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On the Possible Concepts of the Transition to a Low-carbon Economy

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Thesis Summary

The present century has registered a growing scientific consent regarding the need to reduce global emissions in order to limit significant temperature increases. This implies a change in the prevailing technological paradigm, production processes and infrastructure, as well as in consumption behavior. Such a structural adjustment can be defined as a "transition". This is inherently a cross-sectoral phenomenon, which could enable the global economy to mitigate the challenges generated by climate change. However, it implies enormous adjustment costs in terms of technological investments and infrastructures development, which private investors are generally not able or willing to undertake. Accordingly, such a transformation paves the way for policy intervention, which aligns individual behavior with the overall climate goals.

In the present dissertation, the transition to a low-carbon economy is analyzed in the energy, transportation and financial sectors, illustrating the diverse implications that it can generate. In particular, the fundamental questions to which this thesis contributes are: how does the transition materialize in the different sectors and how does it impact them? Which policies can contribute to achieve the transition to a low-carbon economy? Which factors influence the effectiveness of these policies?

The transition to a low-carbon economy especially concerns the energy generating and energy intensive sectors, such as transportation. Given the high level of emissions that they produce, these sectors are directly addressed by policy inter-

vention, promoting, for instance, a shift from fossil to renewable energy sources or towards alternative fuels. Moreover, the transition intertwines with the financial sector. On the one hand, climate change and the climate policies implemented may alter the risk-return structure of financial assets. On the other hand, the transition relies on the financial sector to provide the funding for sustainable investments.

Throughout the dissertation, measures that can support the transition to a low-carbon economy, such as subsidies for clean technologies, taxes on polluting vehicles and a climate-oriented monetary policy, are analyzed. Moreover, the thesis identifies elements which can inform policymakers designing the transition. In particular, it studies the effect of knowledge spillovers and of the substitutability between clean and dirty energy, as well as labor mobility. Additionally, it investigates the presence of network effects between electric vehicles and charging stations. Finally, the dissertation discusses a climate-oriented monetary policy in the form of an emission-based interest rate policy adopted by the central bank. The present thesis contributes to the general debate about the transition to a sustainable economy by analyzing its distinctive traits across various sectors.

Chapter 1 emphasizes the relevance of the transition in the current economic conjuncture and the actions undertaken at global and national level. It also discusses the challenges and the role of policies, by providing an overview of factors that influence the effectiveness of policy intervention. Furthermore, the Chapter provides a more in-depth discussion of what the transition implies for the energy, transportation and financial sector, by referring to stylized facts and the existing literature.

As the transition is a cross-sectoral phenomenon, which presents distinctive features in each sector, Chapter 2 and Chapter 3 use different modeling approaches to analyze the transition in the context of energy production and transportation, respectively. Specifically, Chapter 2 introduces the possibility of a regime shift from polluting to renewable sources in energy generation. This Chapter deals with the introduction of clean energy generation targets and studies how the cost of a regime shift is affected by the knowledge spillover intensity in the economy, the substitutability between clean and dirty energy, as well as labor mobility. All these channels are shown to ease the regime shift by reducing its costs, thus highlighting the importance of including these factors when designing the transition to a low-carbon economy.

Chapter 3, in turn, deals with the switch towards alternatively fueled vehicles in the transportation sector. In particular, it discusses how the presence of network effects between electric vehicles and charging stations can be crucial for the diffusion of the former, reducing overall carbon emissions. Moreover, the Chapter highlights the welfare implications of a reduction in the number of polluting vehicles in the presence of a negative environmental externality and shows the existence of a double dividend. Decreasing the quantity of internal combustion engine vehicles can be economically improving, while reducing the negative impact of pollution. The results of this Chapter help to shed the light on the mechanism underlying the adoption of electric vehicles and the contribution they could provide to the transition to a low-carbon economy.

Climate change and environmental policies may impact financial intermediaries due to their effect on the risk-return structure of financial assets. At the same time, because of its high investment costs, the transition to a low-carbon economy entails a prominent role for the financial sector. Chapter 4 develops a theoretical model to study the impact of a climate-oriented monetary policy with regard to the transition. It emerges that such a central bank policy is able to channel more resources to sustainable production activities and incentivizes firms to adopt cleaner technologies. Thus, with this Chapter it is shown that central banks can play an active role in the fight against climate change and that a climate-oriented monetary policy represents a valid instrument to reduce emissions and climate damage.

Kurzfassung

Das gegenwärtige Jahrhundert verzeichnet eine wachsende Zustimmung innerhalb der Wissenschaft zur Notwendigkeit der Reduzierung globaler Emissionen, um einen signifikanten Temperaturanstieg zu vermeiden. Dies impliziert einen Wandel des vorherrschenden technologischen Paradigmas, der Produktionsprozesse und Infrastrukturen sowie des Konsumverhaltens. Eine solche strukturelle Anpassung kann als "Transformation" definiert werden. Letzteres ist von Natur aus ein sektorübergreifendes Phänomen, das es der Weltwirtschaft ermöglichen kann, die durch den Klimawandel verursachten Herausforderungen zu bewältigen. Damit verbunden sind enorme Anpassungskosten, gekennzeichnet durch technologische Investitionen und die Entwicklung von Infrastrukturen, die private Investoren im Allgemeinen nicht übernehmen können oder wollen. Dementsprechend ebnet eine solche Transformation den Weg für eine politische Intervention, die das individuelle Verhalten an den allgemeinen Klimazielen ausrichtet.

In der vorliegenden Dissertation wird die Transformation hin zu einer kohlenstoffarmen Wirtschaft im Energie-, Verkehrs- und Finanzsektor analysiert und die vielfältigen Auswirkungen, die daraus resultieren können, veranschaulicht. Die grundlegenden Fragen, zu denen diese Arbeit beiträgt, sind die Folgenden: Wie findet ein solche Transformation in den verschiedenen Sektoren statt und wie wirkt sich diese auf sie aus? Welche Maßnahmen können dazu beitragen, den Übergang zu einer kohlenstoffarmen Wirtschaft zu erreichen? Welche Faktoren beeinflussen die Wirksamkeit dieser Maßnahmen?

Der Übergang zu einer kohlenstoffarmen Wirtschaft betrifft insbesondere Energie erzeugende und energieintensive Sektoren, wie beispielsweise den Verkehrssektor. Angesichts der hohen Emissionen, die sie verursachen, sind diese Sektoren direkt durch politische Maßnahmen betroffen, die beispielsweise den Übergang von fossilen Brennstoffen zu erneuerbaren Energiequellen oder zu alternativen Brennstoffen fördern. Darüber hinaus ist die Transformation der Wirtschaft mit dem Finanzsektor verflochten: Einerseits wirkt sich der Klimawandel und die implementierte Klimapolitik auf die Produktivität der Wirtschaft aus, und verändert so die risikogewichtete Rendite von Finanzanlagen. Andererseits beruht die Transformation auf dem Finanzsektor, da dieser elementar für die Finanzierung nachhaltiger Investitionen ist. In der gesamten Dissertation werden die Maßnahmen, die den Übergang zu einer kohlenstoffarmen Wirtschaft unterstützen können, wie zum Beispiel die Förderung sauberer Technologien und eine klimaorientierte Geldpolitik, analysiert. Darüber hinaus werden Faktoren identifiziert, welche die politischen Entscheidungsträger bei der Gestaltung der Transformation beeinflussen können. Ein besonderes Augenmerk wird auf die Auswirkungen von Übertragungseffekten und der Substitutionselastizität zwischen nachhaltig und conventionell produziert Energie sowie der Arbeitsmobilität, das Vorhandensein von Netzwerkeffekten zwischen Elektrofahrzeugen und Ladestationen und die klimaorientierte Geldpolitik in der Form von emissionsbasierten Liquiditätskosten für Geschäftsbanken gelegt. Diese Dissertation trägt zu der allgemeinen Debatte bezüglich der Transformation hin zu einer nachhaltigen Wirtschaft durch die Analyse ihrer charakteristischen Merkmale in verschiedenen Sektoren bei.

Kapitel 1 betont die Relevanz der Transformation in der aktuellen Wirtschaftslage und die Maßnahmen auf globaler und nationaler Ebene. Darüber hinaus werden die mit einem solchen Strukturwandel verbundenen Herausforderungen und die Rolle der Politik diskutiert. Insbesondere gibt es einen Überblick der Faktoren, die die Wirksamkeit politischer Maßnahmen beeinflussen. Dieses Kapitel bietet auch eine vertiefte Diskussion darüber, was die Transformation für den Energie-, Verkehrs- und Finanzsektor bedeutet, indem es sich auf stilisierte Fakten und die vorhandene Literatur bezieht.

Da die Transformation ein sektorübergreifendes Phänomen ist, das in jedem Sektor Besonderheiten aufweist, verwenden Kapitel 2 und Kapitel 3 unterschiedliche Modellierungsansätze, um die Transformation im Kontext der Energieerzeugung und Mobilität zu analysieren. Insbesondere wird in Kapitel 2 die Möglichkeit eines Systemwechsels von umweltbelastenden zu erneuerbaren Quellen in der Energieerzeugung vorgestellt. Das Kapitel befasst sich konkret mit der Einführung einer Zielvorgabe für die Erzeugung sauberer Energie und untersucht, wie sich die Kosten eines Systemwechsels durch die Intensität von Übertragungseffekten in der Wirtschaft, die Substituierbarkeit zwischen sauberer und schmutziger Energie und die Arbeitsmobilität beeinflussen. Alle diese Kanäle sollen den Regimewechsel erleichtern, indem sie die damit verbundenen Kosten senken und so die Bedeutung der Einbeziehung dieser Faktoren bei der Gestaltung des Übergangs zu einer kohlenstoffarmen Wirtschaft unterstreichen.

Kapitel 3 dagegen befasst sich mit der Umstellung auf alternative Kraftfahrzeuge im Verkehrssektor. Es wird dabei insbesondere erörtert, wie das Vorhandensein von Netzwerkeffekten zwischen Elektrofahrzeugen und Ladestationen die Verbreitung von Elektrofahrzeugen beeinflusst, um die Kohlenstoffemissionen auf globaler Ebene zu reduzieren. Darüber hinaus befasst sich das Kapitel mit den Auswirkungen auf die Wohlfahrt, die sich aus einer Verringerung der Zahl umweltbelastender Fahrzeuge bei negativer Umweltexternalität ergeben und zeigt dabei die Existenz eines wirtschaftlichen Effizienzgewinnes bei gleichzeitiger Reduzierung der Umweltbelastung. Die Ergebnisse dieses Kapitels tragen dazu bei, den Mechanismus, der der Einführung von Elektrofahrzeugen zugrunde liegt, und den Beitrag, den sie zum Übergang zu einer kohlenstoffarmen Wirtschaft leisten könnten, aufzuzeigen.

Klimawandel und Umweltpolitik können sich auch auf den Bankensektor auswirken, da sie die risikogewichtete Rendite von Finanzanlagen verändern können. Gleichzeitig bringt der Übergang zu einer kohlenstoffarmen Wirtschaft aufgrund der

hohen Investitionskosten eine besondere Rolle für den Finanzsektor mit sich. Kapitel 4 entwickelt ein theoretisches Modell, das die Auswirkungen einer klimaorientierten Geldpolitik im Hinblick auf die Transformation analysiert. Es zeigt sich, dass eine solche Zentralbankpolitik ein angemessenes Instrument ist, um mehr Ressourcen einer nachhaltigen Produktion zuzuführen sowie Unternehmen einen Anreiz zu bieten, nachhaltigere Technologien anzuwenden. So wird mit diesem Kapitel gezeigt, dass die Zentralbanken eine aktive Rolle im Kampf gegen den Klimawandel spielen können und, dass eine klimaorientierte Geldpolitik ein wirksames Instrument zur Reduzierung von Emissionen und Klimaschäden darstellt.

Chapter 1

Introduction

The need for a shift. The "Paris Agreement", negotiated in December 2015 by 197 Parties of the United National Framework Convention on Climate Change (UNFCCC) sent a clear signal on the need to limit the global temperature rise. To keep global temperature increases below 2°C above the pre-industrial level, the global economy has to undertake a technological transformation, leading to its decarbonization by 2050. Specifically, switching to a system that is cleaner, more efficient, and reflective of the environmental costs of greenhouse gas emissions is necessary. This global policy action is mirrored by policies and technological developments that are taking place at the national level. Member countries of the UNFCCC have adopted national determined contributions (NDCs), which represent country-specific plans determining climate-related targets and policies. The NDCs are thus attempts to transfer the requirements for a global transition into national strategies. Such developments show that governments and societies are increasingly aware of the risks posed by climate change and, consequently, of the need for an appropriate response. However, there is no single solution; instead, the transition requires a broad approach, tackling various sectors and using diverse and dynamic strategies. For example, the initial formulation of NDCs will be regularly updated to be in line with the developments of the transition.

The aim of the present thesis is to illustrate how the transition might unfold in the energy, transportation and financial sector, to examine various measures that can be adopted to foster the transformation of the economy and to identify factors that should be taken into account when adopting these measures.

The transition. Shifting to a low-carbon economy presents both a significant opportunity and an enormous challenge. On the one hand, it offers the prospect of developing new markets and technologies, which can lead to environmental benefits maintaining or even improving the current living standards. On the other hand, the climate challenge implies a remarkable adjustment process, which involves developing new forms of production and closing the existing infrastructure investment gap in a climate-friendly manner (OECD 2017). The transition to a low-carbon economy displays various features and faces diverse issues and hurdles across sectors, which need to be considered when designing the required policy measures. On this account, the most directly affected sectors are either energy generating industries such as oil, coal and gas, or energy intensive sectors, such as transportation.

Chapter 2 argues that, in the energy sector, the transition involves a switch from the reliance on fossil fuels to renewable energy sources. For the transportation sector, in turn, it implicates, as discussed in Chapter 3, a shift away from internal combustion engine vehicles towards alternatively fueled vehicles. The present thesis also discusses the effect of climate change and the adoption of environmental policies on the risk-return structure of financial assets and the financial sector as a whole. On this account, Chapter 4 analyzes the impact of a climate-oriented monetary policy assuming the form of an emission-based interest rate policy adopted by the central bank, which aims at improving the financing conditions for cleaner firms.

Policies. The transition to a low-carbon economy is characterized by a particular time component because long-term benefits will only materialize if a large amount of economic resources is channeled to green investments in the short term. The high short-term costs due to, among others, infrastructure investments, technology development, path-dependence and behavioral aspects may impair the unfolding of the economic transformation. As a consequence, policy intervention is needed to create a coherent and integrated regulatory framework, that induces the transition and at the same time reduces the overall adjustment costs faced by economies. For example, consistent long-term policies may have the advantage to provide financial institutions with the confidence to invest in low-carbon technologies.

As climate change is a cross-cutting topic, environmental policies need to be broad in scope. Accordingly, tackling different sectors is crucial for the success of the transition. For sectors such as energy production and transportation, long-term targets in terms of emission reduction have been set. Such measures have been widely analyzed in the literature, but factors that may determine their effectiveness deserve a more in-depth discussion.[1] Thus, this thesis analyzes channels that may influence the adoption of standard policy measures. In this regard, Chapter 2 studies the impact of knowledge spillovers, the substitutability between clean and dirty energy and labor mobility on the subsidy to clean technologies needed to achieve a given target in terms of energy generation from clean sources. Chapter 3, instead, models the network effects between electric vehicles and charging stations, to derive policies which are suited to achieve a given reduction of the share of polluting cars circulating. Recently, the debate about climate policies in the financial sector has become more prominent. In particular, a more active role of central banks in steering finance towards low-carbon activities, has been discussed. In this regard, Chapter 4 analyzes a climate-oriented monetary policy which aims at improving the financing conditions for sustainable projects and thereby promoting low-carbon investments.

The word "transition" alludes to the change from the present regime to a future one, where the term "regime" refers to the dominant practices and rules that pertain in a domain (Elzen et al. 2004). In what follows, the meaning of the tran-

[1] See, for example, Haas et al. (2011), Knopf et al. (2015), Carley et al. (2017) for the introduction of targets in the energy generation and Yang et al. (2009) and Jenn et al. (2019) for a focus on the automobile industry.

sition for different sectors is discussed, highlighting the importance of a transversal approach.

1.1 Energy sector

Accounting for 40% of global emissions, the energy generation represents the most polluting economic sector (IEA 2015). However, energy has always played a crucial role in the economic development and it will most likely continue to be an important determinant of economic growth. Hence, a structural change, so that demand for energy can be satisfied while generating fewer emissions, is needed.

Despite a widespread understanding of the necessity of a transition to renewable energy, there are a number of risks and barriers to making renewable energy more appealing than conventional energy. The goal of transforming economies that have been reliant on a fossil-fuel based energy system bears significant costs in the short term. In order to enforce the transition, countries have started to set long-term goals for energy generated from clean sources, which requires the economy to integrate innovative technology and processes. These targets can be achieved by the adoption of subsidy-based schemes. However, the level and evolution of such support measures, as well as the factors that determine their effectiveness are a topic of discussion among academics and policymakers.

Chapter 2 contributes to the debate about a regime shift in the energy sector by introducing targets in terms of production from clean sources in an endogenous growth model. Moreover, it analyzes how the presence of knowledge spillovers, the substitutability between clean and dirty energy inputs and labor mobility can affect the subsidy needed to achieve such targets and, ultimately, cover the cost of the regime shift. Whereas spillovers represent a transfer of technology or knowledge which can ease the transition, the substitutability measures to what extent clean technologies can replace dirty technologies in the production of output. Finally, labor mobility offers an additional channel of adjustment for an economy undertaking the transition, as it allows to correct for potential imbalances emerging in the labor market, thus reducing the cost of the regime shift. These channels have already been studied individually in the literature (Acemoglu et al. 2012, Dechezleprêtre et al. 2014, Aghion et al. 2016, Papageorgiou et al. 2017). However, the contribution of this Chapter is to develop a unified framework, which allows us to study the impact of these factors jointly.

1.2 Transportation sector

At present, the transportation sector is responsible for one third of the global final energy demand and is second only to the energy industry in the generation of greenhouse gas emissions (IEA 2019). Specifically, the sector emits 23% of global emissions overall, while road vehicles (cars, trucks, buses and two- and three-wheelers) account for nearly three quarters of global transportation CO_2 emissions. Hence, this sector can play a pivotal role in the transition to a cleaner economy and in the effort to mitigate climate change. If emissions from the transportation sector have to be reduced, traditional technologies must be replaced by alternative ones. This issue becomes more urgent due to the growing global demand for automobiles. According to OECD (2019), the number of vehicles on the road could increase from 900 million to around 2.4 billion by 2050.

Indicators such as the market share of electric vehicles show that some countries have already made strides in restructuring their transportation system for the sake of reducing pollution (IEA 2019). However, the transition in the transportation sector faces many challenges due to the costs of suitable substitute technologies and the limited availability of alternative energy sources. It is thus not surprising that in many countries emissions from the transportation sector are not on a reduction path (Agora-Verkehrswende 2017). This aspect calls for policy intervention in the form of fiscal and regulatory instruments, as well as for studies that analyze the channels influencing the policy measures adopted. Although there is still uncertainty about the energy type that should substitute fossil fuels in the transportation sector, there exists widespread support for the adoption of electric vehicles as a means to reduce emissions from the transportation sector (Agora-Verkehrswende 2017, Dominković et al. 2018). However, the diffusion of electric vehicles is currently far from widespread: high purchase costs, range anxiety, long charging times and the lack of an appropriate charging infrastructure hinder the adoption of these alternative fueled vehicles (Agora-Verkehrswende 2017).

In order to describe the diffusion process of electric cars, as well as the channels affecting it, Chapter 3 uses a two-sided market approach, in the spirit of Rochet and Tirole (2003) and Springel (2016), to capture the positive network externalities between electric vehicles and charging stations. Moreover, it is shown how policies tackling electric vehicles (charging stations) also have positive repercussions on the amount of charging stations (electric vehicles). As governments can set targets in terms of emission outcomes to steer the behavior of consumers, Chapter 3 focuses on a percentage reduction in the number of internal combustion engine vehicles circulating. The main contribution of the Chapter is to show that, when taking into account network externalities, the introduction of targets may lead to a double dividend effect, so that an environmental benefit can be achieved while improving economic welfare.

1.3 Financial sector

Climate change and environmental policies affect not only the real economy, but also the financial sector. We can identify at least three dimensions of this interaction, which justify the increasing interest for sustainable finance matters. First, there exists physical risks due to climate events, which harm physical capital and infrastructure, reducing the production capacity of firms and increasing their production costs due to adaptation spending or replacement investments. This, in turn, can alter the risk-return structure of financial assets and influence the financial conditions of firms. Second, there exists transition risks as policies aiming at mitigating climate change could lead to significant investments, for example in new types of energy and transportation networks, and potentially stranded assets. Furthermore, transition risks imply an increase in the production costs due to changes in the input structure or reduced revenues following alterations of the market demand patterns. Third, while the financial sector is affected by climate change and environmental policies, reducing the carbon intensity in sectors such as energy and transportation requires investments, for which financial markets and financial intermediaries can provide the necessary funds (Campiglio 2016, Battiston et al. 2017, Campiglio et al. 2018).

Given the implementation difficulties related to traditional fiscal measures, such as political acceptability, sustainable finance might represent a tool to complement the existing policy measures (Rozenberg et al. 2013, Fay et al. 2015, Campiglio 2016). For example, financing conditions for firms depending on the emission intensity of the technology applied could have a more direct impact on innovation activities than traditional fiscal measures. In this regard, a climate-oriented monetary policy may represent a way to create incentives for commercial banks to provide cheaper financing to clean firms. This seems to be particularly relevant in the case of the Euro Area, as a large share of external funding of private corporations originates from loan financing by commercial banks (De Fiore and Uhlig 2011).

Chapter 4 illustrates the role of the financial sector in the transition to a low-carbon economy by using a neoclassical growth model which is extended by climate damage in the spirit of Nordhaus and Boyer (2000), Van den Bijgaart et al. (2016) and Bretschger and Pattakou (2019). In particular, this Chapter assumes a climate-oriented monetary policy in the form of an emission-based interest rate policy adopted by the central bank. The latter is shown to represent a valid instrument to promote the transition to a low-carbon economy, if banks pass the emission-based liquidity costs on to the real economy. Clean sectors are directly favored by lower financing costs and the carbon-based pricing incentivizes the overall adoption of cleaner technologies. With this analysis, the Chapter contributes to informing the current debate about the role of central banks in promoting sustainable finance.

1.4 Outline of the thesis

This thesis uses different modeling approaches to study diverse aspects of the transition towards a low-carbon economy across sectors. Moreover, the thesis identifies channels which potentially affect the outcome of the policies adopted to undertake the transition. Each chapter responds, analytically and through numerical simulations, to the following questions:

- Chapter 2: Which policies can favor the shift from fossil to renewable energy sources? How is the cost of the regime shift affected by knowledge spillovers, the substitutability between clean and dirty energy, and labor mobility?
- Chapter 3: What is the role of network effects in the transition to a low-carbon transportation sector? What are the welfare implications of reducing the share of polluting vehicles in the presence of network effects?
- Chapter 4: Can a climate-oriented monetary policy in the form of emission-based interest rates foster the transition to a low-carbon economy? How do climate change and environmental policies affect the banking sector?

Aiming for a reduction of the dependence on polluting energy sources, countries set targets in terms of energy generation from renewables. This translates into a regime shift in the production of energy, with costs for the economy. Subsidizing clean production represents thereby one possible policy measure to cover such costs. Chapter 2 develops a general equilibrium model to analyze the subsidy required to achieve a target of clean energy production, while accounting for spillovers from knowledge-capital, substitutability between clean and dirty energy and labor mobility. The findings of the Chapter show that, in order to reduce the costs of the regime shift to a low-carbon economy, policies should improve the absorption capacity of the clean energy sector, ease the substitutability between clean and dirty energy and promote labor mobility.

Decarbonizing the transportation sector is a key measure to reduce carbon emissions at the global level. A crucial factor to achieve a sustainable transportation system is the diffusion of electric vehicles. Accordingly, Chapter 3 studies the network effects inducing a positive relationship between electric vehicles and charging stations. To do so, a two-sided market model that captures such network externalities is developed. A platform provides one side of the market with electric and internal combustion engine vehicles to consumers, while it supplies retailers with charging stations on the other side. This framework is used to study policies tackling different sides of the market. In the presence of network effects and environmental damage from polluting cars, optimal policies can lead to a double dividend: decreasing the quantity of internal combustion engine vehicles can be economically improving, while reducing the negative impact of pollution.[2]

Finally, having established the different contexts in which the transition can take place, Chapter 4 demonstrates the importance of including the financial sector in the analysis. The Chapter uses a dynamic general equilibrium model to study a climate-oriented monetary policy in the form of emission-based interest rates set by the central bank. Liquidity costs of banks increase with the emission intensity of their asset portfolio, leading banks to favor low-carbon assets and to improve the financing conditions for clean sectors. The Chapter shows that such a monetary policy supports the decarbonization of the economy and reduces climate damage, as more resources are channeled to low-carbon sectors and incentives to adopt cleaner technologies increase across all sectors. These effects are illustrated by calibrating the model to data for the Euro Area.[3]

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[2] My contribution to Chapter 3 lies in the development of the theoretical model and the simulation analysis.

[3] In Chapter 4, I contributed to the development of the model and of the simulations.

Chapter 2

Regime Shift, Spillovers and the Elasticity of Substitution*

Abstract

Aiming for a reduction of the dependence on polluting energy sources, countries set targets in terms of energy generation from renewables. This translates into a regime shift in the production of energy, with costs for the economy. Subsidizing clean production represents one possible policy measure to cover such costs. We develop a general equilibrium model to analyze the subsidy required to achieve a target of clean energy production, while accounting for knowledge spillovers, substitutability between clean and dirty energy and labor mobility. Our findings show that, in order to reduce the costs of the regime shift to a low-carbon economy, policies should improve the absorption capacity of the clean energy sector, ease the substitutability between clean and dirty energy and promote labor mobility.

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2.1 Introduction

The need to limit emissions in order to avoid the undesirable consequences of climate change and promote sustainable development is nowadays widely recognized. Identifying opportunities to cut emissions of greenhouse gases and to promote the transition to a low-carbon economy requires a clear understanding of the main sources of those emissions. The energy sector is responsible for about 40% of global emissions according to the International Energy Agency's estimates (IEA 2015). Tackling emission from this sector may have therefore a remarkable impact in terms of reducing damages from climate change. In particular, a greater reliance on energy generated from clean sources may play a fundamental role. Hence, the purpose of this Chapter is to analytically and numerically explore the shift from fossil fuels towards less polluting energy sources, which we define as a regime shift.

Countries such as Germany, with the *Energiewende*, and Switzerland, with the *Energy Strategy 2050*, have started to set goals in terms of energy generated from clean sources, in order to enforce a structural change, which would ultimately reduce the share of fossil fuels in the energy mix. The shift to a greater reliance on clean energy has a cost for the economy; producing energy from renewables is, at least in the short term, more expensive than from conventional technologies as it requires the development of new production processes and the adaptation of infrastructures. Moreover, some renewable energies exhibit specific characteristics such as variability and non-storability, which make them more expensive.[1]

The regime shift can therefore only succeed if the costs associated with newer and cleaner technologies are reduced. This could be induced through a support scheme in the form of a subsidy to energy generated from clean sources, such as a feed-in tariff, an innovation subsidy, which reduces the fixed costs of installing the cleaner technology, or a subsidy to clean research and development (R&D) (Acemoglu et al. 2012, Heggedal 2015, Greaker et al. 2018). A second oppor-

[1] These characteristics do not apply to all renewable energies, e.g. hydro energy.

tunity to ease the regime shift, other than a rationale for policy intervention, is represented by technological learning in the form of knowledge accumulation and diffusion through spillovers, which has been shown to be generally stronger for newer and cleaner technologies (McDonald and Schrattenholzer 2001, Hart 2004, Dechezleprêtre et al. 2014, Bretschger et al. 2017). Finally, previous works have emphasized that the costs of the regime shift can be reduced by an improved substitutability between clean and dirty energy technologies (Acemoglu et al. 2012, Greaker et al. 2018).

The aim of this Chapter is to analyze how the subsidy needed to achieve a given target in terms of energy generation from clean sources is affected by knowledge spillovers, while accounting for the substitutability between clean and dirty energy intermediates and labor mobility. In order to answer this question we develop a general equilibrium model in the spirit of Romer (1986): we consider an economy in which final production is based on the aggregation of clean and dirty energy intermediates according to a certain degree of substitutability. Each intermediate combines knowledge-capital, that is, physical capital together with the knowledge embedded in it, and labor to produce clean and dirty energy, respectively. Each sector receives spillovers from clean and dirty knowledge-capital stocks.[2] However, the intensity of spillovers, which in our setting can be interpreted as absorption capacity, is heterogeneous across sectors (Bosetti et al. 2008, Bretschger et al. 2017). We also allow for state dependence in the spillover effects, as analyzed, for instance, by Acemoglu (2002) and Aghion et al. (2016). Our focus is on governmental targets in terms of energy production from clean sources, which can be achieved by providing subsidies to clean firms. Although, we acknowledge that there might be other welfare costs due to the shift in the energy production structure, this is not the focus of the present Chapter. Instead, we investigate which channels affect the

[2] Although we acknowledge that the stock of knowledge for clean and dirty energy is to a large extent global stocks of knowledge—meaning that the production of clean energy and subsidies to it in a small country will have a marginal impact on the global stock of knowledge—this does not impair our results as the mechanisms described are qualitatively not affected.

cost of the regime shift and, consequently, the value of the subsidy. In particular, we analyze the impact of knowledge spillovers and substitutability between clean and dirty energy intermediates, as well as labor mobility. Given the uncertainty about the structural impact of a regime shift and the lack of consensus about the correct formalization of spillovers, our model includes different specifications. In particular, we develop cases where (i) spillovers are a Cobb-Douglas combination of clean and dirty knowledge-capital stocks, (ii) the two stocks are perfect substitutes in the determination of spillovers, and (iii) no spillovers are present. Moreover, we consider fixed and mobile labor in order to allow for adjustments in the labor supply following government intervention. The objective of the theoretical model is to understand which channels affect the outcome of energy policies. We then provide numerical simulations of our model using parameter values in accordance with the literature to illustrate the impact of the relative spillover intensity, the substitutability between clean and dirty energy and labor mobility on the subsidy provided to clean firms.

