2%)	725 (2.3%)
D	(101-130)	26,220 (18.5%)	39,100 (27.5%)	476 (1.5%)	952 (3.1%)
E	(131-160)	30,360 (21.4%)	42,895 (30.2%)	600 (1.9%)	1,201 (3.9%)
F	(161-200)	34,500 (24.3%)	46,690 (32.9%)	745 (2.4%)	1,490 (4.8%)
G	(201-250)	38,640 (27.2%)	50,485 (35.6%)	932 (3.0%)	1,863 (6.0%)
H	(251+)	42,780 (30.1%)	54,280 (38.2%)	1,346 (4.4%)	2,691 (8.7%)

In a second step, the impact of three different scenarios on expected credit loss, given the current "brown" portfolio and the aggregate mortgage portfolio of all banks in Germany of 1,229 bn Euro, was estimated:

- Scenario 1 (low costs): a decrease in the market value of buildings with label D-H due to an energy performance standard (assuming that C buildings will not be part of the performance standard at first).
- Scenario 2 (low cost): an increase in energy prices due to the introduction of a carbon price (affecting all buildings depending on their energy label).
- Scenario 3: a combination of scenario 1 & 2, assuming that an increase in energy prices would trigger a value adjustment or vice versa, hence assuming a correlation between *PD* and *LGD*.

These scenarios simulate possible changes in policy or consumer preferences, which might change the risk profile of a bank's mortgage portfolio. For the purpose of this scenario analysis, it is assumed that the impact on the value of the house is stronger than the effect of the increase energy costs on default rates, because households can adjust their consumption or because a CO_2 price could be redistributed per capita. Furthermore, if a CO_2 price is redistributed to households, the income effect will be lower. Therefore, a sensitivity of *PD* of 0.5 and a sensitivity of *LGD* of 0.75 was chosen. Resulting changes in expected loss for each energy label, depending on the scenario, are depicted in Figure 5.2.

For the "brown" mortgage portfolio, expected loss increases by 124% for Scenario 1 (performance standard), by 51% for Scenario 2 (increase in energy price) and by 256% for Scenario 3 (the combined scenario), compared to the baseline scenario. Potential losses concentrate on the energy-intensive buildings, the right-hand side of the distribution.

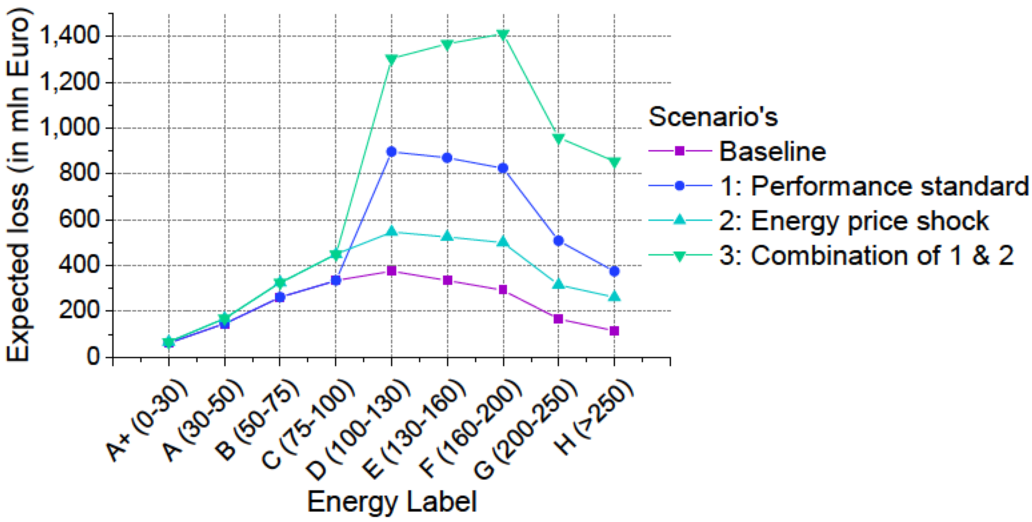

Figure 5.2: Expected credit loss for the current (brown) portfolio in three scenarios.