The main findings of the Chapter are: (1) the subsidy needed to increase clean energy generation is lower in the presence of knowledge spillovers and decreases (increases) with the spillover intensity in the clean (dirty) sector; (2) the costs of the regime shift are lower when the two energy intermediates are better substitutable; (3) unrestricted labor mobility eases the regime shift. Our results show that the spillovers, the substitutability between clean and dirty energy intermediates and the structure of the labor market should be taken into account when designing a shift towards a more sustainable production structure. Specifically, policymakers should adopt measures to foster the absorption capacity of firms in the clean sectors, such as relaxing patent policies. Moreover, investments should aim at easing the substitution between clean and dirty energy technologies, promoting for instance storage options for intermittent renewable energies. Finally, policies should aim at reducing the frictions in the labor market by providing, among others, job training programs.

2.1.1 Relation to the literature

In the present Chapter, the feasibility of the regime shift depends on the possibility to reduce the costs of the clean energy technology. We argue that this can be achieved by policy intervention in the form of a subsidy to clean production, while accounting for knowledge spillovers and substitutability between clean and dirty energy. Thus, in what follows, we discuss how the present Chapter relates to the existing literature analyzing these issues.

The Chapter relies on the literature which studies the measures enforcing an energy transition by increasing the share of renewable energy in the total energy mix (Anderson and Winne 2007, Johnstone et al. 2010, Popp 2010, Proença and Aubyn 2013, Greiner et al. 2014). The most widely studied measures in the literature are subsidies to R&D for clean technologies, which are identified as a driver of costs reduction and technological innovation. Acemoglu et al. (2012), for example, show that subsidies for R&D are crucial for tackling climate change. Greaker et al. (2018) analyze R&D subsidies as well as carbon taxes, and find that subsidies to clean R&D should be prioritized because the knowledge spillovers overweight the ones of the dirty sector. Heggedal (2015) provides another rationale for subsidies to clean R&D by linking them to the growth rates of the knowledge stocks: the production of new ideas depends on the accumulated stock of knowledge and the productivity gain from new ideas is declining in the size of the knowledge stock; as the clean knowledge stock is relatively small, this provides a rationale for subsidies to clean R&D.

Importantly, all the previous papers focus on clean R&D subsidies, but none of them considers a subsidy to production in the form of a feed-in tariff, which is the focus of the present work. In this we follow Johnstone et al. (2010), who find that targeted subsidies are needed to induce innovation on more costly energy technologies.

The connection between spillovers and R&D subsidies has been studied extensively; for example, the papers by Heggedal (2015) and Greaker et al. (2018)

mentioned before, recognize the presence of higher knowledge spillovers in clean technologies as a rationale for policy support, particularly in the form of R&D subsidies to clean research. Moreover, spillovers represent a channel affecting the policy measures adopted to support clean technologies. Therefore, the Chapter builds on the literature on technology adoption and knowledge spillovers, both for modeling and calibration. Spillovers, within and across sectors, as well as across countries, can play an important role in promoting technological change and can mitigate the negative impact on welfare from environmental policies (Grossman and Helpman 1991, Mäler and Munasinghe 1996, Eaton and Kortum 1999, Bretschger et al. 2017). Hart (2004) builds a model where knowledge spillovers can lead to a cost-offset at the inter-firm level; however, unlike us, they exclude intra-sectoral knowledge spillovers from the ordinary sector to the clean one. Energy technology advances also rely on knowledge originating in other technological areas; in this respect, Nemet (2012) uses patent data to analyze inter-technology spillovers: he finds that knowledge spillovers across technological domains are an essential aspect of energy innovation. Accordingly, in our model specification, we allow for cross-sectoral spillovers. For our spillover specification, we rely on the concepts of absorption capacity, state dependency and learning rates, as discussed in the following.

The absorption capacity is an important element in the literature on knowledge diffusion, as it represents the ability to recognize the value of new information, assimilate and apply it. On this regard, the present Chapter builds on Bosetti et al. (2008): although we consider spillovers across sectors and not across countries, our paper also relies on the concepts of a knowledge pool, captured by the relevant knowledge-capital stocks firms are exposed to, and of absorption capacity, in the form of the intensity of spillovers in each sector. Determinants of the absorption capacity may be industrial policies and the legal environment, but it is generally recognized as a function of prior related knowledge (Cohen and Levinthal 1989, Levinthal 1990, Griffith et al. 2003, Keller 2004). Our results are in line with Cohen and Levinthal (1989), showing that for a lower absorption capacity the costs of the regime shift are higher. Bretschger et al. (2017) introduce a knowledge pool and absorption capacity to show that knowledge diffusion leads to a "greening" of economies; however, we deviate from their work as our focus is on the specific impact of the knowledge spillover intensity on the subsidy provided to clean firms. Our results are in line with Greaker et al. (2018), who study the impact of spillovers on the optimal subsidy, accounting for the degree of spillovers. However, we abstain from the modeling of innovation and we do not focus on R&D provisions. Moreover, in their specification the spillovers are between clean and dirty R&D and not between knowledge-capital stocks as in our case and we consider spillovers between the two energy sectors also in the theoretical analysis.

A crucial assumption of our model is that, using the terminology introduced by Acemoglu (2002), spillovers are state-dependent, so that productivity in one sector builds to a larger extent on the knowledge-capital stock in that sector. Specifically, Acemoglu (2002) adopts a knowledge-based R&D specification, whereby spillovers are due to the fact that current researchers "stand on the shoulders of giants". Similarly, Aghion et al. (2016) show a path-dependence in innovation in the automotive sector, following from spillovers and firms' histories.

Turning to the third characteristic of our spillover specification, newer and cleaner energy technologies are usually found to have relatively high learning rates compared to mature fossil energy technologies, that is, the constant percentage decrease in unit costs due to a doubling of experience is larger (Jamasb et al. 2007). In our simulation exercise, the choice of the relative spillover intensity between clean and dirty technologies reflects the energy-related learning rates provided by McDonald and Schrattenholzer (2001) and Kouvaritakis et al. (2000). Moreover, in our specification we rely on Dechezleprêtre et al. (2014) and Bretschger et al. (2017), who find that clean spillovers have on average a stronger impact on productivity than dirty spillovers. Another important reference for us is Van Benthem et al. (2008), where it is shown that a "learning by doing" effect for clean technologies justifies a much higher subsidy scheme than the one determined by the negative environmental externality alone. Unlike us, they consider subsidies on the demand side; however, we model the same positive externality as productivity in our model depends on the knowledge-capital stock.

Last, the feasibility of the regime shift is analyzed by accounting for the substitutability between clean and dirty energy intermediates. In our framework the degree of substitutability is assumed to be exogenous; however, factors determining the substitution possibilities between goods have been the object of previous studies. Therefore, the Chapter is related to the literature on endogenous substitutability between products, product differentiation and trade openness (Dixit and Stiglitz 1977, Broda and Weinstein 2006, Arkolakis et al. 2008, Lorz and Wrede 2009). For instance, Ferguson (2015) predicts an inverted U-shaped relationship between trade liberalization and product differentiation, which implies that the substitutability between products first decreases and then increases depending on the degree of openness of a country. The substitutability between inputs of production has been studied, for example, by Bretschger (1998) and Bretschger and Smulders (2012) who focus on the implication of substitution possibilities between inputs for sustainable growth.
The value of the elasticity of substitution between clean and dirty goods at broad and specifically between clean and dirty energy intermediates is a discussed topic. In our calibration we adopt values of the elasticity in line with Greaker et al. (2018) and we follow Papageorgiou et al. (2017), who estimate the elasticity of substitution between clean and dirty inputs within the energy aggregate and find evidence that it significantly exceeds unity. The choice of the value of the elasticity of substitution has implications for the cost of the policy analyzed. In their numerical simulation, Greaker et al. (2018) find that if the elasticity of substitution between clean and dirty inputs is relatively high, the cost of relying on a subsidy to clean R&D is smaller than for lower values of the elasticity. We find an equivalent result, when considering the effect of the elasticity of substitution between clean and dirty

energy inputs on the subsidies to production.

Our contribution is to identify channels that can determine the size of the subsidy needed for the transition to a low-carbon economy and to integrate them into a unified general equilibrium framework. The model is used to study the steady-state equilibria under a specific target in terms of clean to dirty energy production.[3] We determine the share of inputs allocated to each sector and the value of the subsidy needed to increase energy generation from clean sources, depending on the strength of spillovers and on the elasticity of substitution. The model analysis is accompanied by simulations illustrating the effect of spillover intensity and elasticity of substitution on the subsidy needed to achieve a specific target.

The Chapter is organized as follows. In section 2.2, we develop the theoretical model. In section 2.3, we present our simulation exercise and provide a discussion of the results, whereas in Section 2.4 we perform a sensitivity analysis for crucial parameters of the model. Section 2.5 concludes and introduces possible lines for future research.

2.2 Model

In this section we present the general equilibrium model. Time is discrete and indexed by $t = 0, 1, \dots$. We consider a closed economy populated by a continuum of households with mass normalized to unity, so that we focus on a representative household. In our analysis, we assume no population growth and that households supply their endowment of physical capital K_t and of labor L_t to firms. We normalize the labor endowment to unity, that is, $L_t = 1$. There are two stages of production. A continuum of final sector firms produces output Y according to a constant elasticity of substitution (CES) aggregation. We assume that final production is based on the conversion of clean energy Y_c and dirty energy Y_d generated

[3]Due to the complexity of the analysis, the results are derived in the steady state. Important contributions on the timing are Acemoglu et al. (2012), Gerlagh et al. (2014) and Bjertnæs et al. (2018).

by intermediate firms.[4]

Assumption 2.2.1 (Final good production) *The production function for the final good reads*[5]

$$Y = \left[\gamma Y_c^{\frac{\sigma-1}{\sigma}} + (1-\gamma) Y_d^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{2.1}$$

where $\gamma \in (0,1)$ denotes the distribution parameter and $\sigma \in (0,\infty)$ denotes the elasticity of substitution between inputs.

For $\sigma > 1$ the two input factors are substitutes, whereas for $\sigma < 1$ they are complements. Although it is unclear to what extent, the case of substitutable clean and dirty energy inputs appears as the more empirically relevant and will be the focus of the present Chapter (Papageorgiou et al. 2017). Intermediate energy outputs Y_i are produced combining knowledge-capital, that is, physical capital as well as the knowledge embedded in it, denoted by K_i, and labor L_i; the latter is augmented by a sector-specific productivity term A_i.[6] The productivity level A_i can increase following technological development or decrease if sector-specific knowledge becomes obsolete. As we will outline later, productivity depends on the spillovers received by each sector. The production technologies for clean and dirty energy intermediates satisfy a symmetric Cobb-Douglas structure and are assumed to be known by the firms.

[4] We acknowledge that energy can be considered as a homogeneous good; however, homogeneity only applies at a certain point in time and in a given location. Heterogeneity may result from specific attributes of each energy source, such as fixed costs, supply intermittency, back-up capacity, and pollution intensity. Consequently, energy generated from one source is not perfectly substitutable with energy generated from another source (Hirth et al. 2016).

[5] The assumption that final output is only produced with energy intermediates relies on the energy services interpretation of the outputs produced by intermediate firms. Such services can be used for production of every good in the economy.

[6] In this we follow the standard neoclassical approach of Harrod-neutral technical change; moreover, labor augmenting technical change is consistent with the long-run stability of factor shares and with the medium-term responses to changes in capital stock, labor supply or technology (Barro and Sala-i Martin 1995).

Assumption 2.2.2 (Intermediate good production) *The two factors of production are combined in a Cobb-Douglas fashion, so that*

$$Y_i = K_i^{\alpha}(A_i L_i)^{1-\alpha}. \tag{2.2}$$

where $\alpha \in (0,1)$ represents the capital intensity.

Capital is assumed to be perfectly mobile across sectors. Due to market clearing for physical capital, in equilibrium total capital in the economy is given by $K = K_c + K_d$. Physical capital follows a standard law of motion, which entails a depreciation in each period by a share $\delta \in [0,1]$, so that

$$K_{t+1} = (1-\delta)K_t + I_t.$$

We consider both fixed and mobile labor. Specifically, we assume that sector i hires a share $L_i \in (0,1)$, with $L_c + L_d = 1$, where the share is fixed when labor cannot move across sectors and can vary otherwise. The assumption of fixed labor might not seem reasonable, but is used in the model for comparison with the more empirically relevant case of mobile labor, which we introduce at a later stage.

2.2.1 Households

The representative household maximizes a discounted, time-separable utility across the infinite horizon.

Assumption 2.2.3 (Utility function) *The utility function of households is given by*

$$\mathcal{U}(C) = \sum_{t=0}^{\infty} \beta^t u(C_t),$$

where $C = \{C_t\}_{t=0}^{\infty}$ represents life-time consumption, $\beta \in (0,1)$ is the discount factor and $u(\cdot)$ is continuously differentiable, strictly increasing, strictly concave and satisfies the Inada conditions.

Final output can be used for consumption C_t and investment I_t, leading to the standard resource constraint $Y_t \geq C_t + I_t$. Besides the resource constraint and the law of motion for physical capital, households face the budget constraint

$$Y_t \leq q_t K_t + w_{c,t} L_{c,t} + w_{d,t} L_{d,t} + \Pi_t + T_t,$$

where q_t is the real rental rate of capital, $w_{i,t}$ is the wage rate in sector i, Π_t represents the real profits of intermediate and final producers, and T_t represents lump-sum transfers from the government. The latter operates with a balanced budget. Thus, as long as no policies are applied it holds $T_t = 0$. The output good is the numeraire in our economy, so that real prices are in terms of the final output good. As the utility of households is strictly increasing, it follows that the resource and budget constraints are binding, and can be consolidated into a single constraint, that is,

$$C_t = (1 + q_t - \delta) K_t - K_{t+1} + w_{c,t} L_{c,t} + w_{d,t} L_{d,t} + T_t,$$

where we used the law of motion for physical capital. The first-order conditions of the maximization problem are then given by

$$u'(C_t) = \beta u'(C_{t+1})(1 + q_{t+1} - \delta), \quad \forall t \geq 0.$$

The Euler equations represent necessary optimality conditions, which however in combination with the transversality condition $\lim_{t \to \infty} \beta^t u'(C_t) K_{t+1} = 0$ are sufficient for the optimization problem of households.

2.2.2 Final output producers

Firms producing final output exist in a continuum and combine energy produced by clean and dirty intermediate sectors in a CES fashion. As the production function is homogeneous of degree one, final producers make zero profits in each period.

Thus, we can focus on the static maximization problem in each period

$$\max_{Y_c, Y_d} \; Y - p_c Y_c - p_d Y_d,$$

where Y is given by (2.1) and p_c and p_d denote the real prices for clean and dirty energy respectively. The first-order conditions are therefore given by

$$p_c = \gamma \left(\frac{Y_c}{Y} \right)^{-\frac{1}{\sigma}} \qquad \text{and} \qquad p_d = (1-\gamma) \left(\frac{Y_d}{Y} \right)^{-\frac{1}{\sigma}}. \tag{2.3}$$

2.2.3 Intermediate producers

Intermediate firms in sector $i \in \{c, d\}$ exist in a continuum. They rent capital K_i from households at price q and demand labor L_i at wage rate w_i, where the latter can differ across sectors when labor is fixed and is identical otherwise. Similar to final producers, intermediate firms operate with a technology that satisfies constant returns to scale, so that they make zero profits in each period. Since firms do not account for spillovers, their optimization problem in each period is given by

$$\max_{K_i, L_i} p_i Y_i - q K_i - w_i L_i,$$

where Y_i is given by (2.2). The first-order conditions of the maximization problem are given by

$$q K_i = \alpha p_i Y_i \qquad \text{and} \qquad w_i L_i = (1-\alpha) p_i Y_i. \tag{2.4}$$

2.2.4 Spillovers

Given the uncertainty about the correct specification of spillovers, we analyze various functional forms within our framework: in particular, we consider a Cobb-Douglas and a perfect substitute combination of clean and dirty knowledge-capital stocks, as well as a no spillover case.

Cobb-Douglas spillovers

Following Acemoglu (2002), we assume that sectoral productivities depend on spillovers from knowledge-capital stocks allocated to each sector according to a Cobb-Douglas specification.[7]

Assumption 2.2.4 (Cobb-Douglas specification of spillovers) *Spillovers from capital stocks follow a Cobb-Douglas specification, so that*

$$A_c = B_c K_c^{\frac{1+\phi_c}{2}} K_d^{\frac{1-\phi_c}{2}} \qquad \textit{and} \qquad A_d = B_d K_c^{\frac{1-\phi_d}{2}} K_d^{\frac{1+\phi_d}{2}}, \tag{2.5}$$

where $B_i > 0$ represents the spillover intensity and $\phi_i \in [-1, 1]$ denotes the state-dependence in sector i.

Our specification implies that the productivity is affected by both the intensity of spillovers (or absorption capacity) B_i and the amount of capital allocated to each sector, K_c and K_d.[8] In particular, the term $K_c^{\frac{1+\phi_c}{2}} K_d^{\frac{1-\phi_c}{2}}$ represents the knowledge-capital stock relevant to firms in the clean sector, that is, their knowledge pool. The same holds for firms in the dirty sector. The parameter ϕ_i represents the state-dependence in sector i and determines the impact of each type of capital on the productivity in the respective sector. With $\phi_i = 0$ there is no state-dependence, as K_c and K_d create the same spillovers for current productivity in both sectors. With $\phi_i = 1$ state-dependence is strong and spillovers from the other sector do not play any role: clean capital increases the clean sector productivity, but has no effect on the productivity of the dirty sector. Thus, we only observe a self-reinforcing effect of K_c (K_d) on A_c (A_d). On the contrary, for $\phi_i = -1$ spillovers from the other sector are all that matters. Following Greaker et al. (2018) and Aghion et al. (2016), we assume that sectoral productivity is more strongly driven

[7]See Acemoglu (2002) for the knowledge-based R&D specification, where spillovers ensure that the marginal productivity of research does not decline, and Dechezleprêtre et al. (2014) and Bretschger et al. (2017) for a discussion of the impact of cross-sectoral and cross-countries spillovers.

[8]The AK structure is justified by the fact that the model provides a comparative static exercise to analyze the steady-state equilibrium.

by spillovers from capital allocated to the same sector; accordingly, we restrict our analysis to $\phi_i \in [0, 1]$. However, the magnitude of the impact of sectoral capital on sectoral productivity differs between the clean and dirty sector; we assume a stronger effect in the clean sector ($\phi_c > \phi_d$), although this does not affect the results qualitatively. Empirical evidence argues in favor of stronger spillover from clean technologies compared to dirty ones (Dechezleprêtre et al. 2014). In our model, this implies a stronger absorption capacity of the clean sector, that is, $B_c > B_d$.[9] Given Assumption 2.2.2, this implies that A_c is more sensitive than A_d to shocks in the knowledge-capital stock. However, the larger availability of dirty capital compared to clean capital ($K_c < K_d$) decreases the initial spillover effect in the clean sector. We study the initial situation in which the clean sector is backward relative to the dirty sector, that is $A_c < A_d$, even though $B_c > B_d$. The relationship might reverse over time, also due to government intervention (for instance, as a consequence of subsidies to clean energy production). The condition $A_c < A_d$ is satisfied for

$$\frac{K_c}{K_d} < \left(\frac{B_c}{B_d}\right)^{-\frac{1}{\phi_c+\phi_d}},$$

showing that if $B_c = B_d$, the productivities only depend on the stock of capital allocated to each sector. For $B_c = B_d$, $K_c < K_d$ implies $A_c < A_d$ meaning that the switch to higher productivity in the clean sector relative to the dirty one can only take place if K_c becomes larger than K_d. For $B_c > B_d$, instead, the switch can already take place for a capital allocation satisfying $K_c < K_d$. Defining the share of capital allocated to the clean sector as $\zeta := K_c/K$, and using Assumption 2.2.2,

[9] Admittedly, this represents a reasonable assumption in the short run, but may be not satisfied in the long run as technologies become mature. However, following the introduction of policy measures, the share of capital allocated to each sector in the economy adjusts over time; in particular, as productivity increases in the clean sector, more capital will be allocated to it, so that, even if intensity of spillover decreases, the economy is by then locked-in the green sector (Acemoglu et al. 2012).

sectoral production can be expressed as

$$Y_c = \zeta^{\Theta_c}(1-\zeta)^{1-\Theta_c}\tilde{B}_c^{1-\alpha}K =: Z_c(\zeta)K, \quad (2.6)$$
$$Y_d = \zeta^{1-\Theta_d}(1-\zeta)^{\Theta_d}\tilde{B}_d^{1-\alpha}K =: Z_d(\zeta)K,$$

where we use the notation $\tilde{B}_i := B_i L_i$ and $\Theta_i := \frac{2\alpha+(1+\phi_i)(1-\alpha)}{2} > 1 - \Theta_i := \frac{(1-\phi_i)(1-\alpha)}{2}$; this implies that the share of capital allocated to the clean sector plays a major role in the determination of output in the clean sector; on the contrary, output in the dirty mostly relies on the share of capital allocated to that sector. In what follows we let $\Theta := (\Theta_c + \Theta_d)/2$.

Perfect substitute spillovers

As a second specification for spillovers, we assume perfect substitutability of clean and dirty knowledge-capital stocks.

Assumption 2.2.5 (Perfect substitute specification of spillovers) *Spillovers from capital stocks follow a perfect substitute specification, so that*

$$A_c = B_c[\psi_c K_c + (1-\psi_c)K_d] \qquad \textit{and} \qquad A_d = B_d[(1-\psi_d)K_c + \psi_d K_d],$$

where $B_i > 0$ and $\psi_i \in [0,1]$ is the state-dependence parameter.

For $\psi_i = 1$, sectoral productivities only depend on sectoral capital; for $\psi_i = 0$, sectoral productivity only depends on capital allocated to the other sector. Thus, the parameter ψ_i captures the relative weight of the two capital stocks. Given the new specification, energy generation by the two intermediate sectors can be written as

$$Y_c = \zeta^{\alpha}\tilde{B}_c^{1-\alpha}[\psi_c\zeta + (1-\psi_c)(1-\zeta)]^{1-\alpha}K =: Z_c(\zeta)K,$$
$$Y_d = (1-\zeta)^{\alpha}\tilde{B}_d^{1-\alpha}[(1-\psi_d)\zeta + \psi_d(1-\zeta)]^{1-\alpha}K =: Z_d(\zeta)K,$$

where, as before, $\tilde{B}_i := B_i L_i$.

No spillovers

When the economy does not benefit from spillovers, intermediate production in the two sectors becomes

$$Y_c = \zeta^{\alpha}(A_c L_c)^{1-\alpha} K^{\alpha} =: Z_c(\zeta) K^{\alpha},$$
$$Y_d = (1-\zeta)^{\alpha}(A_d L_d)^{1-\alpha} K^{\alpha} =: Z_d(\zeta) K^{\alpha},$$

where $A_c, A_d > 0$ are constant.

2.2.5 Equilibrium

In this Section we derive the equilibrium allocation for the different spillover specifications, in the case of fixed and mobile labor. We focus on competitive equilibria as defined hereafter.

Definition 2.2.1 (Competitive equilibrium) *A competitive equilibrium is characterized by prices* $\{p_{c,t}, p_{d,t}, q_t, w_{c,t}, w_{d,t}\}_{t=0}^{\infty}$ *and allocations* $\{C_t, K_{t+1}, K_{c,t}, K_{d,t}, L_{c,t}, L_{d,t} Y_{c,t}, Y_{d,t}\}_{t=0}^{\infty}$*, so that*

(1) given prices $\{q_t, w_{c,t}, w_{d,t}\}_{t=0}^{\infty}$*, the choices* $\{C_t, K_{t+1}\}_{t=0}^{\infty}$ *maximize the utility of households,*

(2) given prices $\{p_{c,t}, p_{d,t}, q_t, w_{c,t}, w_{d,t}\}_{t=0}^{\infty}$*, the choices* $\{K_{i,t}, L_{i,t}\}_{t=0}^{\infty}$ *maximize the profits of intermediate producers in sector* $i \in \{c, d\}$*,*

(3) given prices $\{p_{c,t}, p_{d,t}\}_{t=0}^{\infty}$*, the choices* $\{Y_{c,t}, Y_{d,t}\}_{t=0}^{\infty}$ *maximize the profits of final producers,*

(3) each period capital and labor markets clear, that is, $K_t = K_{c,t} + K_{d,t}$ *and* $L_t = L_{c,t} + L_{d,t}$.

Proposition 2.2.1 (Competitive equilibrium) *Any competitive equilibrium is characterized by*

(1) prices $\{p_{c,t}, p_{d,t}, q_t, w_{c,t}, w_{d,t}\}_{t=0}^{\infty}$ *that satisfy* (2.3) *and* (2.4)*,*

(2) consumption C_t *and capital accumulation* K_{t+1} *decisions which follow, for all* $t \geq 0$*, from*

$$u'(C_t) = \beta u'(C_{t+1})(1 + q_{t+1} - \delta)$$

and satisfy the transversality condition $\lim_{t\to\infty} \beta^t u'(C_t) K_{t+1} = 0$*,*

(3) the share of capital allocated to the clean sector ζ_t *follows from equating* (2.3) *and* (2.4) *after substituting for the spillover specifications in intermediate production.*

Proposition 2.2.2 (Capital allocation with fixed labor) *The share of capital allocated to the clean sector differs according to the assumed spillover specification. In particular, we obtain:*[10]

(1) Cobb-Douglas spillovers:

$$\zeta_{CD} = \frac{1}{1 + D_{CD}^{-1}},$$

$$\text{where} \quad D_{CD} := \left[\left(\frac{\gamma}{1-\gamma} \right)^{-\sigma} \left(\frac{\tilde{B}_c}{\tilde{B}_d} \right)^{(\alpha-1)(\sigma-1)} \right]^{\frac{1}{1-2\Theta+2\sigma(\Theta-1)}}.$$

[10] The mathematical derivation of these results is provided in Appendix 5.1.2.

(2) Perfect substitute spillovers (for $\psi_i = 0.5$):[11]

$$\zeta_{PS} = \frac{1}{1 + D_{PS}^{-1}},$$
$$\text{where} \quad D_{PS} := \left[\left(\frac{\gamma}{1-\gamma} \right)^{-\sigma} \left(\frac{\tilde{B}_c}{\tilde{B}_d} \right)^{(\alpha-1)(\sigma-1)} \right]^{\frac{1}{(\sigma-1)\alpha-\sigma}}.$$

(3) No spillovers:

$$\zeta = \frac{1}{1 + D^{-1}},$$
$$\text{where} \quad D := \left[\left(\frac{\gamma}{1-\gamma} \right)^{-\sigma} \left(\frac{A_c L_c}{A_d L_d} \right)^{(\alpha-1)(\sigma-1)} \right]^{\frac{1}{(\sigma-1)\alpha-\sigma}}.$$

Note that in the perfect substitute case (with $\psi_i = 0.5$) and in the no spillover case, the outer exponent of the terms D_{PS} and D is always negative as it holds $(\sigma - 1)\alpha - \sigma < 0$. Therefore, the share of capital allocated to the clean sector increases with the relative importance of the clean sector in total production, as captured by the distribution parameter γ. Clearly, if the demand for clean energy in final production is higher, a higher share of capital has to be allocated to the intermediate production of clean energy. Moreover, for $\sigma > 1$, that is, clean and dirty energy are substitutes, the share of capital allocated to the clean sector is, in the case of perfect substitute spillover, increasing in the relative absorption capacity B_c/B_d and, in the case of no spillovers, increasing in the relative productivity A_c/A_d. By way of example, an increase in the sectoral spillover intensity or total factor productivity leads to an increase of the marginal productivity in the respective sector, so that the latter must receive a larger share of capital to restore the previous level of relative marginal productivities across the two sectors.

If clean and dirty energy are perfect substitutes in final production, marginal

[11] In the case of perfect substitute spillovers, a simple solution can be obtained only for the distribution parameter $\psi_i = 0.5$. Appendix 5.1.3 provides a discussion for the case $\psi_i \neq 0.5$.

productivities must be equal; this is however not necessarily satisfied in the case of imperfect substitutes or complements. Following the same reasoning, in the case of perfect substitute spillovers (with $\psi_i = 0.5$) and no spillovers, the share of capital also increases with the labor supply to the clean sector. For $\sigma < 1$, that is, clean and dirty energy are complements, the impact of the relative spillover intensity, relative total factor productivity and labor supply on the share of capital allocated to the clean sector is reversed. If clean and dirty energy are complements, final production requires using both intermediates in a certain proportion. An increase in the sectoral spillover intensity, total factor productivity or labor supply leads to an increase in production of the respective sector, which, however, needs to counteracted by providing less capital to that sector, so that the previous proportion of clean and dirty energy outputs are restored.

In the case of Cobb-Douglas spillovers, the comparative statics are more difficult to evaluate as they involve not only, as before, the elasticity of substitution σ and the capital intensity α, but also the state-dependence parameters, namely ϕ_c and ϕ_d. In the following, we outline the effects for the extreme cases in which the latter assume values $\phi_c = \phi_d = 1$ and $\phi_c = \phi_d = 0$. If spillovers in one sector only depend on the own knowledge-capital stock, meaning that $\phi_c = \phi_d = 1$, the outer exponent in the term D_{CD} is always negative, so that the previous conclusions for the cases of perfect substitute spillovers and no spillovers still hold. If the knowledge-capital stocks are equally important in the determination of spillovers, that is, $\phi_c = \phi_d = 0$, then the outer exponent is given by $-1 + 2\alpha(\sigma - 1)$. Thus, the capital share allocated to the clean sector reacts positively to an increase in relative spillover intensity B_c/B_d, the relative importance of the clean sector in production γ and relative labor supply L_c/L_d for $1 < \sigma < (1 + 2\alpha)/2\alpha$. For values of the elasticity of substitution above the threshold, all effects are reversed, while for values below unity, only the effects regarding the relative spillover intensity and labor supply are reversed. In the simulation analysis, we illustrate the effects described above and we provide a sensitivity analysis with regard to the parameters

B_c/B_d and σ, as well as A_c/A_d, γ, ϕ_c and ϕ_d.

In what follows, we focus on the case of mobile labor. Due to the market clearing for labor, in equilibrium it holds $L_c + L_d = 1$, or equivalently, $L_d = 1 - L_c$. Production in the final and intermediate sectors is given, as before, by equations (2.1) and (2.2). Since labor is mobile across sectors, it follows from the optimization problem of intermediate firms that the capital-labor ratio must be the same for both intermediate producers, that is,[12]

$$\frac{\zeta}{1-\zeta} = \frac{L_c}{1-L_c}, \qquad \text{or alternatively,} \qquad L_c = \frac{1}{1+\frac{1-\zeta}{\zeta}}. \tag{2.7}$$

Proposition 2.2.3 (Capital allocation with mobile labor) *The share of capital allocated to the clean sector differs according to the assumed spillover specification. In particular, we obtain:*[13]

(1) Cobb-Douglas spillovers:

$$\zeta^m_{CD} = \frac{1}{1+(D^m_{CD})^{-1}},$$
$$\text{where} \quad D^m_{CD} := \left[\left(\frac{\gamma}{1-\gamma}\right)^{-\sigma}\left(\frac{B_c}{B_d}\right)^{(\alpha-1)(\sigma-1)}\right]^{\frac{1}{[1-\alpha+2(\Theta-1)](\sigma-1)-1}}.$$

(2) Perfect substitute spillovers (for $\psi_i = 0.5$):

$$\zeta^m_{PS} = \frac{1}{1+(D^m_{PS})^{-1}},$$
$$\text{where} \quad D^m_{PS} := \left[\left(\frac{\gamma}{1-\gamma}\right)^{-\sigma}\left(\frac{B_c}{B_d}\right)^{(\alpha-1)(\sigma-1)}\right]^{\frac{1}{1-2\sigma+2\alpha(\sigma-1)}}.$$

[12] See Appendix 5.1.4 for a derivation of this result.

[13] The mathematical derivation of these results is again provided in Appendix 5.1.2.

(3) No spillovers:

$$\zeta^m = \frac{1}{1 + (D^m)^{-1}},$$
$$\textit{where} \quad D^m := \left[\left(\frac{\gamma}{1-\gamma} \right)^{-\sigma} \left(\frac{A_c}{A_d} \right)^{(\alpha-1)(\sigma-1)} \right]^{\frac{1}{1-2\sigma+2\alpha(\sigma-1)}}.$$

Note that in the case of perfect substitute spillovers and no spillovers, the outer exponent on the terms D_{PS} and D is negative if it holds $\sigma > (1/2 - \alpha)/(1 - \alpha)$. Thus, for any such σ, which is also larger than unity, the share of capital allocated to the clean sector responds positively to an increase in the relative spillover intensity, relative importance of the clean sector and relative total factor productivity. The effect of the relative spillover intensity and relative total factor productivity is maintained for any σ lower than the threshold, but is reversed for any σ exceeding the threshold and smaller than unity. In contrast, the effect of the distribution parameter γ stays the same for any σ greater than the threshold, but is reversed for any σ below this value. The intuition for these effects follows from the previous remark provided for the case of fixed labor. Accounting for mobile labor thus does not alter our conclusions in the case of clean and dirty energy being substitutes. On the other hand, it complicates the analysis in the case in which energy intermediates are complements; however, the latter is less empirically relevant and therefore will not be the focus of the subsequent analysis (Papageorgiou et al. 2017).

In the case of Cobb-Douglas spillovers, we outline the effects for the extreme cases in which the state-dependence parameters assume values $\phi_c = \phi_d = 0$ and $\phi_c = \phi_d = 1$. In the first case, the outer exponent in the term D_{CD} is always negative, so that the previous conclusions for the cases of perfect substitute spillovers and no spillovers still hold. For $\phi_c = \phi_d = 1$, the outer exponent is given by $(1 - \alpha)(\sigma - 1) - 1$. Therefore, the capital share allocated to the clean sector reacts positively to an increase in relative spillover intensity B_c/B_d and in the relative importance of the clean sector in production γ for $1 < \sigma < (2 - \alpha/1 - \alpha)$.

2.2.6 Regime shift

In what follows, we introduce the possibility of undertaking a regime shift, assuming different spillover specifications and modeling fixed as well as mobile labor. We assume that the government sets a target ratio $x \in [0, \infty)$ of energy generated from the clean sector, that is,

$$x = \frac{Y_c}{Y_d}.$$

The introduction of the target entails distortions in the economy so that the capital share allocated to the clean sector will, in general, be different from the one emerging in the equilibrium with no policies.

Proposition 2.2.4 (Capital allocation with target and fixed labor) *The share of capital allocated to the clean sector in order to achieve the target differs according to the assumed spillover specification. In particular, we obtain:*[14]

(1) Cobb-Douglas spillovers:

$$\bar{\zeta}_{CD} = \frac{1}{1 + \bar{D}_{CD}^{-1}}, \qquad \textit{where} \qquad \bar{D}_{CD} := \left[x \left(\frac{\tilde{B}_c}{\tilde{B}_d} \right)^{\alpha - 1} \right]^{\frac{1}{2\Theta - 1}}.$$

(2) Perfect substitute spillovers (for $\psi_i = 0.5$):

$$\bar{\zeta}_{PS} = \frac{1}{1 + \bar{D}_{PS}^{-1}}, \qquad \textit{where} \qquad \bar{D}_{PS} := \left[x \left(\frac{\tilde{B}_c}{\tilde{B}_d} \right)^{\alpha - 1} \right]^{\frac{1}{\alpha}}. \tag{2.8}$$

(3) No spillovers:

$$\bar{\zeta} = \frac{1}{1 + \bar{D}^{-1}}, \qquad \textit{where} \qquad \bar{D} := \left[x \left(\frac{A_c L_c}{A_d L_d} \right)^{\alpha - 1} \right]^{\frac{1}{\alpha}}. \tag{2.9}$$

[14] The mathematical derivation of these results is provided in Appendix 5.1.5.

Proposition 2.2.4 shows that for all the spillover specifications, the capital share moves with the target and decreases with the relative absorption capacity. This depends on the fact that the larger the spillovers received by the clean sector, the higher its productivity and, thus, the lower the share of capital needed to achieve the chosen target. In the case of Cobb-Douglas spillovers, this effect is not only influenced by capital intensity, but also by the state-dependence parameters related to knowledge-capital spillovers.

The difference between the target share and the share prevailing in the decentralized economy provides a rationale for policy intervention. However, for the economy to increase reliance on clean compared to dirty energy, policies covering the costs of the regime shift are required. The government can adopt a subsidy s under the constraint of a balanced budget, so that $T_t = sY_{c,t}$.[15] We assume that all proceeds are financed lump sum, so that revenues are raised in a non-distortive way. Alternatively, the government could introduce a tax on the dirty sector and thereby finance the subsidy to the clean sector. Both a subsidy and a tax alter the relative prices of energy intermediates, leading to a different composition of the final output good in terms of clean and dirty energy usage. As we are mostly interested on the impact of the subsidy, we prefer not to introduce other fiscal distortions in order to avoid the fiscal interaction between different instruments.

In order to determine the subsidy required to achieve a given target, we use the share of capital which emerges from imposing the target on clean to dirty energy production. Introducing an R&D sector in our framework, with R&D being the growth engine of the model in the spirit of Acemoglu et al. (2012) or Greaker et al. (2018), a subsidy to clean R&D would complement the subsidy to clean production introduced above. This, in turn, would lead to a lower subsidy than the one obtained in the present setup. However, the introduction of such a subsidy in the present framework, would imply an overlap with models already existing in the literature and does not serve the purpose of analyzing the impact of spillover

[15] The regime shift may involve also other welfare costs, but in this Chapter we assume that the subsidy is a proxy for such costs.

intensity, substitutability of clean and dirty energy intermediates and labor mobility on the subsidy required to achieve a certain target for clean energy production.

We now focus on mobile labor and study how this affects the outcomes when a regime shift is undertaken. Perfectly mobile labor illustrates an hypothetical situation in which labor supply responds immediately to government intervention in the form of a regime shift.

Proposition 2.2.5 (Capital allocation with target and mobile labor) *The share of capital allocated to the clean sector in order to achieve the target differs according to the assumed spillover specification. In particular, we obtain:*[16]

(1) Cobb-Douglas spillovers:

$$\bar{\zeta}^m_{CD} = \frac{1}{1 + (\bar{D}^m_{CD})^{-1}}, \qquad \textit{where} \qquad \bar{D}^m_{CD} := \left[x \left(\frac{B_c}{B_d} \right)^{\alpha - 1} \right]^{\frac{1}{2\Theta - \alpha}}. \tag{2.10}$$

(2) Perfect substitute spillovers (for $\psi_i = 0.5$):

$$\bar{\zeta}^m_{PS} = \frac{1}{1 + (\bar{D}^m_{PS})^{-1}}, \qquad \textit{where} \qquad \bar{D}^m_{PS} := x \left(\frac{B_c}{B_d} \right)^{\alpha - 1}. \tag{2.11}$$

(3) No spillovers:

$$\bar{\zeta}^m = \frac{1}{1 + (\bar{D}^m)^{-1}}, \qquad \textit{where} \qquad \bar{D}^m := x \left(\frac{A_c}{A_d} \right)^{\alpha - 1}. \tag{2.12}$$

Note that, with the introduction of mobile labor, the share of capital needed to achieve a given target x is generally lower than in the case of fixed labor; this can be obtained by comparing the terms D^m_{CB}, D^m_{PS} and D^m, with the ones obtained in the fixed labor specification.

[16] The mathematical derivation of these results is again provided in Appendix 5.1.5.

2.3 Simulations

In this section, we simulate the different model specifications developed in the theoretical part, in order to provide an insight into the magnitude of the effects considered. We show how the results are affected by the presence of spillovers, their intensity and the elasticity of substitution between clean and dirty energy, as well as labor mobility. In the next Section, we also perform a sensitivity analysis on other parameters which are relevant for our analysis.

The parameter values used in our simulations are in accordance with the literature.[17] The share of capital in intermediate production α is set to 0.3 and the discount factor β to 0.98. We assume that the distribution parameter γ is 0.5, to avoid that the relative importance of the intermediate sectors in final production biases our results. In the case of no spillovers, the productivity in the clean sector A_c is assumed to be 50% of the productivities of the dirty sector A_d, to capture the relative backwardness on the clean sector. Following Greaker et al. (2018), in our Cobb-Douglas specification we assume that intra-sectoral spillovers are stronger than inter-sectoral spillovers meaning that $\phi_i \in [0, 1]$. Furthermore, the impact of clean capital on clean productivity is stronger than the one of dirty capital on dirty productivity, that is $\phi_c > \phi_d$. In the perfect substitute case, we assume for simplicity that $\psi_c = \psi_d = 0.5$. Finally, in the fixed labor specification, we assume that 20% of labor is allocated to the clean sector and 80% to the dirty one; this assumption reflects the fact that the clean sector is initially relatively small.

Especially relevant to our analysis are the relative spillover intensity, B_c/B_d, and the elasticity of substitution, σ. We first focus on the policy implications of varying the relative intensity of knowledge spillover, keeping the value of the elasticity of substitution fixed ($\sigma = 1.1$). We set the initial intensities to be the same in the two sectors ($B_c = B_d = 0.9$); then, following Dechezleprêtre et al.

[17]See, for example, Acemoglu et al. (2012) and Greaker et al. (2018). Notice that we choose the specific parametrization only to illustrate the results in an intuitive way. The aim of the present paper is not a quantitative analysis of policy shocks.

(2014), we focus on a stronger intensity of the spillovers in the clean sector and we thus increase the intensity in that sector up to $B_c = 9$. The choice of the relative spillover intensities reflects the estimated energy-related learning rates provided by McDonald and Schrattenholzer (2001), showing that for some technologies, such as solar panels and offshore gas pipelines in the US, the learning rates are almost the same, whereas in other cases, such as wind power plants and coal power plants in OECD countries, the learning rate of clean technologies is more than two times greater and the learning rate for wind power in the US is estimated to be almost seven times bigger than the one for crude oil at well.

Secondly, we consider the impact of the elasticity of substitution, for a fixed value of relative spillover intensities ($B_c/B_d = 1.1$). We focus on the case in which clean and dirty energy energy are substitutes as it is the more established case in the literature (Papageorgiou et al. 2017). In particular, we consider low ($\sigma = 1.5$), intermediate ($\sigma = 2$) and high ($\sigma = 3$) elasticity of substitution. In this we follow Greaker et al. (2018) and we abstain from high values of the elasticity as the ones used, for instance, by Acemoglu et al. (2012).

Given the parameter values assumed above, Figure 2.1 shows the distortions in the economy entailed by the target. Note that the shares of clean and dirty output do not depend on the relative intensity of spillovers, nor on the elasticity of substitution.

In what follows, we first provide a graphical representation of the regime shift, showing how a given target transfers into a capital share allocated to the clean sector. Then, we compute the subsidy needed to achieve the target; this allows us to illustrate how the cost of the regime shift is affected by the presence of spillovers, their intensity as well as the elasticity of substitution, in the case of fixed and mobile labor.

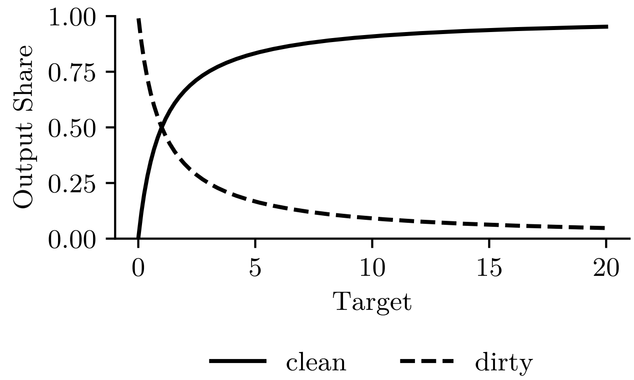

Figure 2.1: Share of clean and dirty energy as a function of the target.

2.3.1 Relative intensity of spillovers

We analyze our model for different values of the relative intensity of spillovers. Figure 2.2 shows how the regime shift takes place in the fixed (upper panels) and mobile (lower panels) labor specifications. In particular, we depict how the target adopted shapes the structure of the economy, leading to a different capital share from the one emerging in the steady state, as represented by the dots. We are interested in values of the target entailing a larger capital share allocated to the clean sector than its steady-state value. The left panels represent the Cobb-Douglas specification, the right panels the perfect substitute case; we depict the no spillover case by the black solid line. The other curves show how the share evolves as a function of the target, for different relative intensities of spillovers B_c/B_d. A high relative spillover intensity implies a high productivity of the clean sector compared to the dirty one, meaning that less additional capital needs to be allocated to the clean sector in order to achieve the target.

When labor is mobile, another channel of adjustment exists next to capital allocation, so that, compared to the fixed labor specification, the share of capital that needs to be allocated to the clean sector to achieve the same target is lower, for any values of the relative spillover intensity.

Remark 2.3.1 (Share of capital allocated to the clean sector depending on the relative intensity of spillovers) *A higher relative intensity of spillovers reduces the costs of the regime shift. Independently of the relative spillover intensity, labor mobility decreases the respective capital share further.*

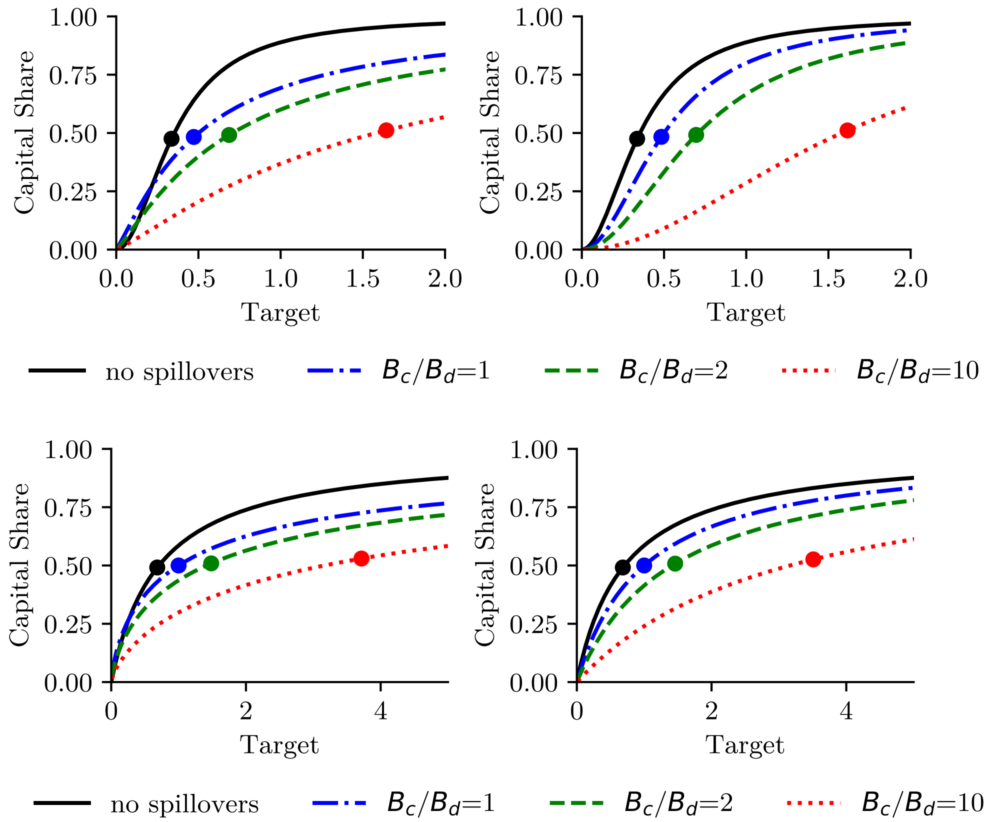

Figure 2.2: Share of capital allocated to the clean sector as a function of the target when labor is fixed (upper panels) and when labor is mobile (lower panels). The left panels represent the Cobb-Douglas specification, the right panels the perfect substitute case, for different values of the relative spillover intensity.

We can then compute the subsidy needed to achieve a given target.[18] Figure 2.3 shows the no spillover case (left panels), the Cobb-Douglas (central panels) and the

[18]See Appendix 5.1.5 for the mathematical derivations.

perfect substitute specifications (right panels). The upper panels depict the fixed labor case, whereas the lower ones the mobile case. Obviously, in the no spillover case, the subsidy does not depend on the relative intensity of spillovers. The dots represent the steady-state values of relative production in the absence of policy intervention. Our focus is on values of the target that require the introduction of a subsidy increasing the ratio of clean to dirty production compared to the one emerging in the decentralized economy without policies. Negative values of the subsidy, below the steady-state values, are thus not of interest for us, as they represent a policy intervention worsening the state of clean production compared to the market equilibrium. From Figure 2.3, it appears that spillovers always reduce the cost of the regime shift; this effect is strengthened by labor mobility.

Remark 2.3.2 (Subsidy to clean production depending on the relative intensity of spillovers) *In any specification, the presence of spillovers and higher values of their relative intensity reduce the costs of the regime shift. This effect is enhanced by labor mobility.*

Figure 2.3 also shows that the higher the relative intensity of spillovers, the higher the steady-state values of relative production. That is, the usage of clean versus dirty energy which is achieved with no subsidy is higher, as the clean sector is already more productive. Moreover, when labor is mobile, the steady states occur generally for higher values of the target. As pointed out earlier, the spillover intensity can be interpreted as the absorption capacity of a sector. This interpretation is in line, for instance, with Cohen and Levinthal (1989), who show that for a lower absorption capacity, the impact of spillovers decreases. The absorption capacity may depend on industrial policies or the legal environment. For example, exogenous factors such as patent policy, used to prevent duplication or to secure royalty income, secrecy and lead time, can represent an important limitation to the appropriability of knowledge (Cohen and Levinthal 1989). Following Remark 2.3.2, policies should enhance the absorption capacity of the clean sector in order to reduce the costs of the regime shift. This may take place by relaxing patent

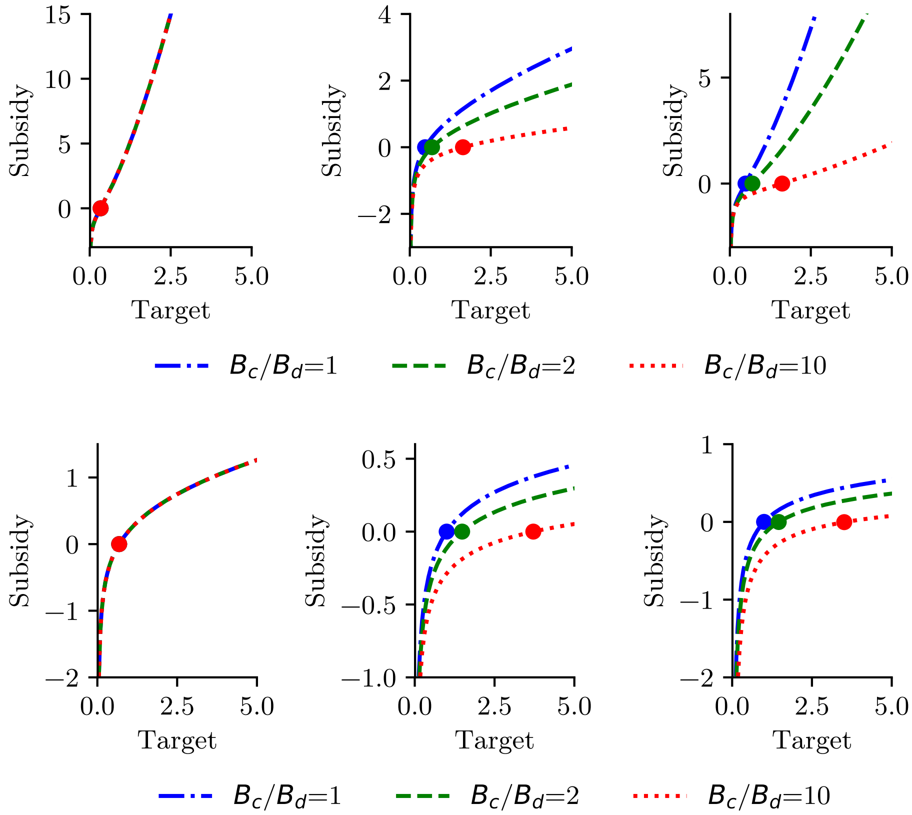

Figure 2.3: Subsidy with fixed (upper panels) and mobile (lower panels) labor as a function of the target, for different values of the relative spillovers intensity. The left panels represent the no spillover case; the central panels the Cobb-Douglas specification and the right panels the perfect substitute case.

policies, as patents give the holder the right to exclude others from the production of a specific good or from using a specific process for a defined number of years, thus preventing knowledge diffusion. Thus, the general policy recommendation results in a greater degree of openness in knowledge circulation across firms, sectors and countries.

The literature suggests that the absorption capacity can also be improved by R&D, which eases the incorporation of external knowledge (Cohen and Levinthal 1989, Bosetti et al. 2008). By way of example, countries with experience from offshore oil production such as Norway, should rely on their expertise to promote clean R&D, which would enable the development of offshore windmills. Similarly, Germany's well-developed automobile industry would provide the country with a comparative know-how advantage, which could be directed to the production of cleaner alternative vehicles.

Remark 2.3.2 also shows that the regime shift is less costly overall when labor can move freely; thus, policies should also tackle this channel as well. Labor mobility represents a means of knowledge diffusion and encompasses two dimensions: geographical and occupational. Although the latter is more relevant for us, geographical mobility also plays a role as the transition to a low-carbon economy can generate imbalances in the regional labor supply and demand, which could be solved by greater geographical mobility. This would allow workers to broaden their area of job search, but would require policies aiming at unifying the labor market. As for the occupational dimension of labor mobility, the goal of policies is to reduce the costs of adjustment for workers and the fragmentation of the labor market (Botta 2019).

2.3.2 Elasticity of substitution

We now focus on the impact of the elasticity of substitution between clean and dirty energy on the regime shift. Figure 2.4 includes the fixed (upper panels) and mobile (lower panels) labor specifications; it depicts the capital share allocated to the clean sector as a function of the target for the Cobb-Douglas (left panels) and perfect substitute (right panels) specifications as well as the steady-state values emerging in the decentralized economy without policy intervention. The no spillover case is represented by the black solid curve, whereas the dashed curves show how the share evolves when spillovers are present, for different values of the elasticity of substitution. Note that, whereas the share depends on the relative spillover intensity, it is not affected by the elasticity of substitution, regardless of the specification adopted. For the values of the target which are of interest to us, the presence of spillovers implies that a lower share of capital is needed to achieve the desired target.

Remark 2.3.3 (Share of capital allocated to the clean sector depending on the elasticity of substitution) *The elasticity of substitution between clean and dirty energy inputs does not affect the share of capital allocated to the clean sector. When labor is free to reallocate, the share of capital is lower for any value of the target.*

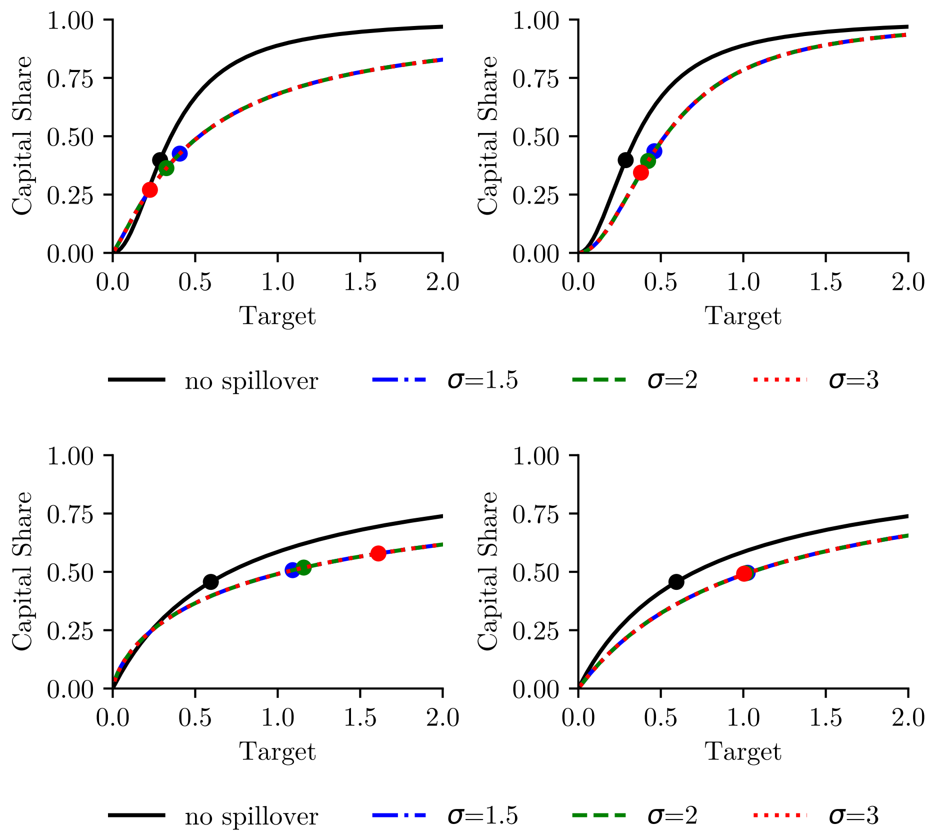

Figure 2.4: Share of capital allocated to the clean sector as a function of the target when labor is fixed (upper panels) and when labor is mobile (lower panels). The left panels represent the Cobb-Douglas specification, the right panels the perfect substitute case, for different values of the elasticity of substitution.

Figure 2.5 shows the subsidy needed to achieve a given target when labor is fixed (upper panels) and mobile (lower panels). The left panels represent the no spillover case, the central panels the Cobb-Douglas spillovers and the right panels the perfect substitute specification. As before, the presence of spillovers, together with labor mobility reduce the costs of the regime shift as they entail a lower subsidy. Moreover, larger values of the elasticity reduce the subsidy needed to achieve the target.

Figure 2.5 also shows that when labor is mobile, the cost of the regime shift is lower for any value of the elasticity of substitution. The steady states emerge for generally higher values of relative production when labor is mobile. As before, negative values of the subsidy represent outcomes which we do not consider as reasonable and are not included in the present analysis.

Remark 2.3.4 (Subsidy to clean production depending on the elasticity of substitution) *In all the specifications, higher substitutability between the clean and dirty energy intermediates reduces the cost of the regime shift. This effect is enhanced by labor mobility.*

Although Greaker et al. (2018) consider R&D subsidies, our result is in accordance with the one obtained by the authors, which shows that in the absence of a carbon tax, the second-best subsidy to clean R&D is remarkably higher for lower value of the elasticity of substitution.

Following Remark 2.3.4, investments in clean energy should be undertaken so that the two sectors become better substitutes and the cost of switching is lowered. By way of example, the substitutability would be increased by devoting more effort to developing cheap storage options for intermittent electricity or by improving public transportation networks and expanding the power grid to renewable sites. The adopted measures should either reduce the relative cost of clean technologies or increase the relative usage of clean inputs (Johnstone et al. 2010).[19] In this respect, investments improving the duration of batteries used for electric vehicles

[19] This would not be true only in the special case of an inferior good.