5.5.2 Risk management: impact on brown and green mortgage portfolio

To demonstrate the possibility of portfolio adjustments, the impact of the scenarios on two different portfolios, a "brown" and a "green" portfolio is compared. Using the aggregate mortgage portfolio of all banks in Germany of 1,229 bn Euro, and repeating the risk assessment for the "green" portfolio, leads to no increase of expected loss for Scenario 1 and a 16% increase of expected loss for Scenario 2 and 3. Hence, the "green" portfolio (such as a "green" mortgage bond) is considerably less sensitive to transition risks than a "brown" mortgage portfolio (a standard mortgage bond). Results are presented in Table 5.8.

Table 5.8: Expected credit loss (*ECL*) for the "brown" and "green" portfolio. Comparison of 3 different scenarios with the baseline scenario.

Portfolio and Scenario	*ECL* in Euro	% increase compared to baseline scenario	*ECL* as % of the mortgage portfolio
"brown" portfolio			
- Baseline scenario	2,089 mln	-	0.17%
- Scenario 1 (low)	4,670 mln	124%	0.38%
- Scenario 2 (low)	3,160 mln	51%	0.26%
- Scenario 3	7,430 mln	256%	0.60%
"green" portfolio			
- Baseline scenario	2,089 mln	-	0.17%
- Scenario 1 (low)	2,089 mln	-	0.17%
- Scenario 2 (low)	2,413 mln	16%	0.20%
- Scenario 3	2,413 mln	16%	0.20%

The size of the effect needs to be verified in future work, which requires more detailed data on portfolio distributions and sensitivities. However, the likelihood, and the timing of transition risks to unfold, involves different uncertainties. Therefore, the adoption of risk mitigation measures will depend on the investors' beliefs about the probability of policy interventions and technological progress to occur.

The lender can strategically manage the distribution of energy labels in financed buildings, hence the exposure at default (EAD) for each energy label. This can be done by shifting the portfolio towards more energy-efficient buildings over time, either by not offering new loans (or renewing loans) for energy-intensive buildings (absent a plan for retrofitting the building) or by adjusting the interest rate depending on the energy efficiency of a building. Early action is important due to the low renovation rates as well as long investment cycles and lifetimes of mortgage loans. Considering the long credit lifetimes of mortgage loans, the 2050 policy target should be used as a reference point.

In light of the growing green mortgage bond market and the introduction of the EU taxonomy for sustainable activities, there is a risk that banks only reclassify all buildings with an energy label A (and B) in their portfolio as "green", and refinance them via "green" mortgage bonds. On the one hand, this would leave all remaining buildings in the standard portfolio (but no A and B buildings anymore) and therefore increase the transition risk in the standard portfolio. On the other hand, it might not lead to increased investments in energy efficiency. Since about 20% of buildings in Germany already have label A or B, a bank will have to increase its share of green buildings to more than 20% to have a (positive) influence on energy efficiency investments. A target, which is in line with policy goals, would be at least 40% by 2030 and 100% by 2050. Green mortgage bonds of different issuers should be seen in the context of the whole portfolio of the issuer.

5.5.3 Strategy: Identifying opportunities

The same data can be used to identify business opportunities. The transition from the "brown" portfolio to a "green" portfolio determines the investment needs and hence the lending opportunities. According to the assessment of the EU 2050 Strategy (European Commission; 2018b), the average annual investments in energy demand (hence, energy efficiency) are larger than the investments in renewable energy. Estimated investment needs for residential energy efficiency were 198.1 bn to 235.1 bn Euro[14], depending on the scenario (European Commission; 2018b). In 2016 investments in energy efficiency in buildings in Europe according to the IEA (2017) were around 120 bn USD (with the EU share of 30% of global investments in the sector). This means that compared to the more ambitious EU scenario (235.1 bn Euro), energy efficiency investments would have to be around two times the current level. For Germany, this would mean energy efficiency investments of 38 bn Euro per year (or 1.2% of GDP in 2016)[15]. If the same ratio of current investments compared to required investments is assumed, Germany would need to increase its investments in energy efficiency in buildings by around 18.5 bn Euro per year. This is roughly in line with BCG and Prognos (2018), which estimate additional investment needs for Germany