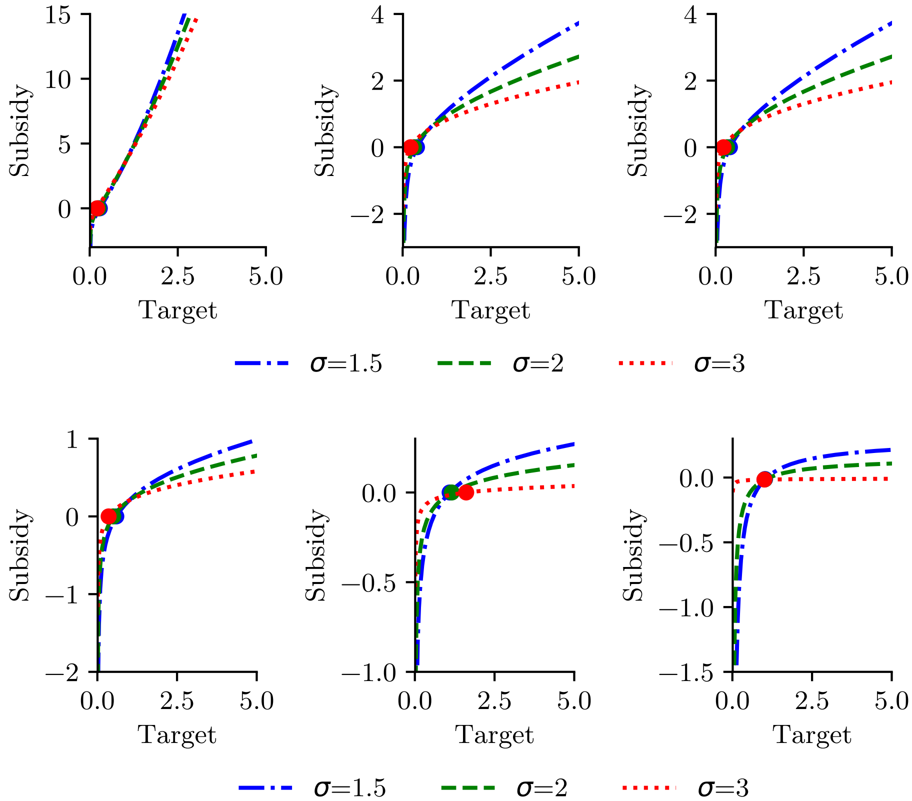

Figure 2.5: Subsidy with fixed (upper panels) and mobile (lower panels) labor as a function of the target, for different values of the elasticity of substitution. The left panels represent the no spillover case; the central panels the Cobb-Douglas specification and the right panels the perfect substitute case.

would improve their substitutability with internal combustion engine vehicles. Similarly, a larger number of electric vehicles also improves their substitutability with traditional ones as it would trigger infrastructure development compatible with the new technology; as a consequence, the perceived difference with the more established dirty technology would vanish. Following Ferguson (2015), policies aiming at improving the substitutability between intermediates should also favor trade liberalization, as the latter leads to an inverted U-shaped effect on product differentiation. As in the case of absorption capacity, higher openness would reduce the cost of the regime shift. Finally, similarly to the previous analysis, policies should focus on improving labor mobility across sectors.

2.4 Sensitivity analysis

In the present Section, we perform some sensitivity analysis on crucial parameters of the model to show the robustness of our results.

2.4.1 Total factor productivity

Following Greaker et al. (2018), we half and double the level of the clean sector productivity A_c, keeping the other parameter values constant; in particular, we still assume $B_c/B_d = 1.1$ and $\sigma = 1.1$. Figure 2.6 shows that the share of capital allocated to the clean sector in order to achieve a given target is reduced for higher technology levels of the clean sector. As spillovers are not affected by the productivity level, we only represent the no spillover case for fixed (left panel) and mobile (right panel) labor. As before, mobile labor reduces the required share of capital, for any value of the target.

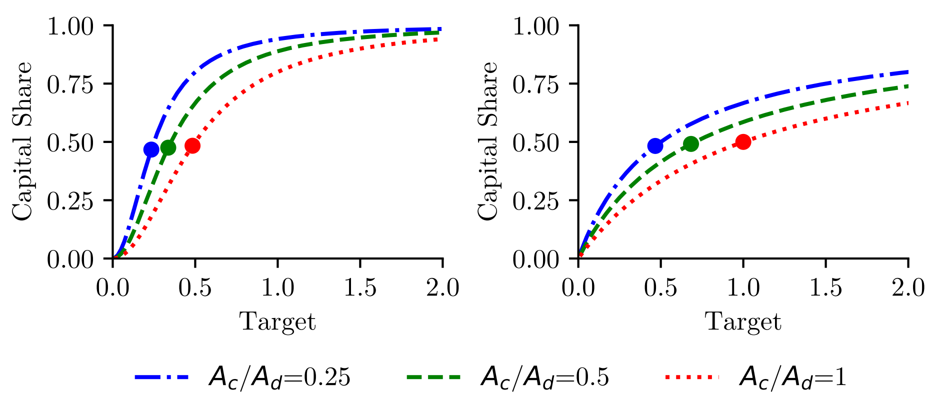

Figure 2.6: Share of capital allocated to the clean sector, for different values of the relative total factor productivity. The left panels represent the fixed labor case; the right panels the mobile case.

We now investigate the impact of relative total factor productivity on the subsidy. As Cobb-Douglas and perfect substitute spillovers are not affected by the value of relative total factor productivity, we only represent the no spillover case. Figure 2.7 shows that with a higher clean technology level, the subsidy is reduced, as less support is needed to switch from dirty to clean energy generation. Labor mobility reduces the cost of the regime shift, for any value of the target.

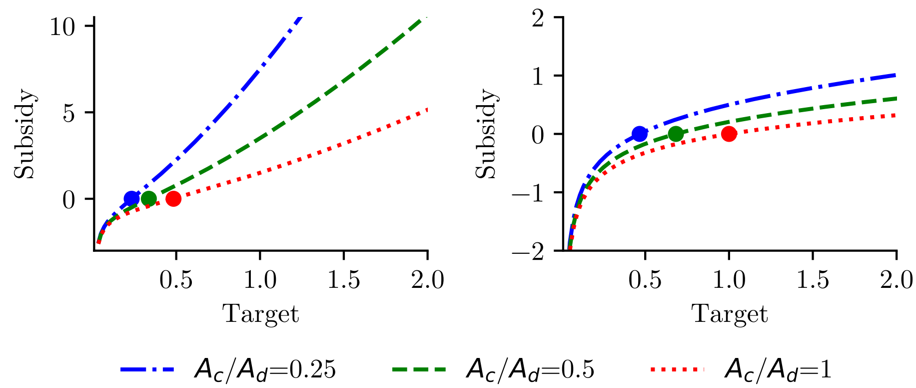

Figure 2.7: Subsidy with fixed (left panel) and mobile (right panel) labor as a function of the target, for different values of the relative total factor productivity.

2.4.2 Distribution parameter

The distribution parameter γ captures the relative importance of the clean and dirty intermediates in final production. The share of capital allocated to the clean sector to achieve a given target is not affected by γ, as the target itself determines the relative importance of the two sectors. Thus, we do not provide an illustration of the capital share as a function of the target. In what follows, we investigate the impact of the distribution parameter on the subsidy; Figure 2.8 shows that a larger relative importance of the clean sector reduces the value of the subsidy, as it implies that the clean sector already plays an important role in production. Moreover, labor mobility reduces the size of the subsidy in any specification considered.

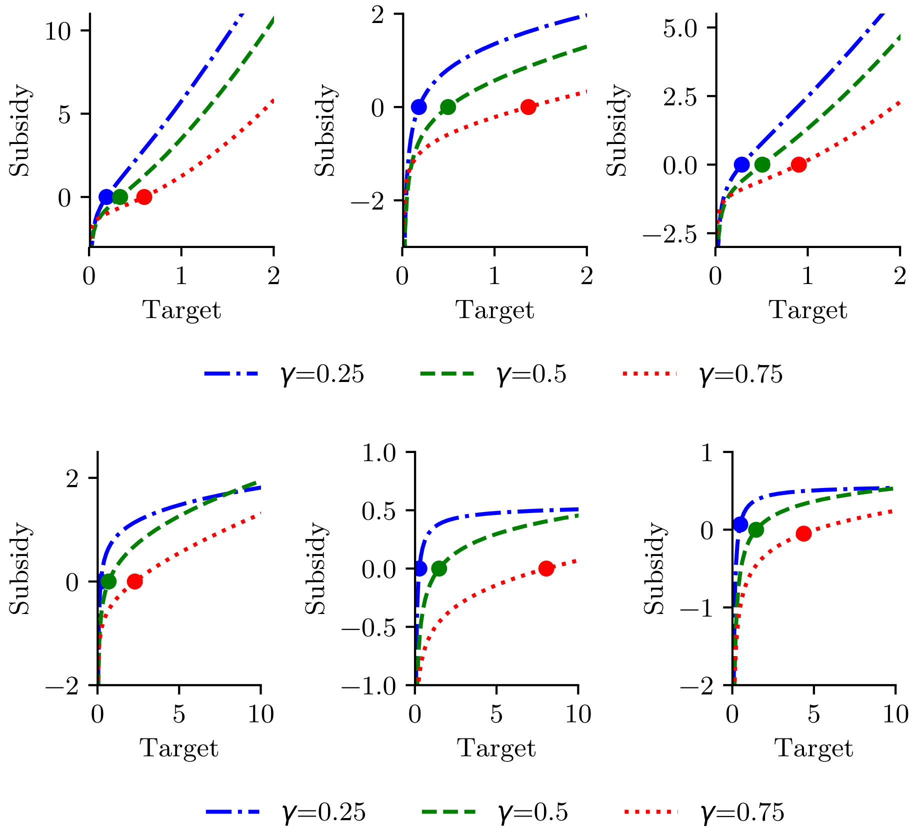

Figure 2.8: Subsidy with fixed (upper panel) and mobile (lower panel) labor as a function of the target, for different values of the distribution parameter. The left panels represent the no spillover case; the central panels the Cobb-Douglas specification and the right panels the perfect substitute case.

2.4.3 State-dependence parameters

In the Cobb-Douglas spillover specification, the state-dependence parameters ϕ_c and ϕ_d capture how strongly clean and dirty sectoral productivity depends on the stocks of clean and dirty knowledge capital, respectively. As the effects of the two parameters are symmetric, we only analyze the effect of varying the parameter for the clean sector. The share of capital allocated to the clean sector as a function of the state-dependence parameter is represented in Figure 2.9 for the fixed (left panel) and mobile (right panel) case. For values of the target above the steady-states, a lower state-dependence in the clean sector implies higher values of the share of capital allocated to the clean sector. This effect holds both for fixed and mobile labor, but in the latter specification the capital share is generally smaller.

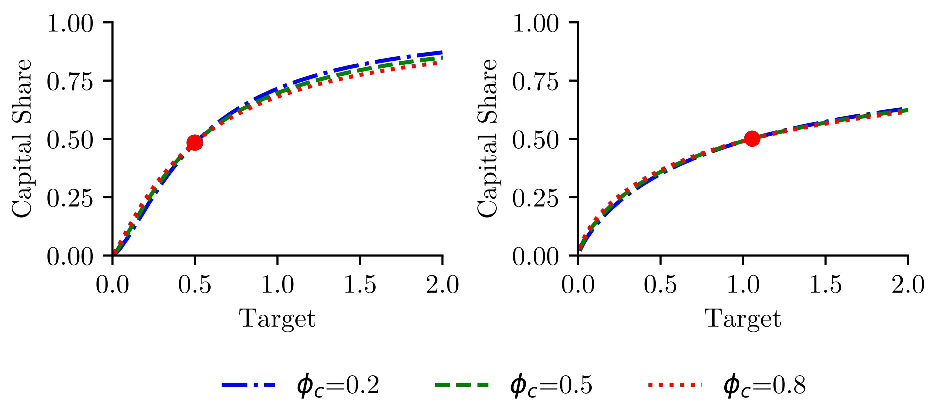

Figure 2.9: Share allocated to the clean sector with fixed (left panel) and mobile (right panel) labor as a function of the target, for different values of the clean state-dependence parameter.

The state-dependence parameters also affect the value of the subsidy provided to clean production. Figure 2.10 shows that when the path-dependence is stronger, meaning that the clean sector relies more on the knowledge-capital stock related to clean technologies, the subsidy is lower both in the case of fixed (left panel) and mobile (right panel) cases. This is due to the fact that a low ϕ_c implies that the clean sector relies relatively more on the dirty capital stock; thus, when the dirty sector shrinks the clean suffers as well and necessitates a stronger support in the form of the subsidy. We obtain the same effect for a low ϕ_d, which implies that the dirty sector absorbs relatively more from the clean sector. In order to reduce production in the dirty sector, the clean one has to be more generously subsidized to offset the gains that the dirty sector receives when more capital is allocated to the clean one.

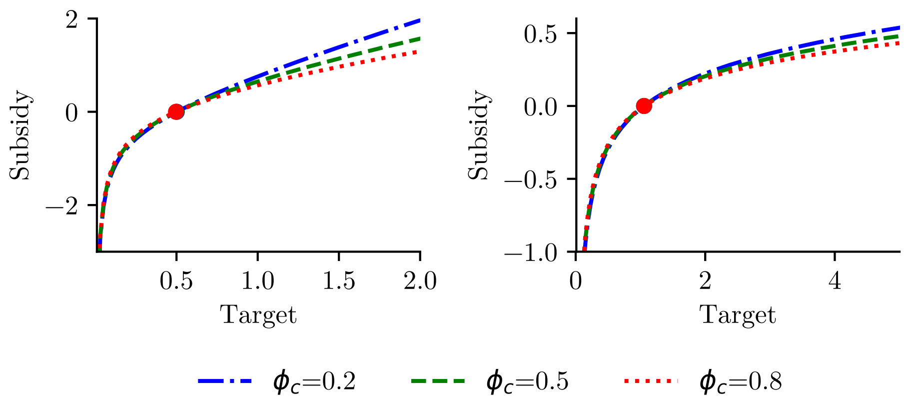

Figure 2.10: Subsidy with fixed (left panel) and mobile (right panel) labor as a function of the target, for different values of the clean state-dependence parameter.

2.5 Conclusions

This Chapter is motivated by the fact that countries such as Germany and Switzerland have started to set targets in terms of energy generation from clean sources, in order to mitigate the negative consequences of carbon emissions from the energy sector. To promote such a regime shift towards a low-carbon economy, several policy measures have been adopted; among others, countries have chosen to subsidize the renewable energy sector through feed-in tariffs. However, which channels might influence the effect of the policy measures adopted is a topic under discussion. The aim of the present Chapter is to contribute to this debate, by studying the impact of spillovers from the knowledge-capital stocks existing in the economy, the substitutability between clean and dirty energy intermediates, as well as labor mobility on the subsidy needed to achieve the shift towards a low-carbon economy. Moreover, we show how the results change under different assumptions on the spillover specification.

We develop a model of endogenous growth to study the regime shift from the reliance on dirty to clean energy intermediates. In the model, final output is produced with two energy inputs, combined according to a given elasticity of substitution. Intermediate energy producers receive spillovers from clean and dirty knowledge-capital stocks. We consider fixed and mobile labor, and study a Cobb-Douglas and a perfect substitute specification of spillovers, which are compared to the no spillover case. The government uses subsidies to achieve a given target in terms of energy generated from clean sources. We then offer an insight into the magnitude of the effects considered by simulating the model. In particular, we provide a graphical representation of the regime shift, which shows how the target transfers into a capital share allocated to the clean sector, generating distortions in the economy. We use our model equations to compute the subsidy needed to achieve a given target and look at the impact of the relative spillover intensity and the elasticity of substitution, in the case of fixed and mobile labor.

The goal of the Chapter is to analyze which factors determine the subsidy needed to undertake the shift to a low-carbon economy. We find that the presence of spillovers reduces the costs of the regime shift, although to a different extent depending on the specification adopted. Moreover, a higher relative intensity of clean to dirty spillovers implies a lower subsidy. Accordingly, policy measures should aim at enhancing the absorption capacity of the clean sector by relaxing patent policies and generally promoting knowledge diffusion. Additionally, governments should promote R&D in the clean sector in order to improve its absorption capacity and reduce the cost of the regime shift. By way of example, countries such as Norway should invest in R&D for offshore windmills so that the latter can gain from the existing expertise in offshore oil production. Similarly, Germany's well-developed automobile industry would provide the country with a comparative advantage in the production of cleaner alternative vehicles.

Higher substitutability between the clean and dirty sectors also translates into a lower subsidy being needed to achieve the regime shift. Thus, policies should favor investments in clean energy to ease the substitutability of the two sectors, such as developing storage options for intermittent energy, improving public transportation networks and expanding the power grid to renewable sites. Policymakers have the option to favor investments improving the duration of batteries for electric vehicles in order to improve their substitutability with internal combustion engine vehicles. Another example from the automobile industry is that policies leading to a larger number of electric vehicles would support the development of the compatible infrastructure, thus improving the substitutability between the two types of vehicles.

When labor is mobile, another channel of adjustment exists other than capital allocation, lowering the subsidy needed for the regime shift regardless of the spillover intensity or the degree of substitutability. Consequently, policies should tackle labor mobility to promote the shift to a low-carbon economy, both in the geographical and occupational dimensions. The former matters as the regime shift might lead to imbalances in the labor market, which can be solved by higher geographical mobility. This, however, requires policies unifying the contribution systems across countries, decreasing the transaction costs connected to the buying and selling of real estate and promoting a uniformed recognition of professional qualifications. As for the occupational dimension of labor mobility, the goal of policies is to reduce the cost of adjustment for workers and the fragmentation of the labor market. This involves active labor market policies including: job training programs reducing the frictions in the adjustment process due to skill mismatches, job search training programs, helping workers to identify suitable employment opportunities in other sectors, and brokerage services improving the quality of information about the labor market in order to reduce search costs.

The main contribution of this Chapter is to show that that the impact of spillovers and of substitution possibilities should be linked to the effect of the subsidy when designing a regime shift towards a low-carbon economy. Moreover, the labor market can play a role in easing the structural change. Several extensions of the model presented are possible; by way of example, we assume an exogenous elasticity of substitution and we only discuss potential measures affecting this channel; however, it would be interesting to model such an impact also analytically. Furthermore, studying the transitional dynamic of the model would provide additional insights into the relevance of spillovers and elasticity of substitution as well as of labor mobility for the value of the subsidy. All these aspects are left to future research.

Chapter 3

Green Transportation Policies: The Double Dividend Effect in a Two-sided Market*

Abstract

Decarbonizing the transportation sector is a key measure to reduce carbon emissions at the global level. A crucial factor to achieve a sustainable transportation system is the diffusion of electric vehicles. We study the network effects inducing a positive relationship between electric vehicles and charging stations. To do this, a two-sided market model capturing such network externalities is developed. A platform provides one side of the market with electric and internal combustion engine vehicles to consumers, while it supplies retailers with charging stations on the other side. We use this framework to show that in the presence of network effects and environmental damage from polluting cars, optimal policies can lead to a double dividend: decreasing the quantity of internal combustion engine vehicles can be economically improving, while reducing the negative impact of pollution.

*This work is a joint effort with Noe Reidt (ETH Zurich).

3.1 Introduction

The present Chapter focuses on how the transition to a low-carbon economy can take place in the transportation sector. In 2019, the latter accounted for 23% of the global carbon emissions, making it the second largest contributor after the electricity and heat generation sector. Moreover, road traffic alone accounted for three-quarters of transportation emissions (IEA 2019). Reducing carbon emissions from the transportation sector is thus crucial for combating climate change. Electric vehicles (EVs) can play a major role in achieving this goal. However, economies are far from achieving the potential emission reduction offered by EVs. The reasons for their slow adoption are manifold:[1] among others, the purchase costs of EVs are still high compared to internal combustion engine vehicles (ICEVs) and the driving distances are limited. Moreover, the charging infrastructure is still inadequate due to the "chicken-egg" relationship existing between EVs and EV charging stations (EVCSs). The latter hinders a further expansion of the EV market: because the number of EVCSs is low, the value of EVs decreases, limiting EV sales and hence the profitability of charging stations (Caillaud and Jullien 2003). To overcome this deadlock, governments use a wide array of policy measures to expand the usage of EVs.[2] Furthermore, cars manufacturers increase their brand specific EVCS network to spur the adoption of their products. Recently, retailers assumed an important role in providing EVCSs. Shopping malls (such as IKEA, Rewe, Aldi) have started to install charging stations in their parking lots: the aim is to attract customers, by offering the possibility to charge their EVs while shopping. This class of actors and their interaction with the diffusion of EVs will be the focus of the present Chapter.

To the best of our knowledge, to date there exists little research that explores which policies are optimal to advance EV sales, taking into account the network

[1] See Hidrue et al. (2011), Koetse and Hoen (2014), Helveston et al. (2015), Zhou et al. (2016).

[2] For instance, income-tax credit or deduction for purchase of EVs, reduction of or exemption from purchase or registration tax, free battery charging, free parking, support for the deployment of charging infrastructure, grants for private installation of charging stations.

externality between EVs and charging stations. The aim of this Chapter is to progress in this area by explicitly modeling the relationships between EVs adoption and EVCSs availability. For this purpose, we develop a two-sided market framework with network externalities, which we then use for a study of policies that foster the diffusion of EVs. Moreover, we account for the possibility of substitution between EVs and ICEVs. In the model, a monopolistic platform sells EVs and ICEVs to one side of the market (consumers) and EVCSs to the other side (retailers). Two-sided markets are particularly suited to capture the valuation of the existing charging station network by EV owners and of the circulating base of EVs by retailers. We introduce policies tackling the different sides of the market and we study how they affect quantities and prices. Finally, we analyze which policy mix maximizes welfare and how the latter is affected by a target reduction of the number of ICEVs in the presence of a negative environmental externality and network effects.

The main contribution of the Chapter is to show that: (1) policies targeting one side of the market generate feedback effects on the other; network externalities affect outcomes through their absolute size and relative intensity; (2) in the presence of network effects and environmental damage from polluting cars, policies can lead to a double dividend: decreasing the quantity of internal combustion engine vehicles can be economically beneficial, while reducing the negative impact of pollution. This result can represent a turning point in today's discussion about policies fostering EVs: even if EVs are technologically less advanced than ICEVs, the presence of network effects implies that such policies can generate a double dividend. Hence, our analysis provides novel insights about the effects operating in the EV market and their implications for policymaking.

Two-sided markets are characterized by three elements (Rochet and Tirole 2004): first, the presence of a platform providing distinct services to two or more distinct groups of consumers, which rely on the platform to intermediate transaction between them; second, network externalities exist across groups of consumers: one side's utility from participation depends not only on the value of the goods themselves, but also on the number of users on the other side of the market. Network externalities generate feedback loops between the two sides that can exacerbate positive and negative shocks (arising, for instance, from policy implementations).[3] Only the platform internalizes the network effect as it recognizes that a larger network raises the users' willingness to pay and therefore its revenues; third, two-sided markets are characterized by a non-neutral price structure, designed so as to bring both sides on board. The pricing decision on each side depends on the demand faced on both sides of the market and on their interdependence through network externalities. Platforms can deviate from a competitive pricing in order to increase overall profits, for example by generating low revenues on one side and recouping the costs on the other side (Rochet and Tirole 2004). Thus, in a two-sided market we can observe prices below marginal cost.[4] The advantage of using a two-sided market to study our problem follows from the characteristics outlined above: first, car manufacturers produce both EVs and the charging stations, acting as a platform; second, the amount of EVCSs is a relevant element for consumers when purchasing an EV. Meanwhile, retailers only install charging stations if the number of EVs is sufficiently high, showing the existence of network externalities; third, the provision of free charging suggests a non-neutral price structure. Our methodology is close to Filistrucchi et al. (2017) who use a two-sided market structure to analyze the newspaper industry. We deviate from their approach by allowing for the presence of two goods on the same market side, namely EVs and EVCSs. Moreover, we derive the system of demand functions instead of assuming it.

There is a rich body of research analyzing the effect of environmental policies in the automobile market. Many studies focus on the effectiveness of fuel taxes and fuel standards as a response to environmental issues emerging from the trans-

[3]The notion of network externality is not to be confused with the one of complementary goods; in the latter case, consumers internalize the purchase decision of the complement good (for example, razor and blades); when network effects operate, instead, the externality of the purchase decision is not internalized.

[4]For example, the selling for newspapers for free, covering the losses with the money from advertisement.

portation sector.[5] A policy approach analyzed in the literature is the establishment of eco-friendly rules like the Corporate Fuel Economy standard that led to a 50% reduction of fuel consumption per passenger car mile (Greene et al. 2005). Other studies investigate policies targeting alternative fueled vehicles and the response of consumers to subsidies for EVs or installment of EVCSs.[6] Lin and Greene (2011) analyze the impact of promoting charging infrastructure on EV usage, whereas Jin et al. (2014) study road tax exemptions, free use of bus lines and parking areas, subsidized home chargers and license fee reductions. Greaker and Midttømme (2016) study the diffusion of a clean substitute for a dirty durable good in a dynamic model in the presence of an optimal emission tax and the risk of excess inertia.

The literature has already used two-sided models to study the network effects between EVCSs and EVs. For example, Yu et al. (2016), Springel (2016), Li et al. (2017) and Jang et al. (2018) apply such models to analyze the introduction of environmental policies. Yu et al. (2016) consider a sequential game and depict an EVCS investors' operational decision-making, such as pricing and station location. Springel (2016) uses Norwegian data to study the impact of network externalities and a subsidy scheme on the diffusion of EVs, considering a simultaneous move game. Li et al. (2017) provide empirical evidence of existence of indirect network effects in the process of EV diffusion. Jang et al. (2018) consider two different platforms, one producing EVs and one producing ICEVs, competing to attract two types of agents (car consumers and energy suppliers). We deviate from those papers by modeling one market side supplied with two goods (EVs and ICEVs) and the other with one good only (EVCSs). Compared to Springel (2016) and Li et al. (2017), we allow for substitution possibilities between EVs and ICEVs in the analysis and evaluate the outcomes in terms of welfare. In contrast to previous works, our results do not rely on Hotelling's type preferences, but on linear demand

[5]See Jacobsen (2013), DeShazo et al. (2017), Alberini and Bareit (2017), Gerlagh et al. (2018), Grigolon et al. (2018).

[6]See Sierzchula et al. (2014), Pöltz et al. (2014), Lieven (2015), Helveston et al. (2015), Langbroek et al. (2016), Zhou et al. (2016), Coffman et al. (2017).

functions derived from quasi-linear utilities.

The present Chapter is organized as follows: section 3.2 outlines the general model structure and computes the decentralized solution. Section 3.3 analyzes second-best policy instruments favoring the diffusion of EVs. Section 3.4 computes the first-best solution. Section 3.5 identifies the welfare-maximizing policies and shows the existence of a double dividend. In section 3.6, we provide an extension to the baseline model, which relaxes the assumptions of a monopolistic market structure. Section 3.7 concludes and proposes lines for future research.

3.2 Model

3.2.1 Consumers and retailers

We consider a two-sided market with a continuum of potential users on each side, with mass normalized to one. Our economy is populated by two types of agents: consumers (h) and retailers (a). The former purchase vehicles and can choose between EVs (q_c) and ICEVs (q_d), while the latter demand EVCSs (q_f). We denote by p_c and p_d the purchase prices for EVs and ICEVs and by p_f the price of EVCSs. A monopolistic platform (m) produces EVs, ICEVs and EVCSs and sells the goods to the two sides of the market (consumers and retailers). For a graphical illustration of the economic structure see Figure 3.1.

Consumers purchasing EVs and retailers purchasing EVCSs benefit from network effects due to positive externalities between the two goods. Following the empirical literature (Springel 2016, Li et al. 2017), we assume that the network effects are asymmetric: the impact of an additional charging station on the purchase decision of consumers is different from the impact of an additional EV on the purchase decision of retailers. We acknowledge that similar network effects exist between internal combustion engine vehicles and stations; however, we argue that they are of minor importance compared to those between EVs and EVCSs (Greaker and Midttømme 2016). This can be justified by two reasons: first, charging an EV requires more time than fueling an internal combustion engine car; which explains the strong incentive for retailers to install charging stations as consumers can charge their EVs while shopping; second, the marginal impact of a gasoline station is lower compared to that of a charging station, as the number of gasoline stations is already sufficiently high. Moreover, assuming the presence of network effects in the ICEV market, although to a lower degree, this does not affect our qualitative results. Based on this, we focus on the network effect for the new technology only. Accordingly, the number of gasoline stations does not enter the decision to buy an ICEV.

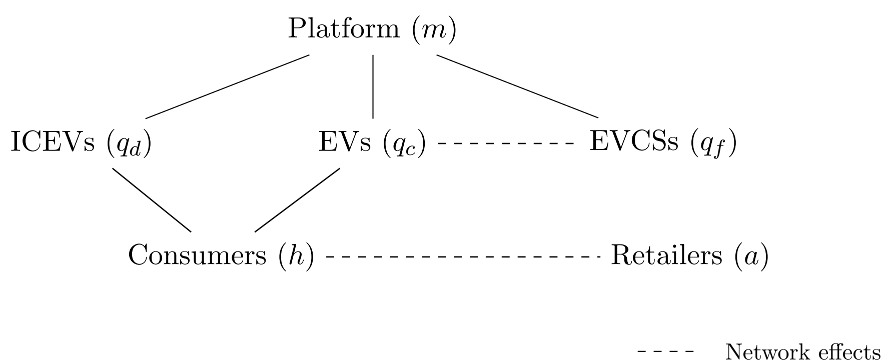

Figure 3.1: Market structure.

Following Singh and Vives (1984), Häckner (2000) and Melitz and Ottaviano (2008), we assume that the aggregate utility function is quasi-linear. This specification implies no income effect; however, since the focus of this Chapter is on vehicle consumption, the assumption that higher income will not lead to the purchase of more cars by the same individual is plausible.[7] Moreover, the quasi-linear utility function allows us to derive linear demand functions, which are standard in the two-sided market literature. The choice variables for the consumers are the quantities of EVs and ICEVs. Still, the quantity of EVCSs enters the utility of

[7]We acknowledge that there can be an argument for income effects as richer households are those who can switch first to EVs; however, in the present work we do not consider this effect in order to isolate the impact of network effects.

consumers because the value of EVs for consumers depends on the availability of EVCSs.

Assumption 3.2.1 (Consumers' utility function) *The utility function of consumers reads*

$$U(q_{0,h}, q_c, q_d; q_f) = q_{0,h} + \sum_{i\in\{c,d\}} \alpha_i q_i - \frac{1}{2}\left[\sum_{i\in\{c,d\}} \beta_i q_i^2 + 2(\gamma_1 q_c q_d - \gamma_2 q_c q_f)\right],$$

where $\alpha_i, \beta_i > 0$*,* $\gamma_1 \in [0, \infty)$ *and* $\gamma_2 \in [0, \infty)$*.*

The parameter $q_{0,h} > 0$ represents the individual consumption level of the homogeneous numeraire good. We assume that the initial endowment of the homogeneous good is large enough for its consumption to be strictly positive at the market equilibrium. The positive demand parameters α_i and β_i measure the preference for the differentiated varieties with respect to the homogeneous good. The parameter $\alpha_i q_i$ represents the direct benefit of owning a car, whereas $\beta_i q_i^2$ represents car type-specific congestion costs (for example, congestion at charging points). The parameter γ_1 captures the substitution effect between EVs and ICEVs. The parameter γ_2 denotes the network effect between EVs and EVCSs so that $\gamma_2 q_c q_f$ represents consumers' indirect benefit from EVCS installment by retailers. Notice that consumers always derive utility from the purchase of EVs, even if q_f goes to zero. This assumption can be justified by the possibility of charging EVs at home. The term $\gamma_1 q_c q_d$ represents the congestion cost due to a higher number of EVs and ICEVs (for instance, traffic jams). We normalize the price of the numeraire good to one; hence, the aggregate budget constraint of consumers reads

$$q_{0,h} + p_c q_c + p_d q_d \leq m_c.$$

Given total income on the consumers' side, m_c, a share of it is allocated to the purchase of the numeraire good, a share to the purchase of EVs and a share to the purchase of ICEVs. The assumption of quasi-linear preferences allows us to measure gains and losses of utility in the same units as consumption. This implies that there is no revenue effect on car purchasing decision and that the quantities of q_c and q_d chosen do not depend on income. Any change in the quantities purchased is only attributable to the substitution effect.

Retailers maximize a quasi-linear payoff function, which depends on the number of EVCSs and EVs. The latter is, however, a choice variable of households and not of retailers.

Assumption 3.2.2 (Retailers' objective function) *The objective function of retailers reads*

$$F(q_{0,a}, q_f; q_c) = q_{0,a} + \alpha_f q_f - \frac{1}{2}\left[\beta_f q_f^2 - 2\gamma_4 q_c q_f\right],$$

where $\alpha_f, \beta_f > 0$ *and* $\gamma_4 \in [0, \infty)$*.*

The parameter $q_{0,a} > 0$ is the purchase level of the numeraire good, whereas q_f is the consumption level of EVCSs. As before, $\alpha_f q_f$ captures the direct benefit for retailers from owning a charging station, whereas $\beta_f q_f^2$ represents the congestion cost due to an excessive number of EVCSs owned by the same retailer (for example, too many charging stations and too many EV charging at the retailer's stations might reduce the parking spots available for ICEVs). The payoff function of retailers also includes the indirect benefit, $\gamma_4 q_c q_f$, due to the usage of EVs by consumers. However, the intensity of the network effect between EVs and EVCSs perceived by retailers, γ_4, might be different from the one perceived by consumers, γ_2 (Li et al. 2017). So far, we have not made assumptions on the relative intensity of the network effects on consumers or retailers; still, this will be relevant for our policy analysis. Given the total income on the retailers' side, m_a, a share of it is allocated to the purchase of the numeraire good and a share to the purchase of EVCSs, that is,

$$q_{0,a} + p_f q_f \leq m_a.$$

The consumers' problem is given by

$$\max_{q_{0,h},q_c,q_d} U \quad \text{s.t.} \quad q_{0,h} = m_h - p_c q_c - p_d q_d,$$

whereas retailers solve

$$\max_{q_{0,a},q_f} F \quad \text{s.t.} \quad q_{0,a} = m_a - p_f q_f.$$

Both constraints hold with equality because U (F) is strictly increasing in $q_{0,h}$ $(q_{0,a})$. Assuming for simplicity $\beta_i = 1$ with $i \in \{c, d, f\}$, the FOCs derived from the maximization problems of consumers and retailers are

$$\begin{aligned}
\lambda_h - 1 &= 0,\\
\alpha_c - q_c - \gamma_1 q_d + \gamma_2 q_f - \lambda_h p_c &= 0,\\
\alpha_d - q_d - \gamma_1 q_c - \lambda_h p_d &= 0,\\
\lambda_a - 1 &= 0,\\
\alpha_f - q_f + \gamma_4 q_c - \lambda_a p_f &= 0,
\end{aligned}$$

where λ_h (λ_a) is the Lagrange multiplier of the consumers' (retailers') budget constraint. The demand functions for EVs, ICEVs and EVCSs are then given by

$$\begin{aligned}
q_c &= \alpha_c - \gamma_1 q_d + \gamma_2 q_f - p_c,\\
q_d &= \alpha_d - \gamma_1 q_c - p_d, \qquad (3.1)\\
q_f &= \alpha_f + \gamma_4 q_c - p_f.
\end{aligned}$$

The choice of quasi-linear utility functions implies that demands are linear in the quantities of goods and prices. From (3.1) we can see that the substitution between EVs and ICEVs leads to a negative impact on the quantities of both goods. On the contrary, the network effect between EVs and EVCSs implies a positive impact of the quantity of EVCSs (EVs) on the demand for EVs (EVCSs), as captured by

γ_2 (γ_4). From (3.1) we can derive inverse demands as

$$p_c = \alpha_c - q_c - \gamma_1 q_d + \gamma_2 q_f,$$
$$p_d = \alpha_d - q_d - \gamma_1 q_c,$$
$$p_f = \alpha_f - q_f + \gamma_4 q_c.$$

In what follows, we assume a profit-maximizing monopolistic platform with perfect information about the demand functions.

3.2.2 Platform

In our setup of a two-sided market, the monopolistic platform chooses the profit-maximizing quantities or prices given the interrelated demands of the two groups of customers. In what follows, we focus on a quantity-setting platform. Car production incurs constant marginal costs c_c and c_d, while the marginal cost of producing charging stations is c_f.

Assumption 3.2.3 (Platform's profits) *Total profits generated by the platform are given by*

$$\pi = (p_c - c_c)q_c + (p_d - c_d)q_d + (p_f - c_f)q_f,$$

where $p_i, c_i > 0$.

The first two terms represent profits extracted from consumers and the third term profits extracted from retailers. Given the demand function in (3.1), the FOCs of the maximization problem are

$$\begin{aligned} \alpha_c - 2q_c - 2\gamma_1 q_d + (\gamma_2 + \gamma_4)q_f - c_c = 0, \\ \alpha_d - 2q_d - 2\gamma_1 q_c - c_d = 0, \\ \alpha_f - 2q_f + (\gamma_2 + \gamma_4)q_c - c_f = 0. \end{aligned}$$

Proposition 3.2.1 (Profit-maximizing quantities) *For an interior solution, the profit-maximizing quantities are then given by*

$$q_c^* = \frac{1}{X}\left[2(\alpha_c - c_c) - 2\gamma_1(\alpha_d - c_d) + (\gamma_2 + \gamma_4)(\alpha_f - c_f)\right],$$
$$q_d^* = \frac{1}{X}\left[-2\gamma_1(\alpha_c - c_c) + \left[2 - \frac{(\gamma_2 + \gamma_4)^2}{2}\right](\alpha_d - c_d) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_f - c_f)\right],$$
$$q_f^* = \frac{1}{X}\left[(\gamma_2 + \gamma_4)(\alpha_c - c_c) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_d - c_d) + 2(1 - \gamma_1^2)(\alpha_f - c_f)\right],$$

where $X = 4(1 - \gamma_1^2) - (\gamma_2 + \gamma_4)^2$.

Based on the literature, we assume $X > 0$ (Economides and Tåg 2012). We will refer to this condition as the *monopoly condition*.[8] The latter implies $\gamma_1 \in [0, 1]$, which allows us to derive an upper bound for the network effects, that is, γ_2, $\gamma_4 \in [0, 1)$. The network effects have a positive (negative) impact on the quantity of EVs (ICEVs). As the number of EVs (EVCSs) increases, it generates a positive externality on the retailers (consumers) purchasing EVCSs (EVs). If the number of ICEVs (EVs) increases, fewer EVs (ICEVs) are purchased, indirectly affecting the quantity of EVCSs as well.

Proposition 3.2.2 (Profit-maximizing prices) *Given the optimal quantities derived in Proposition 3.2.1, we can find the profit-maximizing prices as*

$$p_c^* = \frac{1}{X}[(2(1 - \gamma_1^2) - \gamma_2\gamma_4)(\alpha_c + c_c) - (\gamma_4^2\alpha_c + \gamma_2^2 c_c) - \frac{\gamma_1}{2}(\gamma_2^2 - \gamma_4^2)(\alpha_d - c_d)$$
$$+ (1 - \gamma_1^2)(\gamma_2 - \gamma_4)(\alpha_f - c_f)],$$
$$p_d^* = \frac{1}{2}(\alpha_d + c_d),$$
$$p_f^* = \frac{1}{X}[-(\gamma_2 - \gamma_4)(\alpha_c - c_c) + \gamma_1(\gamma_2 - \gamma_4)(\alpha_d - c_d) + (2(1 - \gamma_1^2) - \gamma_2\gamma_4)(\alpha_f + c_f)$$
$$- (\gamma_2^2\alpha_f + \gamma_4^2 c_f)].$$

[8] Appendix 5.2.1 provides a study of the parameter space satisfying this condition.

Because of the network externalities, the prices of EVs and EVCSs depend on the demand parameters of both sides of the market. This means that when setting the profit-maximizing prices on one side of the market, the producer also takes into account the impact of her decision on the other side. This is a standard result in the literature of two-sided markets,[9] where the price structure is non-neutral because externalities across groups affect the determination of the price. Furthermore, the prices of EVs and EVCSs also depend on the parameters of demand for ICEVs, due to the substitution between EVs and ICEVs; on the contrary, the price of ICEVs only depends on the parameters of its own demand and does not equal marginal cost because of monopolistic power.[10] Note that if we assume the intensity of the network effects to be the same on both sides, that is, $\gamma_2 = \gamma_4$, prices for EVs and EVCSs would depend on the parameters of their own demand only.

3.3 Policy analysis

Several measures are available to policymakers in order to foster the development of the EV market. In our theoretical model, we focus on three such policy instruments: (1) subsidies to consumers for EV purchase (s_c): a price subsidy directly affects the buyers' decision to purchase a vehicle by making the price of an EVs comparable to (or even lower than) the price of a ICEVs; (2) taxes on the purchase of ICEVs (t_d); (3) subsidies to EVCS purchase (s_f): the government can subsidize the provision of charging stations by retailers in order to generate a positive externality on EV consumption (through the network effect).

In our analysis, we consider both the case in which the network effect is stronger for retailers ($\gamma_4 > \gamma_2$) and when it is stronger for consumers ($\gamma_2 > \gamma_4$). The first case implies that retailers care more about the number of EVs than consumers do about the availability of EVCSs. This assumption relies on an asymmetric information

[9] See Rochet and Tirole (2004) and Armstrong (2006).

[10] The substitution effect does not affect the price of ICEVs because, when facing the demand for cars, the monopolist behaves as if the market was not two-sided; hence, the platform does not take into account the presence of externalities when setting the price for ICEVs.

argument: retailers are able to foresee future developments of the market and they can only provide electricity services through EVCSs if consumers buy EVs; hence, the number of EVs is of major importance for them. Moreover, consumers might have the option to charge their EVs at home so that the actual availability of charging stations is less relevant to them. The second case can be justified based on the findings by Li et al. (2017), which argue that a 10% growth in the number of public charging stations increases EV sales by about 8%, while a 10% growth in EV stock leads to a 6% increase in charging station deployment, meaning that the network effect is stronger on the consumers' side.

3.3.1 Policy impacts for $\gamma_4 > \gamma_2$

In what follows, we analyze the effect of policy intervention on quantities and prices when the network effect is stronger for retailers. The results summarized in Table 3.1 are based on analytical derivations provided in Appendix 5.2.2.

	EVs		ICEVs		EVCSs	
	Δq_c	Δp_c	Δq_d	Δp_d	Δq_f	Δp_f
s_c	$+$	$\pm$	$-$	0	$+$	$+$
t_d	$+$	$-$	$-$	$-$	$+$	$+$
s_f	$+$	$-$	$-$	0	$+$	$+$

Table 3.1: Policy impacts for $\gamma_4 > \gamma_2$.

All quantities depend only on the total size of the network effects so that the impacts of subsidies and taxes are independent of the relative intensity of the network effects ($\gamma_4 > \gamma_2$ vs. $\gamma_2 > \gamma_4$).[11] Subsidizing EVs (s_c) and taxing ICEVs (t_d) increases the number of EVs. Moreover, q_c increases with a subsidy for EVCSs (s_f) because of the network effect operating between the two goods. The quantity of

[11]This result is due to the assumption of a monopolistic platform and does not hold when considering different market structures.

ICEVs declines ($\Delta q_d = -$) with all the policies considered because of the substitution with EVs. The quantity of EVCSs increases ($\Delta q_f = +$) with subsidies (s_c and s_f) and taxes (t_d). Our results are in line with the previous literature (Springel 2016, Li et al. 2017) indicating that the positive feedback loops between EVCS and EV sales amplify the impact of subsidies on both sides of the market. Moreover, our model allows us to take into account the effect of policies in the ICEV sector.

The effect of policies on prices is more complex than for quantities; in particular, we observe different outcomes depending on the relative intensity of the network effects. When subsidizing EVs, the effect on their price is ambiguous ($\Delta p_c = \pm$) and depends on the substitution effect as well as on the network effects.[12] If the substitution between EVs and ICEVs is strong or if the network effects are large enough, s_c reduces the price of EVs. The effect on p_c when taxing ICEVs follows from the assumption on the relative intensity of network effects; in particular, the price is reduced ($\Delta p_c = -$) only when retailers attach more importance to the network than consumers. The same outcome occurs when subsidizing EVCSs ($\Delta p_c = -$). Hence, it appears that the monopolist has an incentive to reduce the price of the good which displays the weaker network effect and whose quantity is less sensitive to quantity changes on the other side. When $\gamma_4 > \gamma_2$, an increase in q_c lifts q_f strongly up; hence, the monopolist can reduce p_c and still earn profits from the EV market. Such a result depends on the two-sided market structure of the model, allowing the platform to set prices in order to extract the greatest possible profits from both groups of buyers (Rochet and Tirole 2004). The price of ICEVs only depends on the parameters of its own demand and it is not affected by s_c or s_f ($\Delta p_d = 0$). A tax on ICEV (t_d) decreases the price of ICEVs, that is, the monopolist decides to lower the price of the taxed good in order to create a positive demand despite the policy adopted. The price of EVCSs increases with the subsidy for EVs and by a tax on ICEVs ($\Delta p_f = +$); a result that is similar to

[12] In particular the effect is positive (negative) if $2(1-\gamma_1^2) - \gamma_4(\gamma_2 + \gamma_4) > (<) 0$ and $X > 0$. Figure 5.3 in Appendix 5.2.2 provides a graphical representation of parameter values leading to a positive price effect.

the one obtained for the price of EVs and which crucially relies on the assumption that the network effect is stronger on the retailers' side. The platform increases the price on the side of the market which enjoys the stronger network effect. A policy targeting the EVCS sector directly generates an increase in the price of EVCSs as demand is now higher and the monopolist can charge a higher price. In general, the effect of any subsidy or tax depends on which side of the market is targeted. Quantities and the price of ICEVs are, however, independent of the relative intensity of network effects.

3.3.2 Policy impacts for $\gamma_2 > \gamma_4$

The results obtained when the network effect is stronger on the consumers' side are summarized in Table 3.2. As previously outlined, the effects on the quantities

	EVs		ICEVs		EVCSs	
	Δq_c	Δp_c	Δq_d	Δp_d	Δq_f	Δp_f
s_c	$+$	$+$	$-$	0	$+$	$-$
t_d	$+$	$+$	$-$	$-$	$+$	$-$
s_f	$+$	$+$	$-$	0	$+$	$\pm$

Table 3.2: Policy impacts for $\gamma_2 > \gamma_4$.

are independent of the relative intensity of the network effects.

Considering prices, a subsidy for EVs (s_c) increases the respective price ($\Delta p_c = +$); this happens because the subsidy increases demand for EVs and hence the monopolist can charge a higher price. This result differs from the one we obtained for $\gamma_4 > \gamma_2$, where the impact of s_c on the price of EVs was ambiguous. A tax on ICEVs (t_d) or a subsidy for charging stations (s_f) increase the price of EVs, an opposite outcome compared to the case in which the network effect is stronger on the retailers' side. Since EVs have stronger network effects on charging stations, the platform's profit-maximizing behavior entails a price increase on the consumers' side and a price reduction on the retailers' side. The price of ICEVs behaves in the same way regardless of the relative intensity of the network effects, so it decreases when taxing ICEVs, as before. The price of EVCSs now decreases with both a subsidy for EVs and a tax on ICEVs ($\Delta p_f = -$). The reversed impact of these policies compared to the previous case follows on from the fact that the network effect on consumers is stronger that on retailers; hence, p_f can be reduced without incurring losses. Notice that the decrease in p_f is counteracted by an increase in p_c. Targeting the EVCS sector itself, the subsidy has an ambiguous impact on the price of EVCSs ($\Delta p_f = \pm$), depending on the substitution and network effects.[13] We also find that the effects of s_c on p_c and of s_f on p_f cannot be jointly negative.[14] The economic interpretation of this result derives from the two-sided market structure: as consumers and retailers represent two different sides of the market, the platform never reduces the price on both sides; on the contrary, as explained in the literature (Rochet and Tirole 2003), the platform chooses a price structure, which allows the price to be reduced on one side and covers losses by increasing the price on the other side. From our analysis, we can conclude that the relative intensity of the network effects influences the outcomes of the model in terms of prices[15]. In particular, due to the non-neutral price structure, the effects of some policies reverse depending on their relative intensity. Appendix 5.2.2 provides a deeper discussion of the policy impacts, including the results obtained for relevant values of the parameters.

3.4 First-best solution

In the first-best solution the social planner dictates the quantities that maximize welfare in the economy.[16] We assume that, in contrast to the atomistic agents, the

[13]The condition for a positive (negative) impact on the price is given by $2(1-\gamma_1^2)-\gamma_2(\gamma_2+\gamma_4) > (<) 0$ and $X > 0$. Figure 5.6 in Appendix 5.2.2 provides a graphical representation of parameter values leading to a positive price effect on EVCSs.

[14] Figure 5.10 in Appendix 5.2.2 provides a reasoning for this result.

[15]See Figures 5.7, 5.8 and 5.9 in Appendix 5.2.2. The graphs show how the effect varies depending on the relative intensities of the network effects.

[16]See Appendix 5.2.3 for the derivation of the first-best solution.

social planner acknowledges the negative environmental externality; moreover, it fully internalizes the presence of network effects. The latter are only partly internalized in the decentralized equilibrium as we assume perfect information about the demand functions but the network effects have an additional impact on the utility and payoff functions of consumers and retailers respectively, which is ignored by the atomistic agents. The social planner maximizes welfare (W^P), which given the quasi-linear specification, can be written as the sum of utility, payoff function and profits minus the damage due to pollution

$$W^P(q_{0,h}, q_{0,a}, q_c, q_d, q_f) = U(q_{0,h}, q_c, q_d; q_f) + F(q_{0,a}, q_f; q_c) + \pi(q_c, q_d, q_f) - \phi q_d,$$

where $\phi \in (0, 1)$ represents the intensity of damages due to pollution. The social planner maximizes welfare subject to the resource constraint of the economy

$$q_{0,h} + q_{0,a} + p_c q_c + p_d q_d, +p_f q_f \leq m_h + m_a.$$

Due to the quasi-linear specification, welfare is strictly increasing in the numeraire good and the constraint holds with equality.

3.4.1 Ratio of EVs to ICEVs

Solving the social planner's problem we find the optimal ratio of EVs to ICEVs (ζ_{fb}) and we compare it to the ratio prevailing in the decentralized economy (ζ_m)

$$\zeta_{fb} = \frac{\alpha_c - c_c - \gamma_1(\alpha_d - c_d^P) + (\gamma_2 + \gamma_4)(\alpha_f - c_f)}{-\gamma_1(\alpha_c - c_c) + [1 - (\gamma_2 + \gamma_4)^2](\alpha_d - c_d^P) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_f - c_f)},$$

$$\zeta_m = \frac{2(\alpha_c - c_c) - 2\gamma_1(\alpha_d - c_d) + (\gamma_2 + \gamma_4)(\alpha_f - c_f)}{-2\gamma_1(\alpha_c - c_c) + \left[2 - \frac{1}{2}(\gamma_2 + \gamma_4)^2\right](\alpha_d - c_d) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_f - c_f)},$$

where $c_d^P = c_d + \phi$ represents the cost of producing ICEVs once the negative pollution externality is taken into account. We can show that, given the *monopoly* and *first-best condition*, $\partial\zeta_{fb}/\partial(\gamma_2+\gamma_4) > \partial\zeta_m/\partial(\gamma_2+\gamma_4)$ and $\partial\zeta_{fb}/\partial\phi > \partial\zeta_m/\partial\phi$, meaning that the ratio in the first-best increases more rapidly with the total network effect and environmental externality, compared to the ratio prevailing in the decentralized economy.

Proposition 3.4.1 (Optimal ratios of EVs to ICEVs) *In the presence of network and/or environmental externalities, the ratio of EVs to ICEVs is higher in the first-best compared to the monopolistic case.*[17]

Our findings are represented in Figure 3.2, which demonstrates that the ratio in the first-best (solid line) always implies a larger number of EVs than in the monopoly.[18] The wedge increases for larger values of the total network effect because the decentralized equilibrium completely ignores the environmental damage and only partially internalizes the network externalities. This is because the social planner takes the impact of the network effects on both sides of the market into account, whereas in the decentralized case agents do not consider the positive feedback effect of their decisions on the other side of the market. The lower ratio of EVs to ICEVs in the decentralized economy paves the way for policy intervention in the form of support measures favoring the diffusion of EVs and EVCSs.

3.5 Welfare analysis

In this section, we introduce the possibility for a policymaker to choose the welfare-maximizing combination of subsidies and taxes, under the constraint of a balanced budget and taking into account the negative externality from ICEVs. Moreover,

[17] This generally holds true, independently of the actual values for the demand parameters and the network effects under the assumption of an interior solution. See Appendix 5.2.3 for a proof of this result.

[18] Our model specification allows us to focus on the impact of network effects on welfare; since welfare depends only on the sum of network effects, there is no need to disentangle the relative intensities on the two sides of the market.

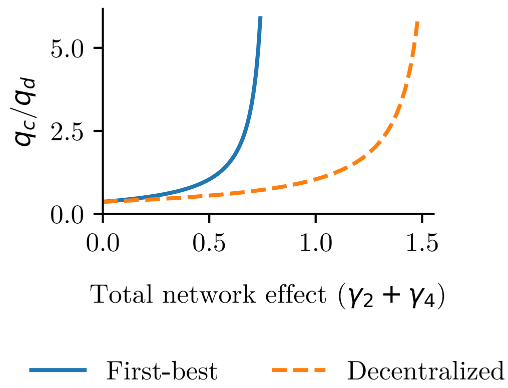

Figure 3.2: Ratio of EVs to ICEVs in the first-best and decentralized case as a function of the total network effect.

we investigate how the presence of network effects impacts optimal welfare, that is, welfare once the optimal combination of policies is applied. In our simulations we focus on the effect of the sum of positive network externalities enjoyed by consumers and retailers rather than on the individual values assumed by γ_2 and γ_4. Our choice is justified by the fact that optimal welfare can be characterized through quantities alone, which only depend on the total network effect $(\gamma_2 + \gamma_4)$.

We find that the optimal combination of policies includes subsidies for EVs and EVCSs (s_c and s_f) and taxes on ICEVs (t_d).[19] In order to show how the optimal policies influence the outcomes of the model, Figure 3.3 builds on Figure 3.2 and represents the ratio of EVs to ICEVs in the first-best (solid line), in the decentralized (dashed-dotted line) and when the optimal combination of policies is applied (dashed line). The optimal policies partially correct for the environmental externality from pollution and for the network effects: the ratio of EVs to ICEVs is higher compared to the monopoly case and the solution is closer to the first-best outcome. However, the assumption of a balanced budget does not allow the

[19]Note that we use the term *optimal policies* to denote policies which correct for the externality due to the network effects and pollution. We do not consider policies tackling the monopoly externality as this is not the focus of our paper.

policymaker to achieve the first-best solution.

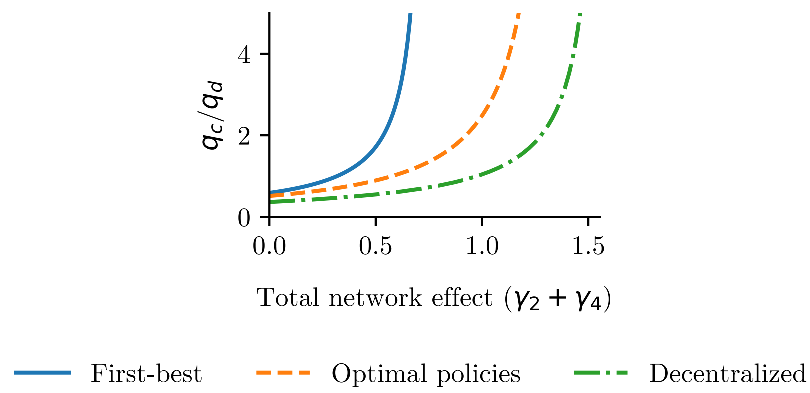

Figure 3.3: Ratios of EVs to ICEVs in the first-best, optimal and decentralized solution.

Figure 3.4 allows for a comparison between welfare in the optimal (dashed line) and in the decentralized case (dot-dashed line). When the optimal policies apply, welfare is higher than in the decentralized equilibrium; this holds true even when the network effects are zero because of the pollution externality, which is not taken into account by private agents. Moreover, in the presence of network effects the gap between the welfare widens because the externality due to network effects kicks in on top of the environmental externality. This means that policies are used to correct for the two externalities; the implications of this mechanism become apparent in the next section.

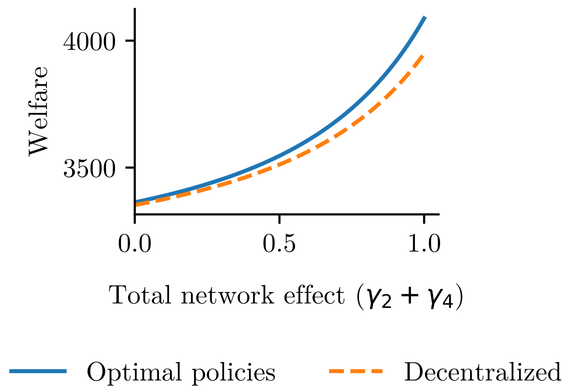

Figure 3.4: Optimal and decentralized welfare as a function of total network effect.

3.5.1 Double dividend

Countries have started to set targets in terms of reducing the number of polluting cars circulating; in order to achieve such targets, policymakers adopted subsidies to EVs and EVCSs and taxes on ICEVs. However, such measures - in particular taxes on ICEVs - have led to political pressure due to discontent in the general public.[20] Indeed, the environmental benefit derived from reducing the number of ICEVs is not sufficient to generate widespread support for such measures. For policies reducing the number of ICEVs to be well received, we need to draw attention to the economic benefits of having a lower number of ICEVs: in this section, we show that the presence of network effects can lead to the emergence of a double dividend, meaning that economic welfare can be improved while reducing the negative impact of pollution. Hence, awareness of the double dividend effect could play a crucial role in the political debate.

We assume that the policymaker maximizes welfare as before with the additional constraint of achieving a given target in terms of the number of ICEVs circulating. In particular, we consider a given target percentage reduction of ICEVs

[20]See for example the "yellow vests" protests in 2018 in France.

compared to the decentralized level (q_d^*) and we simulate the impact on optimal welfare of different values of such target.[21] Figure 3.5 shows how optimal welfare changes with the percentage reduction of ICEVs. We see that using an optimal policy mix to reduce q_d can improve welfare. In the case of no network effects (solid line), the policymaker can maximize welfare by decreasing q_d to account for the negative environmental externality. Adding the network effects, the policymaker faces a second externality and the q_d that maximizes welfare is therefore lower. This effect becomes stronger for higher values of the network effects.

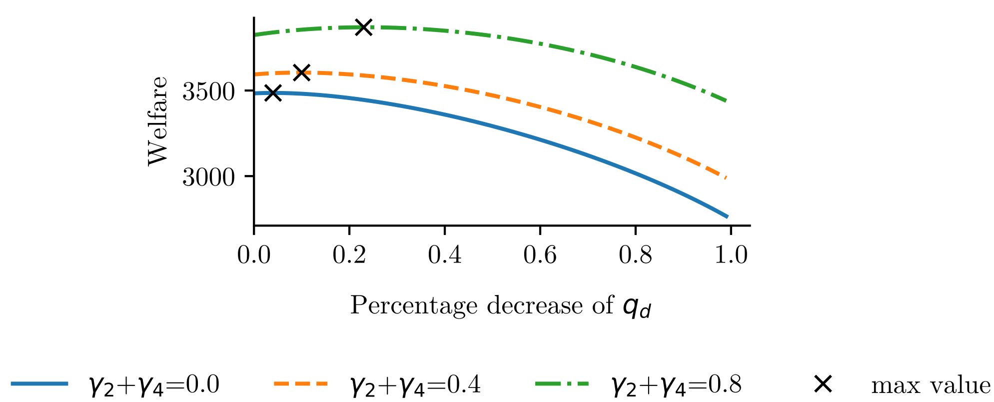

Figure 3.5: Optimal welfare as a function of a percentage decrease of ICEVs, for different values of the total network effect.