[14] Additional investments are needed for energy efficiency in the tertiary sector (58 bn to 76 bn), for energy efficiency in industry (13.2 bn to 35.6 bn) and for energy supply investments, mainly power grid and power plants (133 bn to 246 bn Euro)

[15] 235 bn EUR investment need at EU level divided by 513 million EU citizens times 83 million in German citizens equals 38bn EUR. This is equal to 1.2% of GDP in 2016 (3144 bn Euro GDP for Germany)

to be between 13.7 and 19.7 bn Euro (480-690 bn Euro over 35 years) for residential and commercial buildings.

Currently, the "energy-efficient renovation" program of KfW in Germany finances renovations of around 275,000 residential units per year with an investment volume of 10-11 bn Euro, in 2016 and 2017 respectively (IWU and Fraunhofer IFAM; 2018). If renovation rates need to reach at least 2% of buildings, this would amount to 800,000 buildings per year and about 30bn Euro of investment per year. This means that the potential market for energy efficiency investments in buildings is around three times higher than what is currently invested under the KfW program.

In 2016, 727.400 residential property transactions with a value of EUR 155.7 bn were made (about 1.8% of residential building units) (AK OGA; 2017). About 1/3 of the transactions were new constructions and 2/3 were existing buildings. If all of these buildings would be renovated to an energy label A or B, it would mean an additional renovation potential of about 1.2% of existing buildings per year (assuming the same amount of transactions during the coming years and that these buildings have an energy label of C or worse). Banks have an important advisory role when properties are being sold. One possibility is to include a shadow price for carbon emissions in the investment calculation (similar to Scenario 2) to account for the future risk and to offer renovation advice during the loan origination. Additionally, banks can assist their clients in handling and managing public renovation grants, offering technical advice and ready made tools. Higher renovation rates lead to a growing market for energy efficiency and renewable energy in buildings, opening up new lending opportunities for banks.

5.6 Discussion

Like investors and asset managers, banks are increasingly asked to report the climate risk and climate impact of their investment or lending portfolio (e.g. through the Principles of Responsible Banking (UNEP FI; 2018)). Mortgages make up a large part of the balance sheets of banks (approximately 13.8% in the Euro Area and 15.6% in Germany), as much as corporate loans all together. Additionally, buildings are often used as collateral for other corporate loans or bonds as well. Hence, next to equity and corporate bond portfolios, mortgage loan portfolios are an important element in the analysis of climate-related risks and opportunities.

In a first step, this paper shows how to identify potential transition risks for mortgage portfolios, by reviewing climate policies for the building sector in different European countries. Two main risk drivers are identified, an energy price shock and a performance standard for the entire building stock. Assumptions on energy price increases from 6 to 10.5 ct/kWh are in line with estimates for 2030 and are comparable to the highest gas price in Europe today (in Sweden). As a comparison, the introduction of a CO_2 price of 180 Euro would lead to an increase of approximately 4.5 ct/kWh. Such an increase in energy prices would lead to an increase of energy costs of 0.2 - 4.4% (for energy label A-H) of an average household income in Germany. To estimate the effect of a performance standard, renovation costs (lower cost estimate) between 285 and 465 Euro/m^2 (for energy label D to H) are applied. This leads to a decrease in value for energy-intensive buildings between 18.5% - 30.1% of an average residential unit in Germany. The results should be understood as an exploratory study, as data integrating sustainability and financial metrics for mortgages is still scarce and focused on only a few countries.[16]