In what follows, we disentangle the environmental and network externalities in order to show the existence of a double dividend. Figure 3.6 represents the evolution of economic welfare (W^E), which does not take the environment into account, and total welfare (W^P), as a function of the percentage reduction of ICEVs. The wedge between the two curves represents the environmental damage and it decreases as the number of ICEVs shrinks. Both for economic and total welfare, there is scope for improvement when policies aim at decreasing q_d. This scope is wider when considering total welfare as it takes into account the environmental externality next

[21] We assume $q_d = q_d^*(1-r)$, with $r \in [0,1]$; hence, $r = 1$ means that no ICEVs exist in the economy.

to the network externality. For a decrease in the range from 0 to r^{dd}, the economic and total welfare increase because EVs enjoy network effects; moreover, increasing EVs compared to ICEVs reduces the negative externality due to pollution produced by ICEVs. Reducing q_d up to the threshold r^* increases total welfare, but from r^{dd} to r^* this comes at a cost in terms of economic welfare. Therefore, the policymaker faces a strong double dividend for a reduction of q_d in the shaded gray area. Such a double dividend is attributable to the presence of pollution and network effects.

Remark 3.5.1 (Double dividend) *In the presence of network and environmental externalities a double dividend effect exists. Optimal policies can increase economic welfare while enhancing environmental quality.*

Notice that, combining the findings in Figure 3.5 and Figure 3.6 implies that the scope for a strong double dividend increases with the total network effects.

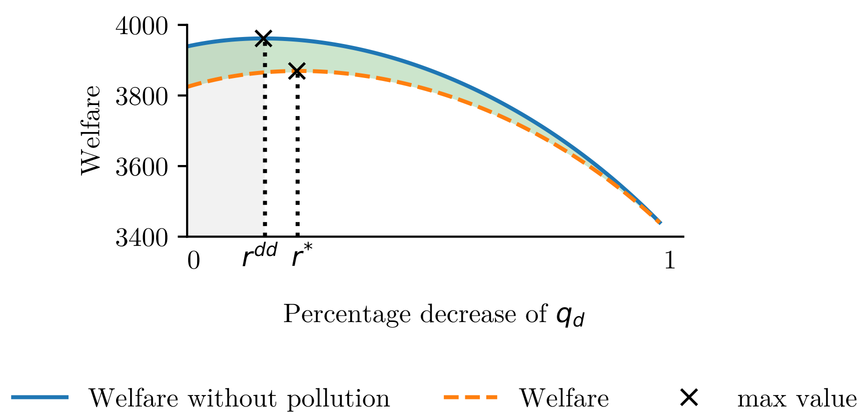

Figure 3.6: Double dividend.

3.6 Extension: oligopoly

In this section we relax the assumption of a monopolistic market structure in favor of an oligopoly. We assume that n identical firms compete *à la Cournot*; each firm i with $i = 1, ..., N$ chooses the quantities of EVs, ICEVs and EVCSs taking into account the decisions of the other firms.[22] As in Figure 3.4 in the monopoly case, it can be shown that for fixed N welfare is increasing with the network effects. Figure 3.7 shows how welfare evolves with the percentage decrease of the quantity of ICEVs, for different numbers of firms. Compared to the monopoly case ($n = 1$), welfare is larger for higher number of firms for any value of the percentage reduction of ICEVs.

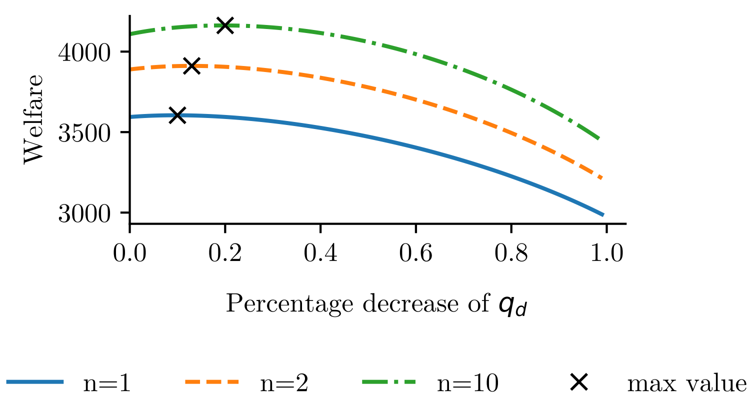

Figure 3.7: Welfare as a function of a percentage decrease in the quantity of ICEVs, for different n, with $\gamma_2 + \gamma_4 = 0.4$.

Figure 3.8 shows that, when assuming an oligopolistic market structure, the double dividend effect is still present: in the gray shaded area welfare without accounting for pollution can be improved with no negative impact on the environment. Moreover, we find that increasing the number of firms, the double dividend effect becomes stronger and welfare is maximized for a lower number of ICEVs.

[22] Appendix 5.2.4 provides the solution to the model when an oligopolistic market structure is assumed.

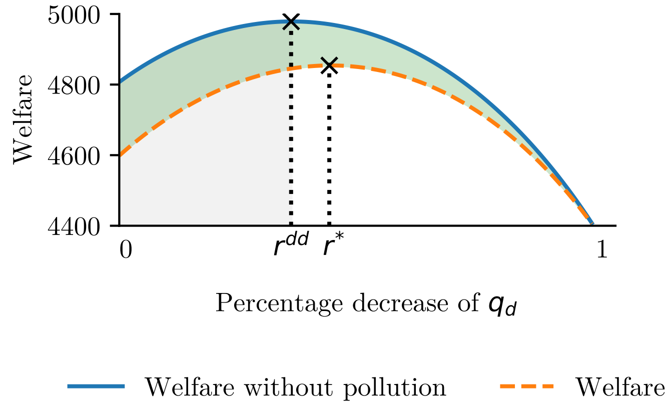

Figure 3.8: Double dividend assuming $n = 10$.

3.7 Conclusion

In this part of the thesis we analyze how the transition to a low-carbon economy can take place in the transportation sector. Following the increasing potential attributed to electric vehicles (EVs) to decarbonize the transportation sector, which is at odd with their still limited diffusion, the debate about the design of policies supporting EV adoption has gained importance. One of the main obstacles identified and the focus of the present Chapter is the lack of an appropriate charging infrastructure. This generates the so-called range anxiety, which reduces the possibility for consumers to perceive EVs and internal combustion engines vehicles (ICEVs) as substitutable. Besides government intervention, the retail sector can play a key role in expanding the charging network. However, the number of electric vehicle charging stations (EVCSs) purchased by retailers will not increase as long as the number of EVs is low. Hence, the market for EVs exhibits a "chicken-egg" problem due to the presence of network externalities operating between the two goods. With this Chapter, we contribute to this debate by providing a theoretical framework that takes into account the two-sidedness of the EV market and the indirect network effects operating between EVs and EVCSs. Additionally, we account for the degree of substitutability between EVs and ICEVs, and for the pollution externality generated by ICEVs.

In our model, a platform sells EVs and ICEVs to consumers on one side of the market and EVCSs to retailers on the other side. Within this framework, consumers make their car purchasing decisions by maximizing utility, which is affected by the number of EVCSs, and retailers choose charging stations based on the maximization of their payoff function, which in turn, depends on the number of EVs. We introduce policies targeting prices of EVs, ICEVs and EVCSs and study how they affect the adoption of EVs in the presence of network externalities. We then introduce a negative externality from ICEVs and compute the welfare-maximizing combination of policies. Finally, we show how a reduction in the number of ICEVs affects optimal welfare.

The main results of the present Chapter are: (1) the presence of network effects has an impact on the profit-maximizing quantities and prices: in particular, policies tackling one side of the market also affect the other side and thus generate feedback loops. The choice of subsidizing EVs does not only have a positive effect on the number of EVs *per se*, but also on the quantity of EVCSs. More charging stations, in turn, generate a positive feedback effect on the number of EVs. Since the network effects work both on the EV and EVCS side, the same positive outcome in terms of EV adoption occurs when subsidizing EVCSs; (2) policies are non-neutral, that is, subsidies to consumers or retailers are not equivalent; this is due to the dependence of prices on the relative intensity of network effects; (3) the set of welfare-maximizing policies implies subsidies to EVs and EVCSs as well as taxes on ICEVs; (4) in the presence of network effects and of a negative environmental externality from ICEVs, there is scope for a strong double dividend: decreasing the quantity of internal combustion engine vehicles can be economically improving, while reducing the negative impact of pollution. The findings of our model imply that it is important to account for network externalities between EVs and EVCSs when designing EV promoting policies. The resulting feedback loops might exacerbate shocks to either side of the market and thus generate effects which are greater than any single market study suggests. Ignoring the interdependence of EVs and EVCSs could therefore lead to an underestimation of the impact of policy measures. Finally, the presence of a strong double dividend implies that a lower number of ICEVs can be economically-improving while reducing the negative impact of pollution.

Future research should focus on introducing non-linearities in the demand functions and on a more in-depth study of alternative market structures. Moreover, our economic setting might be studied in a dynamic framework so that the adoption of new technologies (EVs and EVCSs) follows from non-simultaneous decisions of consumers and retailers. In addition, the pricing decision by the platform might be affected by the production costs of suppliers (for instance, battery production). A more realistic model might therefore also allow for vertical integration of production.

Chapter 4

Emission-based Interest Rates and the Transition to a Low-carbon Economy[*]

Abstract

We use a dynamic general equilibrium model to study a climate-oriented monetary policy in the form of emission-based interest rates set by the central bank. Liquidity costs of banks increase with the carbon intensity of their asset portfolio, leading banks to favor low-carbon assets and to improve the financing conditions for clean sectors. We show that such a monetary policy supports the decarbonization of the economy and reduces climate damage, as more resources are channeled to low-carbon sectors and incentives to adopt cleaner technologies increase across all sectors. We illustrate these effects by calibrating our model to data for the Euro Area.

[*]This work is a joint effort with Florian Böser (ETH Zurich).

4.1 Introduction

In this last Chapter of the dissertation, the role of a climate-oriented monetary policy in supporting the transition to a low-carbon economy is investigated, by introducing an emission-based interest rate policy adopted by the central bank. As damage from weather anomalies ratchets up, climate change and global warming are widely recognized as a threat for the environment, the economy and the society as a whole (IPCC 2018). Carbon emissions, which have been identified as the main driver of global warming, need to be reduced in order to limit the average global temperature increase, as outlined in the Paris Agreement of 2015.[1] Accordingly, developing and adopting clean technologies across sectors, as for example energy generation[2] and transportation, is crucial in order to lower the carbon intensity of the global economy and to achieve the agreed climate targets.

To foster the development and adoption of clean technologies, climate policies have so far mostly encompassed fiscal policies. Specifically, the measures adopted have aimed at reducing the costs of clean technologies and discouraging dirty production activities. Relevant measures include, among others, carbon taxes (Nordhaus 2013, Weitzman 2014, Borissov et al. 2019), cap-and-trade systems for emission certificates (Gersbach and Winkler 2011, Goulder and Schein 2013, Greaker and Hagem 2014), subsidies for clean investments (Acemoglu et al. 2012, 2016, Gerlagh et al. 2018, Greaker et al. 2018, Ramstein et al. 2019) and feed-in tariffs (Proença and Aubyn 2013).[3] In particular, carbon prices should reflect the social

[1] See https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&lang=_en&clang=_en, accessed on 23/11/2019.

[2] The importance of this issue is emphasized, for instance, by the implementation of the EU energy union strategy (https://ec.europa.eu/commission/priorities/energy-union-and-climate_en, accessed on 23/11/2019), the German Energiewende (https://www.bmwi.de/Redaktion/EN/Dossier/energy-transition.html, accessed on 23/11/2019) or the Swiss Energiestrategie 2050 (https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050.html, accessed on 23/11/2019).

[3] Public investment in the form, for instance, of public transportation networks, expansion of the power grid to renewable sites and infrastructure for carbon capture and storage can also play a crucial role.

cost of carbon emissions and are considered to be a critical instrument for the transition to a low-carbon economy (Aghion et al. 2016, IMF 2019). However, carbon pricing might not always be applicable in the absence of cleaner alternatives or due to low credibility (Fay et al. 2015). In addition, it has been stressed that the lack of political acceptability, government and market failures as well as distributive effects limit the feasibility of this instrument (Rozenberg et al. 2013, Baranzini et al. 2017, Krogstrup and Oman 2019, Maestre-Andrés et al. 2019).

Thus, there is an increasing debate about which additional tools policymakers can use to induce the transition to a low-carbon economy. Complementary policies discussed among academics and policymakers include the integration of climate objectives into monetary policy (Rozenberg et al. 2013, Campiglio 2016, Volz 2017). Currently, central banks play a rather passive role in the fight against climate change, as they are, if at all, primarily concerned about including climate risk in their investment decisions and urging commercial banks to apply adequate risk management procedures. In their interaction with the financial sector, central banks do not take the carbon intensity of financial assets and of financial institutions into account. On the opposite, it has been argued that central banks undermine existing efforts to induce the transition to a low-carbon economy by holding portfolios which overweight carbon-intensive compared to low-carbon assets (Matikainen et al. 2017, Jourdan and Kalinowski 2019). Instead, central banks could support the decarbonization of the economy by adopting investment guidelines, when purchasing assets, which favor financial assets with a relatively lower carbon footprint. These types of policies could also reduce the exposure of central banks to potential negative financial asset reevaluations as a result of the introduction of other climate policies. Central banks justify their current approach based on their mandate, which is generally centered around price and economic stability in the short term. Climate change, in turn, constitutes a negative externality in the long run, thus leading to the tragedy of the horizon (Carney 2015). Nevertheless, central banks themselves have started to recognize the possibility of assuming a more active role (Carney 2015, Coeure 2018, ECB 2019, NGFS 2019). A climate-oriented monetary policy can accompany existing measures that target the innovation and adoption of clean technologies. Such a monetary policy would, independent of its actual design, aim at improving the financing conditions for low-carbon sectors (Aglietta et al. 2015, Schoenmaker 2019). Hence, dirty production activities become less attractive, resulting in more resources shifted to clean production and more incentives for polluting firms to adopt cleaner technologies.

The integration of climate objectives into monetary policy can take various forms. Rozenberg et al. (2013) propose the introduction of carbon certificates distributed to low-carbon projects, that can be accepted as part of banks' legal reserves and thus reduce the capital costs for sustainable activities. Campiglio (2016) discusses green reserve requirements, which take the carbon footprint of the asset portfolio held by the individual financial institution into account. Such differentiated reserve requirements based on the composition of a bank's asset holdings are also discussed by Volz (2017) and Fender et al. (2019).[4] Monnin (2018a) and Fisher and Alexander (2019), in turn, propose an overall update of central banks' collateral framework by incorporating sustainability criteria. Green quantitative easing, namely asset purchases by the central bank directed towards low-carbon financial assets, such as green bonds, represents another alternative for a climate-oriented monetary policy (Volz 2017, Monnin 2018a). This Chapter, in turn, focuses on a yet unexplored approach, according to which the central bank adopts an interest rate policy for reserve loans to banks, that depends on the carbon intensity of the asset portfolio held by the individual institution. All the proposed measures, including our approach, make it necessary to amend central bank mandates by integrating climate goals. Admittedly, this represents a major change in the way monetary policy is conducted and may face resistance across the society. However, current climate policies suffer from political uncertainty, so that delegating climate

[4]In addition, Volz (2017) proposes a climate-oriented bank regulation in the form of differentiated capital requirements depending on the type of lending conducted by the individual bank, as for example, higher risk weights for loans to carbon-intensive and carbon-dependent sectors.

actions to an independent authority, such as the central bank, might represent a reasonable strategy to achieve the overall climate targets.

The implications of a climate-oriented monetary policy are, however, still unclear and require further in-depth investigation. To the best of our knowledge, there exists no theoretical model analyzing the integration of climate objectives into monetary policy. We aim to contribute to this gap in the literature by assessing the impact of an emission-based interest rate policy adopted by the central bank on the transition to a low-carbon economy. For our analysis, we attempt to reproduce the current monetary system as closely as possible. In this endeavor, we rely on Faure and Gersbach (2017), who emphasize the hierarchical structure of our monetary system by pointing out various stylized elements: first, the money stock available to the public takes mainly the form of deposits and only to a minor extent the form of cash. Second, deposits are created by commercial banks when granting loans or purchasing assets.[5] Third, the central bank issues reserves to commercial banks that use them to settle claims between each other, which can, for example, arise from interbank deposits flows. Fourth, the central bank issues cash to commercial banks that use them to settle withdrawals of deposits.[6] Our framework accounts for the generation of carbon emissions in the course of production activities, which may lead to increases in temperature and, ultimately, climate damage. We impose a linear relation between carbon emissions and temperature as estimated by Matthews et al. (2009). Climate damage, in turn, takes the form of final output reductions and is modeled as in Nordhaus and Sztorc (2013). Finally, we account for sectoral emission intensities of production and allow for their reduction through the adoption of cleaner technologies.

In our framework, commercial banks finance firms with loans and thereby create deposits, which serve as the only medium-of-exchange. Moreover, a central bank

[5] A comprehensive summary of money creation processes is, for instance, provided by McLeay et al. (2014) and by the Bundesbank (2017).

[6] In what follows, we refer to cash and reserves as central bank money or, more generally, liquidity.

provides liquidity in terms of reserves to commercial banks, while applying an emission-based interest rate policy. Reserve loans are priced depending on the emission intensity of the asset portfolio held by the individual bank. Due to perfect competition in the banking sector, the liquidity costs of banks are passed on to the real economy. The financing costs of firms thus decrease with the emission intensity of the applied technology, so that the central bank policy affects the choice of clean technology adoption by firms. In our setting, the latter requires physical capital and, ultimately, reduces the input available for production. When maximizing profits, firms therefore face a trade-off between lowering financing costs through the adoption of a cleaner technology and reducing their production capacity.

We show that an emission-based interest rate policy adopted by the central bank can represent a valid instrument to promote the transition to a low-carbon economy: first, firms in low carbon-intensive sectors are directly favored by lower financing costs, so that more resources are allocated to sustainable production activities. Second, the carbon-based pricing incentivizes all firms to adopt cleaner technologies. As we focus on a perfectly competitive banking sector, banks themselves do not face any direct costs from such a climate-oriented monetary policy. However, depending on the risk characteristics and emission intensities of sectoral production, such a policy may affect the loan demand of firms and, hence, shape the composition of loan portfolios held by banks. We illustrate these effects by calibrating our model to data for the Euro Area.

The remainder of the Chapter is organized as follows: in Section 4.2, we briefly discuss other proposals for a climate-oriented monetary policy. Section 4.3 outlines our model, capturing the main characteristics of our current monetary system, introducing the emission-based interest rate policy applied by the central bank and highlighting firms' trade-off between technology adoption and production. Section 4.4 provides the theoretical model analysis. In Section 4.5, we outline the adopted numerical solution method, while Section 4.6 discusses the choice of parameters used for calibration and provides the results of our simulation exercise. In Section

4.7 we provide our conclusions and discuss policy implications.

4.2 Climate-oriented monetary policies

We can identify two main arguments in favor of integrating climate objectives into monetary policymaking: first, the financial sector itself is impacted by climate change and environmental policies, potentially leading to financial instability due to their impact on the risk-return structure of financial assets (Schoenmaker and Van Tilburg 2016). Second, the financial sector can play a central role in financing the enormous investments required for the transition to a low-carbon economy, thus facilitating the transition itself. In the following, both arguments are outlined in greater detail.

Climate change and the consequent introduction of climate policies could impact the financial sector through physical risks, transition risks and liability risks (Carney 2015, TCFD 2017, Volz 2017, Campiglio et al. 2018). The physical risks arise from climate-related events, such as droughts, floods, storms and sea-level rise. As illustrated in Dietz et al. (2016), Batten et al. (2016), Dafermos et al. (2017), Dafermos et al. (2018) and Bovari et al. (2018), such events can significantly endanger the value of financial assets in the economy. For example, Dietz et al. (2016) estimate the global climate value at risk at approximately USD 24 trillion. The transition risks arise from the shift towards less carbon-generating technologies and changes in demand patterns. The transition entails costs due to investment and conversion activities, which can impair the ongoing production processes and thereby expose owners of financial assets to a higher risk of low returns (Monnin 2018b). For example, Battiston et al. (2017) discuss that, as a result of climate policies favoring green firms and discouraging brown firms, a large portion of financial assets can be subject to substantial reevaluation. Stolbova et al. (2018), in turn, show that climate policies targeting the financial sector or non-financial firms can result in a significant amplification of shocks to the economy, thus, increasing gains and losses for the financial system. Finally, the liability risks arising from the potential impact of legal actions by parties suffering from climate change against those held responsible is widely discussed among policymakers and practitioners (Carney 2015).

The transition to a low-carbon economy requires significant investments, often characterized by high upfront capital costs and high investment risks (Schmidt 2014). The International Energy Agency (IEA) estimates that the green investment gap, that is, the additional amount of annual investments needed to decarbonize the global economy, is USD 900 billion (IEA 2012); McKinsey (2010) estimates around USD 650 billion, whereas the World Economic Forum reports an intermediate value of USD 700 billion (WEF 2013). Financial policies can help to reduce the green investment gap by mobilizing private funds for sustainable projects, thereby promoting the switch from dirty to clean technologies (Sachs et al. 2014, OECD 2017).

With the adoption of a climate-oriented monetary policy the central bank can align its own investment decisions as well as those of financial institutions with the overall climate targets. Since the financial crisis 2007–08, the policies adopted by central banks have been represented by both unconventional measures, such as quantitative easing in the form of large-scale asset purchases at financial markets, and traditional measures, such as liquidity provisions in the form of loans to banks. With regard to the latter, central banks have several instruments available to control the liquidity costs for financial intermediaries, which indirectly affect their investment behavior. These instruments primarily comprise the reserve requirement, the collateral framework and the interest rate policy. By integrating climate objectives in the design of these instruments, central banks can use the existing framework to condition banks' liquidity costs on the sustainability of their investments. Specifically, the costs imposed by central banks should lead commercial banks to favor low-carbon assets, so that the corresponding sectors benefit from better financing conditions (Schoenmaker 2019). Finally, as banks finance a large share of the economy, there is reason to believe that a shift in banks' investment behavior can have a signaling effect on other financial market participants.[7]

4.2.1 Green quantitative easing

After the financial crisis 2007–08, many central banks adopted unconventional policy measures. Most notably, central banks started to purchase assets at financial markets on a large scale in order to improve the mid- to long-term financing conditions in the real economy. Focusing on the European Central Bank (ECB), Matikainen et al. (2017) and Jourdan and Kalinowski (2019) stress that its portfolio resulting from such asset purchases is currently skewed towards carbon-intensive assets. Such a bias might be detrimental for the achievement of the overall climate targets. Monetary policy could instead support long-term sustainability goals. For example, the central bank could engage in the purchase of green bonds issued by development banks, such as the European Investment Bank (Matikainen et al. 2017). Currently, the market for green bonds shows remarkable growth. However, as of 2016 they made up only one percent of the global bond market as reported by the Climate Bonds Initiative.[8] A climate-oriented monetary policy may help to develop this market further and, ultimately, ensure that sufficient resources are channeled to sustainable activities. Green quantitative easing requires investment guidelines, which account for the sustainability of financial assets. As any other climate-oriented monetary policy, the latter necessitates information disclosure about the carbon footprint of production activities at the firm level and the firms' decarbonization strategies. This issue has been recognized by major stakeholders, as shown by the foundation of the Task Force on Climate-Related Financial Disclosure in 2015.[9]

[7] For instance, De Fiore and Uhlig (2011) show that for corporations in the Euro Area bank finance is significantly more important than market finance for the acquisition of external funds.

[8] Available at https://www.climatebonds.net/resources/publications/bonds-climate-change-2016, accessed on 23/11/2019.

[9] Available at https://www.unepfi.org/climate-change/tcfd/, accessed on 23/11/2019.

4.2.2 Green reserve requirements

In general, financial institutions issuing deposits have a demand for central bank money, as they require cash to meet withdrawals of deposits and reserves to settle interbank claims at the central bank. In order to reduce the illiquidity risk of these institutions, the central bank imposes a reserve requirement. Specifically, banks must hold reserves according to a predetermined share of deposits. These reserves are borrowed from the central bank and are therefore generally costly, so that the reserve requirement, if binding, influences the liquidity costs of banks. As commercial banks fund a large share of their investments with deposits, the liquidity costs impact their incentives to engage into lending activities to the real economy or asset purchases at financial markets. Following this reasoning, central banks can regulate the creation and allocation of credit through a differentiated reserve requirement based on the environmental impact of the financing activities conducted by the individual bank (Volz 2017). Thus, imposing a lower reserve requirement on banks financing sustainable activities would theoretically favor green over conventional investments (Rozenberg et al. 2013, Campiglio 2016). However, unconventional monetary policies applied in the aftermath of the financial crisis 2007–08 led to a tremendous increase in reserve holdings by commercial banks, so that in recent years reserve requirements imposed by central banks are rarely binding. Hence, conditioning reserve requirements on the carbon footprint of banks' asset portfolio must be combined with a significant increase of reserve requirements in order to render such a climate-oriented monetary policy effective.

4.2.3 Green collateral framework

Reserve loans granted by the central bank are generally collateralized. In other words, banks have to pledge assets during the borrowing period in order to secure their loans. The central bank defines the assets eligible as collateral and the collateral value of these assets through the use of haircuts. Both the choice of eligible assets and the choice of haircuts safeguard the central bank from the risk inherent in its lending activities. Nyborg (2017) argues that the collateral framework can distort financial markets as well as the real economy. This is due to the fact that securities which can be used as collateral in the interaction with the central bank become more liquid and, thus, the financing costs for the issuer of the security decrease (Nagel 2016, Nyborg 2017). Similarly, a lower haircut increases the liquidity of the security and therefore reduces the financing costs (Ashcraft et al. 2011). Since the issuers of eligible assets generally enjoy better financing conditions, the collateral framework may represent a tool for central banks to steer funds towards low-carbon projects. Specifically, integrating sustainability criteria into the collateral framework represents an advantage for the issuers of low-carbon assets. This may be particularly relevant as under the current collateral framework, assets from companies which employ new, sustainable technologies may face barriers to eligibility (Matikainen et al. 2017), for example, due to the lower credit ratings obtained by such companies.

4.3 Model

We consider a variation of the neoclassical growth model in discrete time, which features households, firms, banks and a central bank. As in standard classical theory, households are utility-maximizing and are endowed with physical capital and labor. Firms can use physical capital and labor to produce a unique output good or to adopt new technologies. The output good is then consumed or invested by households. Production generates emissions which entail increases in temperature. Higher temperature, in turn, leads to climate damage, which reduces final output. Firms can lower emissions by adopting new technologies, which are cleaner than the old ones. Firms finance their activities with loans from banks. While granting loans, banks issue deposits, which, as a result of trades, may circulate between banks and, hence, give rise to interbank claims. Liabilities among banks are settled with reserves, which the central bank issues in its lending facilities. The central bank pursues a climate-oriented monetary policy, so that reserve loans are priced according to the carbon intensity of the loan portfolio held by the individual bank. In our economy, trades are settled instantaneously, with deposits at banks as the only medium-of-exchange. Households own firms and banks with unlimited liability, so that they receive all available profits and must cover all incurred losses. The government, which in our setting only comprises the central bank, operates with a balanced budget, so that generated profits or losses are distributed to or compensated by households.

In each period, there is uncertainty about the state of the economy, which may affect the productivity of firms and the monetary policy conducted by the central bank. We model a monetary economy in which trades and the related payment processes follow a predetermined order. Accordingly, we divide each period into four stages (I)—(IV), which are described below.

In stage (I), the state of the economy realizes, so that the productivity of firms and the monetary policy of the central bank are determined. Banks grant loans to firms in different production sectors and thereby create deposits. All assets held by banks are funded with deposits; a circumstance which we capture by the so-called "money creation constraint". To settle future deposit outflows resulting from trades between households and firms, banks demand reserve loans from the central bank.[10] In stage (II), households rent physical capital and labor to firms for the production of the output good. Firms finance the rental costs of the input factors with the previously acquired deposits from banks. Trading activities between firms and households lead to interbank deposit flows, which result in claims among banks, which are settled at the central bank by using reserves. In stage (III), firms use the acquired capital and labor to produce the output good and to adopt a cleaner technology. Banks credit deposits held by households with interest, whereas the central bank pays interest on reserve deposits held by banks. The profits (losses) of

[10] Note that we abstract from the possibility of deposit withdrawals, which would further increase the liquidity demand of banks.

firms, banks and the central bank are distributed to (compensated by) households. In stage (IV), households purchase the output good from firms using all available funds. As households and firms trade, deposits circulate among banks resulting in interbank claims, which are settled at the central bank using reserves. Firms use the revenues from sales of the production output to repay their outstanding loans to banks. In the same manner, banks repay the reserve loans to the central bank.

Uncertainty enters our model in the following way: each period $t \in \mathbb{N}_0$ an economic state $z_t \in \mathcal{Z} = \{1, \ldots, Z\}$, with $Z \in \mathbb{N}$ denoting the number of states, is realized. The states are independent and identically distributed across time, with probabilities $\pi(z) > 0$, for all $z \in \mathcal{Z}$. Thus, given the initial state $z_0 \in \mathcal{Z}$, any variable X_t is a function of the history of states $z^t = (z_0, \ldots, z_t) \in \mathcal{Z}^{t+1}$, that is, $X_t : \mathcal{Z}^{t+1} \to \mathbb{R}$, if not defined otherwise. The expectation conditional on the information set available at the end of time period t is denoted by $\mathbb{E}_t[\cdot]$.