In a second step, the analysis shows an increase of expected credit loss for a "brown" mortgage portfolio (based on the current distribution of energy labels in Germany) in different transition scenarios. The climate-related credit risk of a "green" mortgage portfolio is much lower, however. Hence, this analysis shows that transition risks can be decreased considerably, if the portfolio is shifted strategically towards more energy-efficient buildings. With the emergence of green mortgage bonds, there is a risk that banks only reclassify buildings with energy label A and B into green buildings, but do not improve the overall portfolio, which would have no influence on investments into energy efficiency. To be in line with climate policy targets, the target share of green buildings (label A and B) for the overall portfolio needs to be at least 40% by 2030 and 100% by 2050. Additionally, if these "green" labelled buildings are refinanced via green mortgage bonds, this might increase the climate-related risk in the (remaining) standard mortgage bonds. This risk can be reduced, if all banks have to report the share on buildings in the different energy classes for the whole mortgage portfolio. This would ensure the comparability of mortgage portfolios of all banks.

Scenario analysis is a valuable tool for banks and investors, who want to develop strategies to mitigate potential climate-related risks and to identify potential business opportunities. It can also be helpful for investor to compare the transition risk of standard

[16] Only issuers of green mortgage backed securities or green covered bonds (or German "Pfandbrief") are currently disclosing energy related data.

mortgage bonds and green mortgage bonds. Banks can set energy-reduction targets and implement measures to reach them. The national target of energy reduction in buildings should be used as target for mortgage portfolios (as already done for some green mortgage bonds). They can disclose their targets and report on their progress regularly as part of their Corporate Social Responsibility (CSR) report and in this way improve their ESG rating. A good ESG rating can provide a positive signal to the growing share of SRI investors. The energy target can be reached through active energy-related management of the mortgage portfolio, such as offering attractive financing packages and technical assistance for renovations to owners of energy-intensive buildings. As renovations are often implemented when a building or flat changes ownership, banks can play an important role in advising clients when buying property, by applying a shadow carbon price (affecting operational costs), offering discount on interest rates for buildings with labels A and B, or even rejecting financing requests for houses above a certain threshold (e.g. label D-H before 2030 and C-H after 2030), if they do not include a plan for energy-efficiency renovations.

Currently, there is a lack of specific loan products for energy efficiency in households. Online loan portals usually have two main loan categories, mortgages loans or consumer loans (for furniture, sport equipment, travels, etc.) but no specific loan categories for energy efficiency or renewable energy products.[17] Banks can assist their customers in identifying the most cost-effective energy improvements for the different segments and offer more tailor-made products. In collaboration with energy providers and contractors, they can offer standardized financing schemes for energy-efficient heating systems such as heat pumps or solar thermal units to households and real estate companies. Active ESG-management can become a business opportunity – in mortgage lending as well as for loans to businesses offering energy efficiency and renewable energy products, materials and services.

5.7 Conclusion

This paper provides a method of how to identify, assess and manage transition risks (and opportunities) in mortgage portfolios. It complements existing assessments of the financial

[17] Car dealers and consumer electronics store offer standard financing packages, e.g. BNP Paribas is the financing partner of the electronics store, Saturn, offering consumer loans for up to 20 months and 15.000 Euro. However, only few energy providers and technology providers offer energy-specific financing options (e.g. for a new heating system. Often if such loans are available, interest rates are equal to or above interest rates for consumer loans and are offered for a maximum of 5-10 years, although such investments have longer payback times. Additionally, many banks require an ownership claim, which leads to additional costs.)

risk of climate policies, which mainly focus on equity and corporate bonds. A scenario analysis of three different transition scenarios is applied to a “brown” and a “green” mortgage portfolio. Results show that for the “brown” mortgage portfolio, the expected loss can increase substantially, depending on the scenario. This risk can be decreased considerably, when the portfolio is shifted towards more energy-efficient buildings.

The results of this analysis have several important implications. Both, a carbon price and a performance standard, can change the risk profile of energy-efficient vs. energy-intensive buildings. A credible and long-term oriented carbon price can have a substantial impact on the operational costs of a building, which might lead to higher default rates. This income effect can be mitigated by redistributing the revenues back to households. However, it would not automatically lead to higher investments in energy efficiency (especially in the case of rental buildings). Performance standards for existing buildings, on the other hand, influence the value of the building. In this case, the owner has a more direct interest in realising the investment, which can potentially lead to higher investments. This value impact can be mitigated by offering subsidies (e.g. through tax rebates or shorter amortisation period for energy efficiency investments) to reduce the investment costs. To ensure that owners have sufficient time to plan investments into renovations, such policies need to be introduced timely and with a long-term trajectory, which is especially important for buildings due to the long investment cycles. Banks can play an important role in this process.

Currently, energy performance labels (EPCs) are mandatory when selling or renting a flat or house. However, they are not mandatory for financial transactions that involve buildings. Information regarding the energy efficiency of financed buildings (and related risk management processes) are not reported to shareholders or bond holders. However, with the recent growth of SRI investors and green mortgage bonds, this will become more important. To increase transparency for investors and to improve the pricing of transition risks, climate-related disclosure in mortgage portfolios should be promoted.

This analysis shows how the EU taxonomy for sustainable activities (Technical Export Group on Sustainable Finance; 2019), currently developed by the European Commission, should be further developed to improve transparency, and to promote investments into energy-efficient buildings. It is important that all banks have to report the energy labels of their entire mortgage portfolio, not only of their green mortgage bonds. This would improve (climate-related) transparency for investors and would prevent banks from simply splitting the portfolio into "green" and "brown" buildings, without changing the overall portfolio.

In terms of financial regulation, banks could be required to include a risk premium for energy-intensive buildings (EPC label D-H) in the valuation of buildings and to include a shadow price on carbon emissions into their credit scoring.

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Statement of Contribution

Chapter 1 was written by Franziska Schütze.

Chapters 2-5 are the result of research collaborations with different co-authors. The author of this dissertation has made extensive contributions to all four papers, as specified below.

Chapter 2: Carlo C. Jaeger initiated the idea for the approach. All authors (Franziska Schütze, Steffen Fürst, Jahel Mielke, Gesine A. Steudle, Sarah Wolf and Carlo C. Jaeger) contributed to the framing of the research question and specified the changes in the GEM-E3 model. Steffen Fürst analysed and visualized the data. Franziska Schütze conceptualized and wrote the paper with contributions from all other authors.

Chapter 3: Franziska Schütze initiated and developed the idea for the paper. All three authors specified the quantitative analysis. Darko Aleksovski gathered the data. Darko Aleksovski and Franziska Schütze performed the data analysis. Franziska Schütze wrote the paper with contributions from the other authors.

Chapter 4: All authors (Stefano Battiston, Antoine Mandel, Irene Monasterolo, Franziska Schütze and Gabriele Visentin) contributed to the writing of the manuscript, as well as material and analysis tools. Gabriele Visentin and Stefano Battiston also performed the data analysis.

Chapter 5: Franziska Schütze gathered the data, performed the scenario analysis, developed and wrote the paper.

Tools and Resources

All chapters of this dissertation (text and tables) were written in LaTeX, using eclipse and TeXstudio. References were managed using JabRef and added to the manuscript using bibTeX. Additional tools and resources, used for model implementation, data analysis and visualisation are listed below:

Chapter 1: Figure 1.1 was produced with Microsoft Powerpoint.

Chapter 2: Simulations were done with GEM-E3, which is a macroeconomic model implemented in GAMS. Figures were generated using Scala and the JFreeChart Library.[18]

Chapter 3: The analysis was performed with Python (using the Spyder IDE as well as Pandas, NumPy and StatsModels libraries). Figures 3.1, 3.2, 3.3, 3.7, 3.8, 3.9 were generated using Origin. Figure 3.4, 3.5 and 3.6 were generated using the News Stream Portal.[19]

Chapter 4: The data acquisition was done with Microsoft Excel, the model was implemented in Matlab. Figures were generated using Microsoft Powerpoint (Figure 4.1), tableau (Figure 4.2), Matlab (Figure 4.3 and 4.4).

Chapter 5: The analysis was performed with Microsoft Excel. Figures were plotted with Origin.

[18] http://www.jfree.org/jfreechart/
[19] http://simpol.ijs.si/Home/NewsSearch

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