4.3.1 Households

There is a continuum of identical and infinitely-lived households with unit mass, so that we can focus on a representative agent. The household consists of $N_t = N(z^{t-1}) > 0$ identical individuals and is endowed with aggregate capital $K_t = K(z^{t-1}) > 0$. Each individual can supply one unit of labor. We abstract from disutility of labor, so that, in period t, the household provides the total endowment of physical capital K_t and labor N_t to firms in $S \in \mathbb{N}$ different sectors for the production of the single output good. The nominal rental rate of physical capital is given by $Q_t > 0$, whereas the nominal wage rate for labor provided to sector $s \in \mathcal{S} = \{1, \ldots, S\}$ is given by $W_{s,t} > 0$. In what follows, we assume that the size of the household grows each period by η_t percent, that is, $N_t = (1 + \eta_t)N_{t-1}$, for all $t \in \mathbb{N}$. The individual supplies each period a share $n_s \in [0, 1]$ of its labor endowment inelastically to sector s. Thus, the total nominal wage received by the household is given by $W_t N_t = \sum_{s \in \mathcal{S}} W_{s,t} n_s N_t$. As the household rents physical capital and labor to firms, it receives deposits $Q_t K_t + W_t N_t$. These deposits are credited by banks with a nominal gross interest rate $R_t^D > 0$. The household owns banks and firms, so that it receives all available profits and must compensate all incurred losses. Moreover, the central bank generates profits (seigniorage) through its liquidity provisions to banks. The household is exposed to profits or losses of firms Π_t^F, banks Π_t^B and the central bank Π_t^{CB} before the purchase of the output good. The household uses all available funds to purchase the production output of firms reduced by climate damage $\tilde{Y}_t$ at the nominal price $P_t > 0$. Hence, the household faces the budget constraint

$$P_t \tilde{Y}_t \leq R_t^D (Q_t K_t + W_t N_t) + \Pi_t^F + \Pi_t^B + \Pi_t^{CB}.$$

The output good can be used for consumption C_t and investment I_t into the capital stock, as captured by the resource constraint $\tilde{Y}_t \geq C_t + I_t$. Physical capital depreciates each period by a share $\delta \in [0, 1]$ and evolves according to the standard law of motion $K_{t+1} = (1 - \delta)K_t + I_t$. The household maximizes the expected discounted utility from consumption of all individuals across the infinite horizon. The utility of the individuals is weighted equally, that is, the household maximizes the utilitarian welfare given by

$$\mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t N_t \frac{c_t^{1-\sigma} - 1}{1 - \sigma} \right],$$

where c_t represents the consumption per capita and $\sigma \geq 0$ captures the constant relative risk aversion of the instantaneous utility function of each individual. The parameter $\beta = 1/(1 + \rho)$ denotes the discount factor, where $\rho > 0$ represents the discount rate. Given our assumptions on the utility function, the resource constraint and the budget constraint are binding. Hence, when maximizing utility, the household faces a single constraint, that is,

$$P_t(C_t + K_{t+1}) = R_t^D (Q_t K_t + W_t N_t) + P_t(1 - \delta)K_t + \Pi_t^F + \Pi_t^B + \Pi_t^{CB},$$

where we made use of the law of motion for physical capital.

4.3.2 Firms

Each of the S different production sectors in the economy is described by a continuum of identical firms with unit mass. Thus, we can focus on a representative agent for each of the sectors. Firms are assumed to be penniless, so that they rely on external financing in the form of bank loans to cover the rental service of capital and the costs of labor employment. Therefore, in period t, the loans $L_{s,t}$ demanded by the representative firm in sector s are given by

$$L_{s,t} = Q_t K_{s,t} + W_{s,t} N_{s,t},$$

where $K_{s,t}$ and $N_{s,t}$ denote the physical capital and labor employed by the firm. Production generates carbon emissions, which may entail an increase in temperature and ultimately climate damage, as we outline at a later stage. Specifically, one unit of production output in sector s leads to $\Gamma_{s,t} \geq 0$ units of emissions. We can therefore interpret $\Gamma_{s,t}$ as the emission intensity of production in sector s. Each firm can reduce the emission intensity by devoting a share of the acquired capital to the adoption of a cleaner technology. However, this constitutes a trade-off for the firm, as devoting capital to the adoption of a cleaner technology reduces its production capacities. In our model, cleaner technologies are not superior to the old ones in terms of productivity; this extreme view serves our purpose of highlighting the effects of a climate-oriented monetary policy on the adoption of clean technologies, but can generally be relaxed. In what follows, we denote the share of capital devoted to the adoption of a cleaner technology by $\gamma_{s,t} \in [0, 1]$. The firm in sector s produces the output good according to a Cobb-Douglas aggregation, so that production $Y_{s,t}$ in sector s is given by

$$Y_{s,t} = A_{s,t} (\bar{\gamma}_{s,t} K_{s,t})^{\alpha} N_{s,t}^{1-\alpha},$$

where $\bar{\gamma}_{s,t} = 1 - \gamma_{s,t}$ is the share of capital devoted to production, $A_{s,t}$ is the state-dependent and sector-specific total factor productivity, and α is the capital intensity, which we assume to be homogeneous across sectors. The total factor productivity consists of a deterministic part $\hat{A}_t$ which grows each period by a_t percent, that is, $\hat{A}_t = (1 + a_t)\hat{A}_{t-1}$ for all $t \in \mathbb{N}$, and is subject to a stochastic productivity shock $A_s(z_t)$. Hence, the total factor productivity is given by $A_{s,t} = \hat{A}_t A_s(z_t)$. Adoption of a new technology lowers the emission intensity $\Gamma_{s,t}$ according to $\Gamma_{s,t} = (1 - \iota_s \gamma_{s,t})\Gamma_{s,t-1}$. The parameter ι_s is referred to as the innovation impact factor and captures the possibilities for the adoption of a cleaner technology in sector s.[11]

Production generates emissions, which entail temperature increases and climate damage. Emissions depend on the level of production before climate damage and on the emission intensities across sectors, so that they take the form

$$E_t = \sum_{s \in \mathcal{S}} \Gamma_{s,t} Y_{s,t},$$

where emissions are potentially stochastic due to the sectoral productivity shocks. Following Matthews et al. (2009), we impose a linear relationship between carbon emissions and temperature increases. Hence, in our model, the temperature above the preindustrial level T_t evolves according to

$$T_{t+1} = T_t + \tau E_t,$$

where $\tau \geq 0$ represents the carbon-climate response as described by Matthews et al. (2009). Temperature increase leads to higher climate damage, which is modeled as

[11] Note that we abstract from energy as an input factor for production, although energy generation contributes to a large part of global greenhouse gas emissions (IEA 2012). This clearly represents a limitation of our framework, as the shift from fossil fuels to renewable sources exhibits some distinctive traits, which we may be unable to capture by focusing solely on the adoption of clean technologies across sectors. While this assumption serves the purpose of keeping our model tractable, it will be relaxed in future work.

in Nordhaus and Sztorc (2013), so that it is given by

$$\Omega(T_t) = \frac{1}{1 + \pi_1 T_t + \pi_2 T_t^2},$$

where the coefficients $\pi_1 \geq 0$ and $\pi_2 \geq 0$ capture the convexity of the non-linear damage function. Accounting for climate damage, the final production in sector s is given by $\tilde{Y}_{s,t} = \Omega(T_t) Y_{s,t}$. The loans, which the firm obtains from banks, are subject to repayment costs determined by the nominal gross loan rate $R^L_{s,t} > 0$. As discussed in Section 4.4, the emission-based interest rate policy adopted by the central bank leads to liquidity costs for banks, which are passed on to the real economy, so that the financing costs of firms decrease with the sectoral emission intensity. Thus, the loan rate $R^L_{s,t}$ ultimately depends on the emission intensity $\Gamma_{s,t}$ of the applied technology. As the adoption of a new technology requires physical capital, the firm faces a trade-off between lower financing costs and higher production. As the firm is owned with unlimited liability and distributes each period all available profits to the household, we can focus on a static optimization problem. Given the prevailing emission intensity $\Gamma_{s,t-1}$ in sector s and the current temperature T_t, the firm maximizes each period nominal profits with decisions about technology adoption, $\gamma_{s,t}$, and production input factors, $K_{s,t}$ and $N_{s,t}$, that is,

$$\max_{\gamma_{s,t}, K_{s,t}, N_{s,t}} \Pi^F_{s,t} = P_t \tilde{Y}_{s,t} - R^L_{s,t} L_{s,t}.$$

4.3.3 Banks

Banks are identical and exist in a continuum with unit mass, so that we focus on a representative agent.[12] The loans granted to sector s are denoted by $L_{s,t}$, whereas the total loans are given by $L_t = \sum_{s \in \mathcal{S}} L_{s,t}$. The bank creates deposits D_t when providing loan financing, so that all bank assets are funded with deposits; a circumstance that we capture by the money creation constraint $L_t = D_t$. The

[12] Faure and Gersbach (2017) provide conditions, when the representative agent approach can be adopted in the presence of money creation.

repayment costs charged by the bank on the loans provided to sector s are determined by the nominal gross loan rate $R^L_{s,t} > 0$. Deposits are credited with interest according to the nominal gross deposit rate $R^D_t > 0$. Deposits are used by firms to settle the rental costs for physical capital and labor, and are used by the household to finance the purchase of the output good. Both transactions may lead to outflows and inflows of deposits at banks. These interbank deposit flows lead to claims among banks, which must be settled at the central bank by using reserves. Hence, the bank must obtain in advance sufficient reserves from the central bank. Reserve loans are denoted by $L_{CB,t}$, which at origination equal reserve deposits $D_{CB,t}$. In what follows, we assume that due to trading activities on the capital and labor market as well as on the output good market, each time a constant share $\phi_t = \phi(z^{t-1}) \in [0,1]$ of deposits is subject to outflows. We focus on a gross settlement procedure, which does not account for inflows of deposits, so that each time the bank requires reserves in the amount $\phi_t D_t$. In our subsequent analysis, inflows and outflows of deposits match. Thus, after trades have been settled the bank holds the reserves it originally borrowed from the central bank. In addition, the central bank may require the bank to comply with a reserve requirement, that is, the bank must hold reserves at least in the amount of $\varphi_t D_t$. We assume that the reserve requirement $\varphi_t = \varphi(z^{t-1}) \in [0,1]$ does not depend on the current economic state. Reserve deposits are credited with interest according to the nominal gross interest rate $R^D_{CB,t} > 0$, while reserve loans lead to repayment costs that are determined by the nominal gross loan rate $R^L_{CB,t} > 0$. Reserves are generally costly for the bank, that is, $R^L_{CB,t} \geq R^D_{CB,t}$, so that we can, without loss of generality, state $D_{CB,t} = \psi_t D_t$, where we use the notation $\psi_t = \max\{\phi_t, \varphi_t\}$. As banks are owned with unlimited liability and distribute each period all available profits to households, we can focus on a static optimization problem. The bank maximizes each period nominal profits by choosing its lending plans $\{L_{s,t}\}_{s\in\mathcal{S}}$, that is,

$$\max_{\{L_{s,t}\}_{s\in\mathcal{S}}} \Pi^B_t = \sum_{s\in\mathcal{S}} [R^L_{s,t} - R^D_t - \psi_t(R^L_{CB,t} - R^D_{CB,t})] L_{s,t},$$

where we already incorporated the money creation constraint $L_t = D_t$ and used the fact that at origination reserve loans $L_{CB,t}$ and reserve deposits $D_{CB,t}$ equal.

4.3.4 Central bank

The central bank uses its lending facilities to provide liquidity in terms of reserves to banks. In general, the central bank can use three instruments to steer liquidity costs, which in turn affect the investment behavior of banks: the loan and deposit rates for reserves, the reserve requirement and the collateral framework, which defines the assets eligible as collateral for central bank loans and the applicable haircuts on these assets. We abstract from the collateral framework and focus solely on the interest rates for reserves and the reserve requirement; hence, the central bank provides unsecured loans to banks. In our framework, monetary policy is assumed to be climate oriented, so that the liquidity costs depend on the carbon intensity of the financial assets held by the bank. Specifically, we assume that reserve loans $L_{CB,t}$ demanded by the bank are subject to repayment costs determined by the nominal gross loan rate $R^L_{CB,t} = R^L_{CB}(\mathbf{l}_t, \mathbf{\Gamma}_t, z^t) > 0$, where $\mathbf{l} = \{l_{s,t}\}_{s\in\mathcal{S}}$ represents the set of sectoral weights in the loan portfolio of the bank, that is, $l_{s,t} = L_{s,t}/L_t$, and $\mathbf{\Gamma}_t = \{\Gamma_{s,t}\}_{s\in\mathcal{S}}$ denotes the set of sectoral emission intensities. The reserve deposits $D_{CB,t}$ held by the bank are credited by the central bank with interest according to the nominal gross deposit rate $R^D_{CB,t} > 0$. In what follows, we assume that the loan rate on reserves satisfies the following additive form

$$R^L_{CB,t} = R^D_{CB,t} \sum_{s\in\mathcal{S}} \kappa_t(\Gamma_{s,t}) l_{s,t},$$

where $\kappa_t(\Gamma_{s,t}) = \exp(\kappa_{1,t}\Gamma_{s,t})$, with $\kappa_1 \geq 0$, representing the cost factor for loans provided by the bank to sector s. Since the cost factor weakly exceeds unity, reserves are generally costly for the bank. Moreover, the cost factor increases with the sectoral emission intensity, that is, $\partial\kappa(\Gamma_{s,t})/\partial\Gamma_{s,t} \geq 0$. In period t, the realized profits of the central bank are then given by

$$\Pi_t^{CB} = (R_{CB,t}^L - R_{CB,t}^D)L_{CB,t},$$

where we used the fact that reserve loans and reserve deposits are equal at origination, that is, $L_{CB,t} = D_{CB,t}$. The latter can also be interpreted as the money creation constraint on the side of the central bank. The central bank credits the accounts of the household at commercial banks with the generated seigniorage, before the household purchases the production output from firms.

Banks can lend to other banks and deposit at other banks, which is commonly referred to as the interbank market. From the perspective of the bank, interbank loans provide an alternative to central bank loans. Hence, a climate-oriented monetary policy can be undermined, if banks with a relatively low emission-intensive loan portfolio demand reserves at the central bank and channel them further to banks with a higher emission-intensive loan portfolio. Such a situation is ruled out in our model, as we assume that the central bank perfectly observes lending activities between banks and applies a look-through approach, so that the liquidity costs for interbank loans account for the carbon intensity of the assets held by the financed bank. Thus, the equivalence of liquidity provisions from the central bank and other banks is guaranteed. As a consequence, we disregard interbank deposit and lending activities.

As outlined above, the central bank also sets a reserve requirement for banks, that is, the bank must hold at least a share $\varphi_t = \varphi(z^{t-1}) \in [0, 1]$ of deposits D_t in reserves.

In our model, we integrate climate targets into the objective function of the central bank. Specifically, the central bank is interested in reducing the carbon intensity of banks' loan portfolio, ultimately enforcing the decarbonization of the entire economy. It pursues the latter by targeting a reduction of the expected emission intensity of banks' loan portfolio by a constant share $\xi \in [0, 1]$ until the threshold value $\hat{\Gamma}$ is reached. The instruments available to the central bank to achieve its goal are the state-contingent deposit rates on reserves, the emission-based cost factor, which determines the repayment costs on reserve loans, and the reserve requirement. Thus, in period t, the optimization problem of the central bank is given by

$$\min_{R^D_{CB,t},\kappa_{1,t},\varphi_t} d\left(\mathbb{E}_{t-1}[\bar{\Gamma}_t], \xi\mathbb{E}_{t-2}[\bar{\Gamma}_{t-1}]\right),$$

where $\bar{\Gamma}_t = E_t/Y_t$, with $Y_t = \sum_{s\in\mathcal{S}} Y_{s,t}$, denotes the emission intensity of banks' loan portfolio and $d(\cdot,\cdot)$ represents a metric defined on $\mathbb{R}_+$.

4.4 Model analysis

We first outline the equilibrium notion applied in our analysis and then discuss the equilibrium properties.

4.4.1 Competitive equilibrium

In our model analysis, we focus on competitive equilibria, as defined hereafter. For their decisions, households, firms and banks take the monetary policy as given. Hence, we introduce the notion of a monetary framework $\mathcal{M}$, which consists, for all periods $t \in \mathbb{N}_0$, of the the state-contingent deposit rates $R^D_{CB,t}$, the emission-based pricing factor $\kappa_{1,t}$ for loans, the reserve requirement φ_t and the share ϕ_t of deposits circulating among banks.

Definition 4.4.1 (Competitive equilibrium) *Given a monetary framework $\mathcal{M}$ and an initial temperature T_0, a competitive equilibrium is described by prices $\{P_t, Q_t, \{W_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$, interest rates $\{R^D_t, R^L_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$ and allocations $\{C_t, K_{t+1}, \{\gamma_{s,t}, K_{s,t}, N_{s,t}\}_{s\in\mathcal{S}}, \{L_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$, so that*

(1) given prices $\{P_t, Q_t, \{W_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$ and interest rates $\{R^D_t\}_{t\in\mathbb{N}_0}$, the choices $\{C_t, K_{t+1}\}_{t\in\mathbb{N}_0}$ maximize the utility of the household,

(2) given prices $\{P_t, Q_t, W_{s,t}\}_{t\in\mathbb{N}_0}$ *and interest rates* $\{R^L_{s,t}\}_{t\in\mathbb{N}_0}$*, the choices* $\{\gamma_{s,t}, K_{s,t}, N_{s,t}\}_{t\in\mathbb{N}_0}$ *maximize the expected profits of the firm in sector* $s \in \mathcal{S}$*,*

(3) given interest rates $\{R^D_t, \{R^L_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$*, the choices* $\{\{L_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$ *maximize the expected profits of the bank, and*

(4) each period capital, labor and output good markets clear, that is, $K_t = \sum_{s\in\mathcal{S}} K_{s,t}$*,* $N_t = \sum_{s\in\mathcal{S}} N_{s,t}$ *and* $\tilde{Y}_t = \sum_{s\in\mathcal{S}} \tilde{Y}_{s,t}$*.*

In our model, all agents are aware of climate damage due to carbon emissions generated in the course production activities. However, the individual agent is atomistic and, hence, does not internalize the externality, when making its decisions. Rather than analyzing the first-best allocation emerging from a socially optimal equilibrium, we study second-best outcomes resulting from the decentralized equilibrium, assuming that the central bank pursues a climate-oriented monetary policy. Thus, we are interested in the central bank's optimal choice to achieve its targets and the consequent allocations emerging in the economy.

4.4.2 Equilibrium Properties

For our subsequent analysis of the competitive equilibrium, we take the monetary framework $\mathcal{M}$ as given. We analyze the optimization problem of banks, firms and households, in this order, to illustrate how the emission-based interest rate policy adopted by the central bank affects first the financial sector and then the real economy. Using the structure of loan and deposit rates for reserves, as set by the central bank, the necessary and sufficient optimality conditions for the optimization problem of the bank are given by

$$R^L_{s,t} = R^D_t + \psi_t R^D_{CB,t}[\kappa_t(\Gamma_{s,t}) - 1], \qquad \text{for} \quad s \in \mathcal{S},$$

showing that the loan rate charged by the bank must be sufficient to cover the interest promised to depositors and the liquidity costs imposed by the central bank.

We assume that banks cannot discriminate between deposits held by the household and firms, and deposits held by other banks. It then follows from a no-arbitrage argument that the interest rate on bank deposits equals the deposit rate for reserves, that is,

$$R_t^D = R_{CB,t}^D. \tag{4.1}$$

From the perspective of an individual bank, it is not optimal to promise a higher interest rate on deposits than the deposit rate on reserves set by the central bank. This is due to the fact that deposit and reserve flows match. Thus, when the bank receives deposits from other banks, it also receives the same amount of reserves, which, however, are credited with less interest than promised to depositors. In turn, if banks promise an interest rate on deposits which is lower than the deposit rate on reserves, banks themselves deposit only at the central bank. Regarding the deposits of households and firms, the individual bank always has an incentive to promise a slightly higher deposit rate, which is still below the deposit rate on reserves, and thus attracts all available deposits in the economy, resulting in riskless profits for that particular bank. In a competitive banking sector such arbitrage is eliminated, resulting in an interest rate on bank deposits that equals the deposit rate on reserves. Thus, using the equality of deposit rates, the optimality conditions for the bank simplify to

$$R_{s,t}^L = R_{CB,t}^D[1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t], \qquad \text{for} \quad s \in \mathcal{S}. \tag{4.2}$$

Banks operate in a perfectly competitive market, so that they pass the liquidity costs, as determined by the central bank, completely on to the real economy. Firms with a higher emission intensity face higher loan rates. A more detailed analysis of the bank's optimization problem is given in Appendix 5.3. Firms have full knowledge about the structure of loan rates charged by banks. Hence, accounting for the dependency of the loan rates on the emission intensity, the first-order conditions for the optimization problem of the firm in sector s, with respect to $\gamma_{s,t}, K_{s,t}$ and $N_{s,t}$, are given by

$$-\alpha\tilde{A}_{s,t}\bar{\gamma}_{s,t}^{\alpha-1}K_{s,t}^{\alpha}N_{s,t}^{1-\alpha} = q_t K_{s,t}\frac{\partial R_{s,t}^L}{\partial\gamma_{s,t}} - \mu_{s,t}, \tag{4.3}$$

$$\alpha\tilde{A}_{s,t}\bar{\gamma}_{s,t}^{\alpha}K_{s,t}^{\alpha-1}N_{s,t}^{1-\alpha} = R_{s,t}^L q_t, \tag{4.4}$$

$$(1-\alpha)\tilde{A}_{s,t}\bar{\gamma}_{s,t}^{\alpha}K_{s,t}^{\alpha}N_{s,t}^{-\alpha} = R_{s,t}^L w_{s,t}, \tag{4.5}$$

and the complementary slackness condition $\mu_{s,t}\gamma_{s,t} = 0$, where $\mu_{s,t} \geq 0$ represents the Karush-Kuhn-Tucker multiplier for the non-negativity constraint on $\gamma_{s,t}$ and $\tilde{A}_{s,t} = \Omega(T_t)A_{s,t}$ denotes the total factor productivity taking climate damage into account. The variable $w_{s,t}$, in turn, denotes the real wage rate in sector s in terms of the final output good, that is, $W_{s,t}/P_t$. In what follows, we briefly characterize the optimal behavior of firms; a more comprehensive analysis is provided in Appendix 5.3. Note that as the Cobb-Douglas production function satisfies the Inada conditions, firms never decide to devote all their capital to the adoption of a new technology, that is, $\gamma_{s,t} < 1$. Firms face competitive markets, so that they operate efficiently if and only if marginal returns equal marginal costs. Using the first-order condition (4.4) and the market clearing condition for physical capital, we can derive the share $\zeta_{s,t} \in [0,1]$ of aggregate capital K_t allocated to sector s in period t, that is,

$$\zeta_{s,t} = \left(\sum_{\bar{s}\in\mathcal{S}}\left[\frac{A_s(z_t)}{A_{\bar{s}}(z_t)}\frac{\bar{\gamma}_{s,t}^{\alpha}}{\bar{\gamma}_{\bar{s},t}^{\alpha}}\frac{N_{s,t}^{1-\alpha}}{N_{\bar{s},t}^{1-\alpha}}\frac{1+\psi_t\kappa_t(\Gamma_{\bar{s},t})-\psi_t}{1+\psi_t\kappa_t(\Gamma_{s,t})-\psi_t}\right]^{\frac{1}{\alpha-1}}\right)^{-1}. \tag{4.6}$$

In this regard, equation (4.6) shows that a sector with a greater marginal return due to a higher total factor productivity, innovating less, employing more labor or operating with a cleaner technology, attracts more physical capital. Note that climate damage does not play a role in the allocation of capital across sectors, as each sector is impacted with the same intensity. The labor employment $N_{s,t}$ by sector s in period t follows from the clearing condition for the labor market, the household's total labor endowment and the assumption of inelastic supply to each sector, that is, $N_{s,t} = n_s N_t$. The financing costs of firms decrease with the emission intensity $\Gamma_{s,t}$, so that already clean firms (that is, low $\Gamma_{s,t-1}$) and firms adopting cleaner technologies (that is, positive $\gamma_{s,t}$) benefit from relatively lower loan rates. Given that firms have full knowledge, the latter generally devote some capital to the adoption of a cleaner technology. Using the first-order conditions (4.3) and (4.4) of firms, we can obtain the following equation which determines the share $\gamma_{s,t}$, that is, in period t the firm in sector s devotes a fraction

$$\gamma_{s,t} = \max\left\{\frac{\psi_t[1 + (\kappa_{1,t}\iota_s\Gamma_{s,t-1} - 1)\kappa_t(\Gamma_{s,t})] - 1}{\psi_t\kappa_{1,t}\iota_s\Gamma_{s,t-1}\kappa_t(\Gamma_{s,t})}, 0\right\} \tag{4.7}$$

of physical capital to the adoption of a cleaner technology. The share $\gamma_{s,t}$ is weakly increasing in the convexity of the cost schedule $\kappa_{1,t}$, the prevailing emission intensity $\Gamma_{s,t-1}$ and the reserve to deposit ratio ψ_t. To derive the profits of firms, we first use the first-order conditions (4.4) and (4.5) to express the real rental rate of physical capital q_t and the real wage rate $w_{s,t}$ as

$$q_t = \frac{\alpha\tilde{Y}_{s,t}}{R^L_{s,t}K_{s,t}} \qquad \text{and} \qquad w_{s,t} = \frac{(1-\alpha)\tilde{Y}_{s,t}}{R^L_{s,t}N_{s,t}}. \tag{4.8}$$

Due to our Cobb-Douglas specification, the capital rental service is rewarded with a share α of production and labor supply with the residual share $1 - \alpha$. The technologies applied by firms exhibit constant returns to scale, so that firms make zero profits. Moreover, banks make zero profits, while the central bank generates seignorage due to its liquidity provisions to banks, namely

$$\Pi^{CB}_t = \psi_t R^D_{CB,t} \sum_{s\in\mathcal{S}} [\kappa_t(\Gamma_{s,t}) - 1] L_{s,t}.$$

Using the fact that firms and banks make zero profits and the structure of the central bank seigniorage, we can show that any nominal output good price is compatible with market clearing and the budget constraint of households (see Appendix 5.3). The household makes its consumption and capital accumulation decision taking prices as given. From our assumption of exogenous population growth and the inelastic labor supply to each of the sectors, it follows that the necessary first-order conditions of the household's optimization problem are then given by the Euler equations, that is for all $t \in \mathbb{N}_0$

$$c_t^{-\sigma} = \beta \mathbb{E}_t \left[c_{t+1}^{-\sigma} (R^D_{CB,t+1} q_{t+1} + 1 - \delta) \right],$$

where $q_t = Q_t/P_t$ denotes the real rental price of physical capital in terms of the output good. The Euler equations and the transversality condition $\lim_{t\to\infty} \beta^t c_t^{-\sigma} k_{t+1} = 0$ are jointly sufficient for the optimization problem of the household. The characterization of the competitive equilibrium follows then from our previous observations.

Proposition 4.4.1 (Competitive equilibrium) *Given a monetary framework $\mathcal{M}$, initial emission intensities $\Gamma_{s,-1} \geq 0$, with $s \in \mathcal{S}$, an initial capital stock $K_0 > 0$ and an initial temperature $T_0 \geq 0$, the competitive equilibrium is characterized by*

(1) prices q_t and $w_{s,t}$, with $s \in \mathcal{S}$, satisfying (4.8)*,*

(2) interest rates R_t^D and $R^L_{s,t}$, with $s \in \mathcal{S}$, satisfying (4.1) *and* (4.2)*, and*

(3) allocations described by $K_{s,t} = \zeta_{s,t} K_t$, where $\zeta_{s,t}$ follows from (4.6)*, $N_{s,t} = n_s N_t$. Additionally, the loans provided to sector s are given by $L_{s,t} = Q_t K_{s,t} + W_{s,t} N_{s,t}$ and the share $\gamma_{s,t}$ of capital devoted to the adoption of a cleaner technology follows from* (4.7)*, so that the new emission intensity is given by $\Gamma_{s,t} = (1 - \iota_s \gamma_{s,t}) \Gamma_{s,t-1}$. Finally, the aggregate capital stock is given by $K_{t+1} = \tilde{Y}_t + (1-\delta) K_t - C_t$ and consumption c_t satisfies $\lim_{t\to\infty} \beta^t c_t^{-\sigma} k_{t+1} = 0$*

and follows, for all $t \in \mathbb{N}_0$, as a solution from

$$c_t^{-\sigma} = \beta \mathbb{E}_t \left[c_{t+1}^{-\sigma} (R^D_{CB,t+1} q_{t+1} + 1 - \delta) \right].$$

4.5 Solution method

To obtain a solution of our model, we need to determine the optimal climate-oriented monetary policy and the consumption and capital accumulation decisions of households. The two corresponding optimization problems can be solved sequentially, as the central bank policy does not depend on the capital stock available in the economy. Thus, we first solve for the optimal monetary policy and then for the decisions of households.

Given the initial emission intensities across sectors, for each period we derive the optimal emission-based cost factor chosen by the central bank to achieve a reduction of the expected emission intensity of banks' loan portfolio. Moreover, note that deposit rates do not enter firms' decision about the adoption of a new technology. Thus, we disregard deposit rates in the optimization problem of the central bank and leave them unspecified. For simplicity, we set the reserves to deposits ratio to its current level and keep it constant across the infinite horizon. The optimal monetary policy allows us to determine the share of capital that firms in each sector devote to the adoption of a new technology and the resulting new emission intensities.

Given the optimal monetary policy, the innovation shares and the emission intensities, we use the Euler equations and the budget constraint to derive the decisions of the household with regard to consumption and capital accumulation, that is, for all $t \in \mathbb{N}_0$ it must hold

$$\begin{aligned} c_t^{-\sigma} &= \beta \mathbb{E}_t [c_{t+1}^{-\sigma} (R^D_{CB,t+1} q_{t+1} + 1 - \delta)], \\ C_t + K_{t+1} &= \tilde{Y}_t + (1-\delta) K_t. \end{aligned}$$

Note that the choice of consumption C_t and of capital next period K_{t+1} can be described by a policy function which, in our context, depends on sectoral capital $K_{s,t}$, labor employment $N_{s,t}$, total factor productivity $A_{s,t}$, innovation $\gamma_{s,t}$ and the temperature level T_t. We denote these state variables using the vector X_t. The decisions of households can then be obtained either from the consumption function $C_t = C(X_t)$, the capital function $K_{t+1} = K(X_t)$ or from the expectation about next period marginal utility, that is,

$$G(X_t) = \beta \mathbb{E}_t[c_{t+1}^{-\sigma}(R_{CB,t+1}^{D} q_{t+1} + 1 - \delta)].$$

Our model does not allow for an analytical solution, so that we rely on numerical methods to approximate one of these functions. Specifically, we use the parametrized expectations algorithm outlined in Den Haan and Marcet (1990) and Maliar et al. (2001) to approximate the expectation function. The standard algorithm is based on functional approximation using parametrization, for example with polynomial functions, and on an iterative procedure to generate new data, which is then used to update the parameters of the functional approximation. Starting from an initial guess for the parameters of the approximating function and initial values for the state variables, a path of states and controls—in our context represented by consumption—is derived from the Euler equations and the budget constraint. The generated data is then used in a regression analysis to derive new estimates of the parameters of the approximating function. In this respect, note that $G(X_t)$ represents the conditional mean of the realizations $\beta c_{t+1}^{-\sigma}(R_{CB,t+1}^{D} q_{t+1} + 1 - \delta)$, so that a regression analysis is well suited to estimate the function $G(\cdot)$. The generation of new data and the updating of parameters is repeated, with the same initial values for the state variables, until the parameters of the approximating function converge. To the best of our knowledge, there exist no results proving the convergence of this algorithm. Nevertheless, it has been used to solve stochastic dynamic general equilibrium models and has been proven to work well in stationary environments.

Our model is however non stationary due to the time dependence of the innovation shares, total factor productivities, population growth and temperature. Models with constant growth, for example due to technology improvement or population growth, can generally be rewritten as stationary models by using growth-adjusted state variables. However, such an approach is not feasible in our setting as the growth rates of the state variables change over time. We circumvent this issue by generating several paths of states and controls in each updating step in order to approximate the distribution of state variables at each point in time. Our regression analysis uses Bayesian optimization. Specifically, we model our function $G(\cdot)$ as a Gaussian process denoted by

$$G(\cdot) \sim \mathcal{GP}(m(\cdot), \sigma(\cdot, \cdot)),$$

where $m : \mathbb{R}^d \to \mathbb{R}$ represents the mean function and $\sigma : \mathbb{R}^d \times \mathbb{R}^d \to \mathbb{R}$ denotes the covariance function, with $d \in \mathbb{N}$ being the dimension of any input data point X_t. A Gaussian process is a set of random variables with the specific characteristic that any finite sample of it is jointly Gaussian distributed. In the following, we outline the Gaussian process regression used in our simulations. Suppose that we are given a set of data points $\{(X_i, y_i),\ \ i = 1, \ldots, n\}$, so that $y_i = g(X_i) + \epsilon_i$, where ϵ_i is independent and identically distributed according to a Gaussian distribution with mean zero and variance $\sigma_\epsilon^2 > 0$. We define the input data $\mathbf{X} = [X_1, \ldots, X_n]$ and the output data $\mathbf{y} = [y_1, \ldots, y_n]$. The prior on the unknown function $G(\cdot)$ is Gaussian, so that $G(\mathbf{X})|\mathbf{X} \sim \mathcal{N}(\boldsymbol{\mu}, \mathbf{\Sigma})$, where $\boldsymbol{\mu} = [\mu(X_1), \ldots, \mu(X_n)]^T$ and $\mathbf{\Sigma} = [\sigma(X_i, X_j)]_{1 \le i,j \le n}$. The likelihood function of our observed output data is then given by $\mathbf{y}|\mathbf{X}, \sigma_\epsilon \sim \mathcal{N}(\boldsymbol{\mu}, \mathbf{\Sigma} + \sigma_\epsilon^2 I_n)$, with I_n denoting the identity matrix of dimension n. Thus, for any input data point $\tilde{X}$ we can derive the posterior distribution

$$G(\tilde{X})|\mathbf{X}, \mathbf{y}, \sigma_\epsilon \sim \mathcal{N}(\tilde{\mu}(\tilde{X}), \tilde{\sigma}(\tilde{X}, \cdot)),$$

where the updated mean function and covariance function are given by

$$\tilde{\mu}(\tilde{X}) = \mu(\tilde{X}) + \mathbf{\Sigma}_{\tilde{X}}(\mathbf{\Sigma} + \sigma_\epsilon^2 I_n)^{-1}(\mathbf{y} - \boldsymbol{\mu})$$
$$\tilde{\sigma}(\tilde{X}, \cdot) = \sigma(\tilde{X}, \cdot) - \mathbf{\Sigma}_{\tilde{X}}(\mathbf{\Sigma} + \sigma_\epsilon^2 I_n)^{-1}\mathbf{\Sigma}_{\tilde{X}}^T,$$

where $\mathbf{\Sigma}_{\tilde{X}} = [\sigma(\tilde{X}, X_i)]_{1\leq i\leq n}$ represents the covariance of the new data point $\tilde{X}$ with the previously observed input data $\mathbf{X}$. In our analysis, we use the mean $\tilde{\mu}(\cdot)$ of the posterior distribution as the predictor for the unknown function $G(\cdot)$. Throughout our analysis, we use the Matérn kernel as covariance function, that is,

$$\sigma(X_i, X_j) = \frac{2^{1-\nu}}{\Gamma(\nu)} \left(\sqrt{2\nu}\|\hat{X}_i - \hat{X}_j\|_2\right)^\nu K_\nu \left(\sqrt{2\nu}\|\hat{X}_i - \hat{X}_j\|_2\right),$$

where $\|\cdot\|2$ denotes the Euclidean distance, $\Gamma(\cdot)$ denotes the Gamma function and $K_\nu(\cdot)$ is the modified Bessel function of the second kind. We use the notation $\hat{X} = [X(1)/l_1, \ldots, X(d)/l_d]^T$, where $X(k)$ represents the value of X in dimension k and $l_k > 0$ being the scaling parameter in dimension $k = 1, \ldots, d$. In general, $\mathbf{l} = [l_1, \ldots, l_d]$ are also referred to as hyper-parameters. The variance σ_ϵ^2 of the noise as well as the hyper-parameters $\mathbf{l}$ are estimated using maximum-likelihood. In our application, we set $\nu = 1.5$. We use a maximum of 100 iterations in the parametrized expectations algorithm. We then use the estimated posterior distribution to simulate 1'000 paths of our model for a time horizon of 300 periods.

4.6 Simulation

In this section, we illustrate the role of a climate-oriented monetary policy in terms of emission-based interest rates for the Euro Area (EA). We provide empirical support for some fundamental assumptions of our model and discuss the choice of parameters used in our calibration. Finally, we provide the simulation results and discuss policy implications.

4.6.1 Descriptive Statistics

In our model, the loan volume matches at any time the outstanding amount of deposits. Although this represents a strong assumption on the structure of asset markets and banks' balance sheets, it is not at odds with the observed data. The left panel of Figure 4.1 depicts the loan to deposit ratio for the EA, where we distinguish between total outstanding loans and deposits, and loans and deposits of private agents and of governments, excluding monetary financial institutions (MFIs). Since the foundation of the EA, both ratios have never recorded values higher than 1.2 or lower than 0.9. Another crucial assumption of our model is that firms completely rely on external financing in the form of bank loans. Thus, loans are used to cover all production expenses, which consist of capital service and labor income. As we focus on a closed economy, the latter coincide with the gross domestic product (GDP). The right panel of Figure 4.1 shows that, in the EA, this assumption is generally in line with the empirical observation. A rationale for this pattern may be the strong reliance of private corporations within the EA on bank loans in the acquisition of external financing (De Fiore and Uhlig 2011).

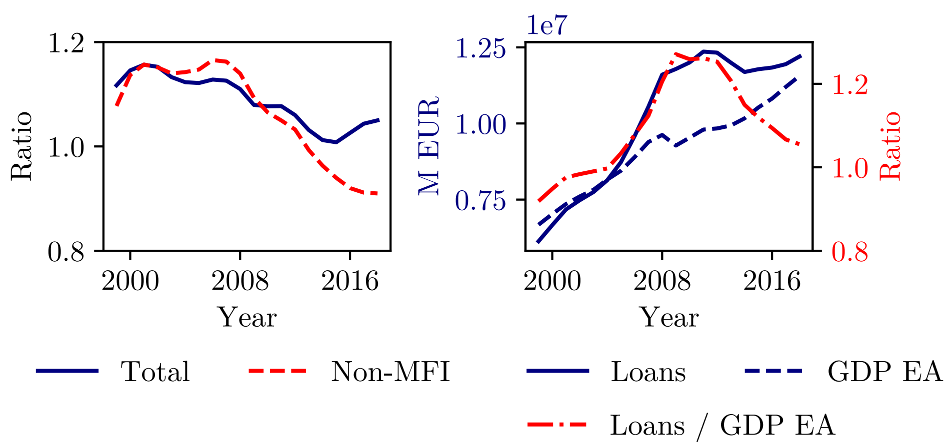

Figure 4.1: Loans to deposits ratio for the EA (left panel); loans, GDP and loans to GDP ratio for the EA (right panel). *Source:* European Central Bank, accessed on 09/11/2019.

In our framework, banks demand reserves at the central bank either to comply with a reserve requirement or to settle claims among banks, which arise from interbank deposit flows. Figure 4.2 depicts the excess reserves held by MFIs in the EA as well as the reserves to deposits ratio. It shows that until 2014 credit institutions in the EA were holding no reserves in excess of the amount required by the central bank. Accordingly, the ratio of reserves to deposits was stable during this period. With the launch of the quantitative easing by the European Central Bank (ECB) in March 2015, MFIs are holding more reserves than necessary under the imposed reserve requirement. This led to an increase in the reserves to deposits ratio, leveling at 0.08 in 2018.

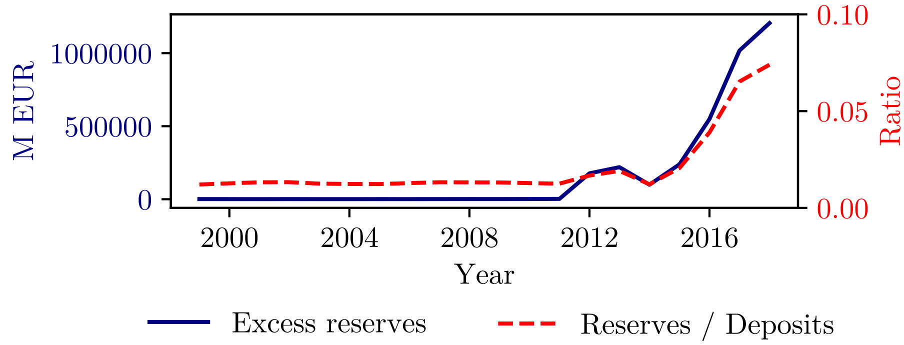

Figure 4.2: Excess reserves and reserves to deposits ratio in the EA. *Source:* European Central Bank, accessed on 09/11/2019.

4.6.2 Parameters

In our simulations, we take 2018 as our initial period and assume that the EA population decreases from 2018 to 2100 by 0.2 percent per year and is constant after this period. That is, $\eta_t = -0.02$ for $t \in \{0, \ldots, 81\}$ and $\eta_t = 0$ otherwise. We justify this assumption based on the projections of the United Nations according to which the EA population will grow from 340 million in 2018 to its peak of 341 million in 2022 and then will steadily decline to 287 million in 2100. Following Nordhaus and Sztorc (2013) in their specification of the 2013R version of the DICE model, we set the relative risk aversion parameter σ to 1.45. We also use their discount rate $\rho = 0.015$, so that the discount factor $\beta \approx 0.985$. We add up the capital stocks for all EA countries as provided by the Penn World Table, so that the initial capital stock is given by USD 66.1 trillion (at constant 2011 national prices).

On the side of firms, we set the capital intensity α to 0.42. We derive this value by computing the share of labor income in the EA GDP as an average from the country-specific labor share estimates provided by Penn World Table, weighting each country by its relative population size. Following this procedure, we obtain a labor income share of 0.58. Physical capital depreciates each period by a share 0.04. We obtain this value by using the country-specific estimates for the average capital depreciation as provided by the Penn World Table and derive the EA depreciation rate by weighting each country according to its capital stock. We use Eurostat data on the sectoral emission intensities for all EA countries as of 2016 to derive estimates of the sectoral emission intensities at the EA level. For the identification of the sectors, we rely on the NACE economic activities classification.[13] We weight the sectoral emission intensity, measured in kilogram of carbon dioxide per Euro at current prices, by the sectoral gross value added of each country at current prices. We model two sectors only, a clean and a dirty one, indexed by c and d, respectively. We use the median sectoral emission intensity in the EA to allocate the different production activities between the two aggregate sectors.[14] By weighting each included sector according to its gross value added, we obtain that the emission intensity of the clean and dirty sector are 0.02 and 0.5, respectively. Next, we derive the shares of labor employed by each of the NACE sectors, which are then aggregated according to our clean and dirty classification. As we find that labor is equally allocated across the clean and dirty sectors, we set $n_s = 0.5$. We assume

[13] See https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF, for a detailed description of the economic activities.

[14] See Appendix 5.3.3, for a more detailed description of the NACE classification and our grouping of sectors into clean and dirty.

that both sectors face the same initial expected total factor productivity $\hat{A}_0$, but are subject to productivity shocks, which cause the realized productivity to deviate in each state by approximately 5 percent from its expectation. There are only two possible states of the economy, which occur each period with equal probability, that is, $\pi(z) = 0.5$. Thus, we denote the set of states by $\mathcal{Z} = \{1, 2\}$. The sectoral productivities exhibit a perfect negative correlation. Thus, if the clean sector incurs a positive productivity shock, the dirty sector experiences a negative shock of the same magnitude, and vice versa. In our analysis, the clean sector experiences a positive productivity shock in the first state, that is, $A_c(1) = 1.05$ and $A_c(2) = 0.95$, while the dirty sector does so in the second state, that is, $A_d(1) = 0.95$ and $A_d(2) = 1.05$. We can obtain the expected total factor productivity by matching the expected production output under the previous assumptions on the capital intensity, the labor share, the productivity shocks, the initial capital stock and the initial population size with the EA GDP.[15] As of 2018, the latter is given by USD 13.7 trillion (in 2011 USD international prices), so that we obtain an initial expected total factor productivity of $\hat{A}_0 = 0.08$. We assume that the expected productivity grows each period by 0.3 percent, that is, $a_t = 0.003$.

Based on IPCC estimates, the initial temperature is set to 0.87°C above the preindustrial level, as defined by the benchmark period 1850-1900.[16] Temperature depends linearly on the generated carbon emissions. For our calibration we rely on Matthews et al. (2009), who find that temperature increases in the range of 1.0-2.1°C (representing the 5th and the 95th percentile) per teraton of carbon. In our specification, we use their best estimate of 1.5°C per teraton of carbon, so that, taking into account that one teraton of carbon represents approximately 3.67 teratons of carbon dioxide, we set $\tau = 0.00041$.[17] In describing the evolution of

[15] Note that the assumption of identical expected total factor productivities, identical labor shares and identical risk across sectors does, in the absence of a climate-oriented monetary policy, lead to identical capital allocation across sectors.

[16] Available at https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf, accessed on 20/10/2019.

[17] Note that carbon has an atomic mass of 12, while oxygen has an atomic mass of 16. Thus, the atomic mass of carbon dioxide is given by 44, so that one kilogram of carbon is equivalent to

emissions and temperature, we take the emissions of non-EA countries as given. Specifically, we use the emission path compatible with the 1.5°C target, as estimated by the Climate Action Tracker.[18] Since these projections are computed at the global level, we need to exclude EA emissions, which are, in turn, modeled within our framework. Accordingly, we subtract from the global emissions the share caused by EA countries, that is obtained through own computations based on data from the World Bank.[19] In our analysis, we set the reserves to deposits ratio to its current value, that is, $\psi_t = 0.08$.

4.6.3 Results

We first discuss the optimal climate-oriented monetary policy and then proceed to the optimal decisions of households. The optimal monetary policy aims at reducing the expected emission intensity of banks' loan portfolio and, ultimately, of the economy as a whole, by a predetermined share until the desired target is achieved. In what follows, we provide an illustration for the case of a 5 and 10 percent annual reduction, that is, $\xi = 0.95$ and $\xi = 0.9$, and a target value of $\hat{\Gamma} = 0.001$. Note that deposit rates do not influence the decision of firms to adopt a cleaner technology. Thus, we leave them unspecified in our analysis. We then solve for the optimal emission-based cost schedule which is needed to achieve the postulated goals, assuming innovation impact factors of $\iota_s = 0.5$ and $\iota_s = 1$. For simplification, the latter are assumed to be homogeneous across sectors. Figure 4.3 and 4.4 show for the cases of a 5 and 10 percent reduction target, the optimal climate-oriented monetary policy in the form of the emission-based cost factor, the expected emission intensity of banks' loan portfolio, the resulting innovation shares and the emission intensities for the clean and dirty sector, as well as the capital allocations in both states. In the case of a 5 and 10 percent annual reduction target,

$44/12 \approx 3.67$ kilograms of carbon dioxide.

[18] Available at https://climateactiontracker.org/methodology/global-pathways/, accessed on 29/11/2020.

[19] We use the most recent data on emissions of carbon dioxide available at https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?locations=XC, accessed on 05/11/2019.

the cost factor $\kappa_{1,t}$ chosen by the central bank steadily increases until the year 2127 and 2071, respectively. After this point, the expected emission intensity of banks' loan portfolio is lower than the target value $\hat{\Gamma} = 0.001$, so that no climate-oriented monetary policy is adopted. As long as the target is not achieved, the central bank continuously increases the cost factor over time in order to maintain the incentives of banks to favor low-carbon assets, while the economy is getting cleaner. Thus, the central bank also indirectly preserves the incentives of firms to adopt cleaner technologies. Starting from an initial expected emission intensity of banks' loan portfolio of 0.26 kilograms of carbon dioxide per USD (in constant 2011 national prices) in 2018, the adopted policy would achieve the target level of 0.001 in the year 2127 (2071) if a 5 (10) percent emission reduction target is applied. For all the different targets ξ and innovation impact factors ι_s, the reduction of the expected emission intensity in the earlier periods is achieved solely by shifting capital from the dirty to the clean sector, without inducing innovation. After this initial phase, the cost parameter chosen by the central bank is such that it leads to innovation of firms. The latter initially takes place only in the dirty sector, as this is sufficient to achieve the desired emission reduction. However, as soon as dirty firms operate with the same emission intensity as clean firms, both sectors start to innovate and devote a share $(1-\xi)/\iota_s$ of their capital to the adoption of a cleaner technology. With a 5 percent emission target and an innovation impact factor of 0.5 (1), innovation by clean firms starts in the year 2068 (2069). With a 10 percent target, in turn, clean firms start innovating in 2042, for an innovation impact factor of 0.5 and in 2043, for an innovation impact factor of 1. Note that for clean and dirty firms the incentives to innovate are not only determined by the monetary policy, but also by their possibilities to adopt cleaner technologies as captured by the innovation impact factor ι_s. As the climate-oriented monetary policy leads to the adoption of new technologies and, thus, affects the sectoral emission intensities over time, the allocation of capital across production sectors is impacted. Specifically, the clean sector benefits from the adoption of cleaner technologies in the dirty sector, by receiving more capital. This effect reduces with the innovation impact factor in the dirty sector and vanishes when the clean sector starts to innovate as well.

In Figures 4.5 and 4.6, we depict the expected capital accumulation, consumption, temperature and climate damage, for a 5 and 10 percent reduction target and considering different values of the innovation impact factor. The vertical lines indexed by the numbers 1-4 indicate different structural breaks of our model: "1" represents the time period in which dirty firms start to innovate, "2" indicates the start of innovation by clean firms, "3" is the time period when both types of firms stop innovating and "4" denotes the time period after which the population size remains constant. For a given emission reduction target, the evolution of temperature and climate damage is independent of the innovation impact factor. However, the possibilities for adopting new technologies, as captured by the innovation impact factor, influence the decisions of the household with regard to consumption and capital accumulation. With a lower innovation impact factor more resources are needed to achieve the same reduction target. Thus, for $\iota_s = 1$ the consumption and the accumulated capital exceed their counterparts for the case of $\iota_s = 0.5$, at least during the period in which a climate-oriented monetary policy is adopted. If the central bank pursues the target of reducing the expected emission intensity of banks' loan portfolio by 5 (10) percent per year, temperature increases until a level of 1.45° (1.43°C) above the preindustrial level in the year 2127 (2071) and then remains approximately constant. Temperature still increases slightly as the emission intensities of the clean and dirty sector have not been driven to zero, but are only lower than the postulated target of 0.001. Following a 5 (10) percent reduction target, climate damage increases until the year 2127 (2071), but remains roughly constant after this period at a level of 0.49 (0.48) percent of GDP. Again, climate damage slightly increases over time, as temperature increases, which is a result of the adopted climate-oriented monetary policy, which does not drive emissions to zero. The small difference in temperature and climate damage between the case of a 5 and 10 percent reduction target is due to the fact that, in our analysis,

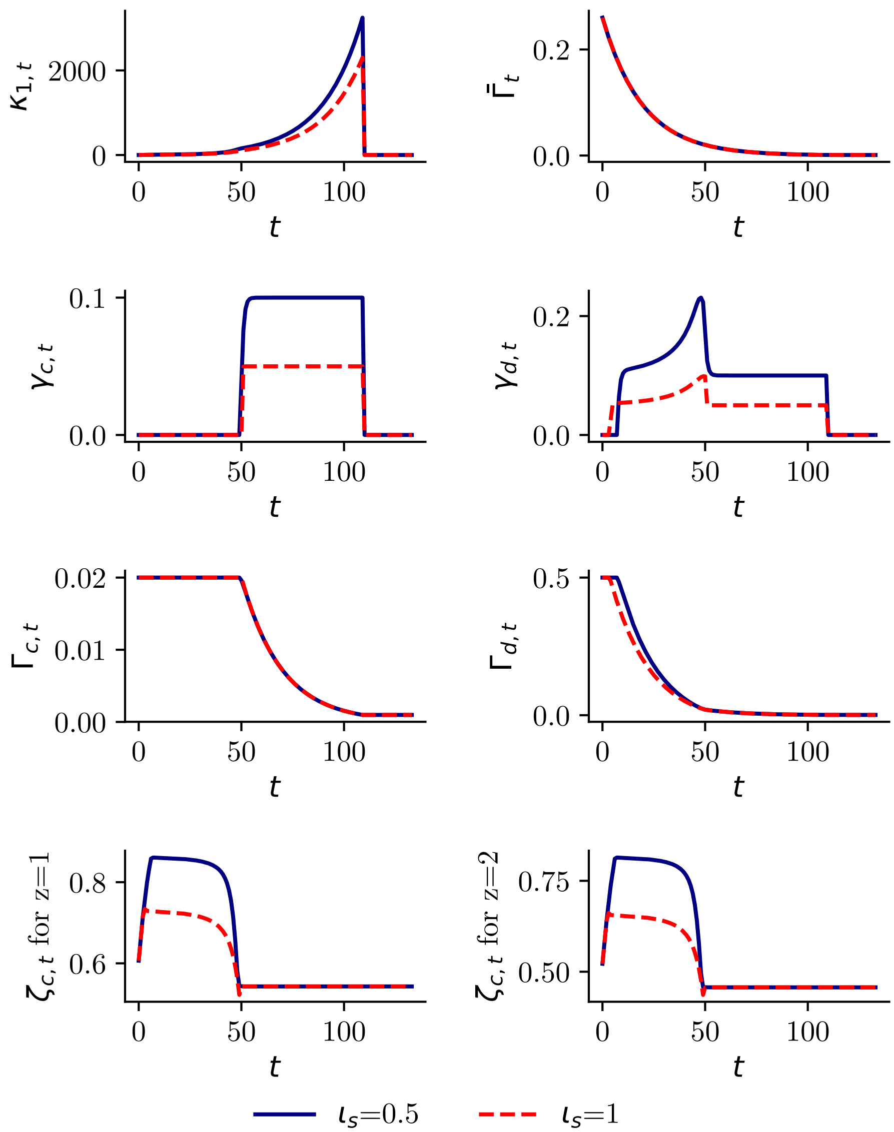

Figure 4.3: Optimal monetary policy and resulting allocations, for a 5 percent emission reduction target and an innovation impact factor of $\iota_s = 0.5$ and $\iota_s = 1$: the cost factor (upper left panel), the expected emission intensity (upper right panel), the sectoral innovation shares (upper center panels), the sectoral emission intensities (bottom center panels) and the capital share allocated to the clean sector in the two states (bottom panels).

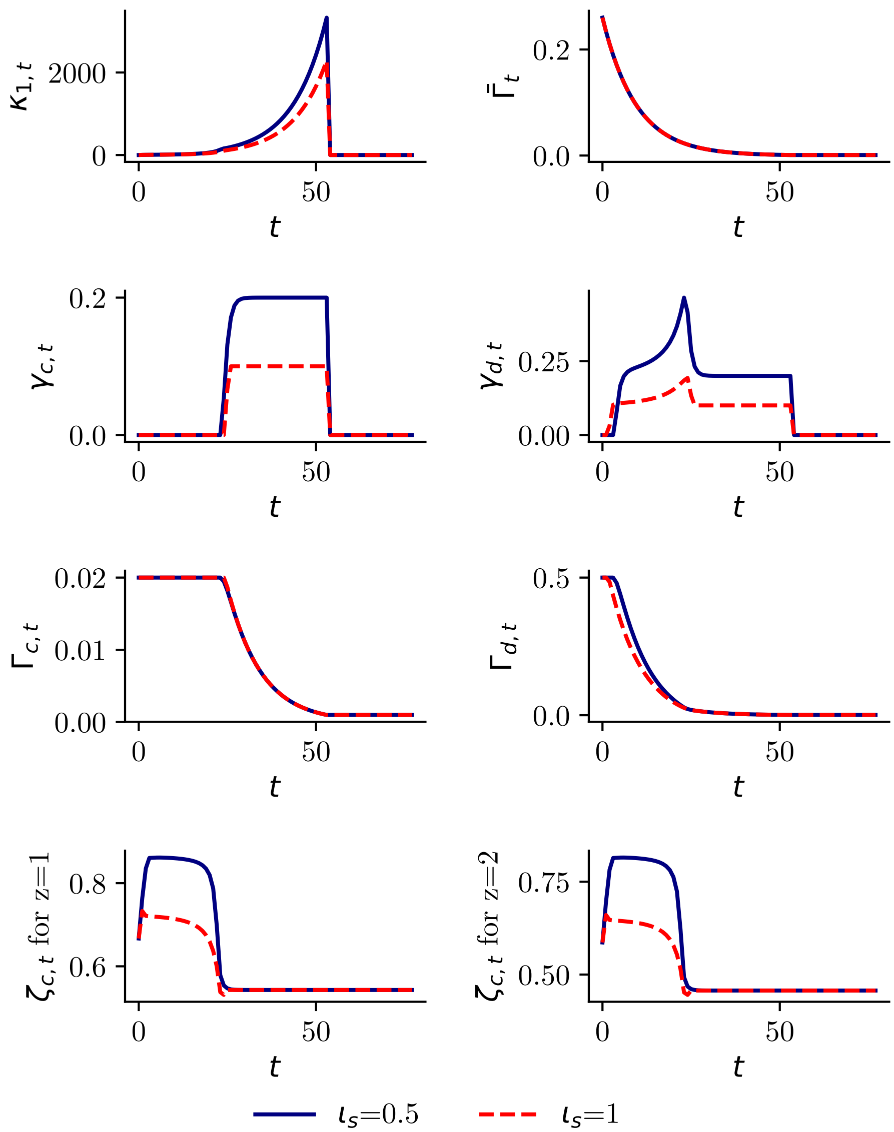

Figure 4.4: Optimal monetary policy and resulting allocations, for a 10 percent emission reduction target and an innovation impact factor of $\iota_s = 0.5$ and $\iota_s = 1$: the cost factor (upper left panel), the expected emission intensity (upper right panel), the sectoral innovation shares (upper center panels), the sectoral emission intensities (bottom center panels) and the capital share allocated to the clean sector in the two states (bottom panels).

the emissions from the EA represent only 6 percent of global emissions, so that the impact of EA emissions on global temperature is generally small and further reduced by innovation, as induced by the climate-oriented monetary policy. We find that with a 5 (10) percent reduction target, temperature is 8 (9) percent lower in the year 2100 compared to the case in which no climate-oriented monetary policy is adopted. In the year, 2200 we find that temperature is reduced by 24 (25) percent compared to the case with no climate policies. Similarly, climate damage is reduced by 16 (17) percent in the year 2100 compared to the no policy case, if an emission reduction target of 5 (10) percent is applied. Finally, in the year 2200, climate damage is 42 (43) percent lower if the emission-based interest rate policy is adopted with a 5 (10) percent reduction target. Across the illustrated cases of different emission reduction targets and innovation impact factors, we find that the climate-oriented monetary policy is welfare decreasing. This might however be due to the fact that in our analysis the EA emissions constitute only a small fraction of global emissions and our welfare analysis excludes other countries, which may benefit from the climate-oriented monetary policy adopted within the EA. Our analysis should therefore be considered as an illustration of the mechanisms embedded in our framework, but is not suited to provide a reliable assessment of the welfare impact of the climate-oriented monetary policy. We aim to integrate a more comprehensive welfare analysis with a particular focus on the optimal climate-oriented monetary policy in future work.

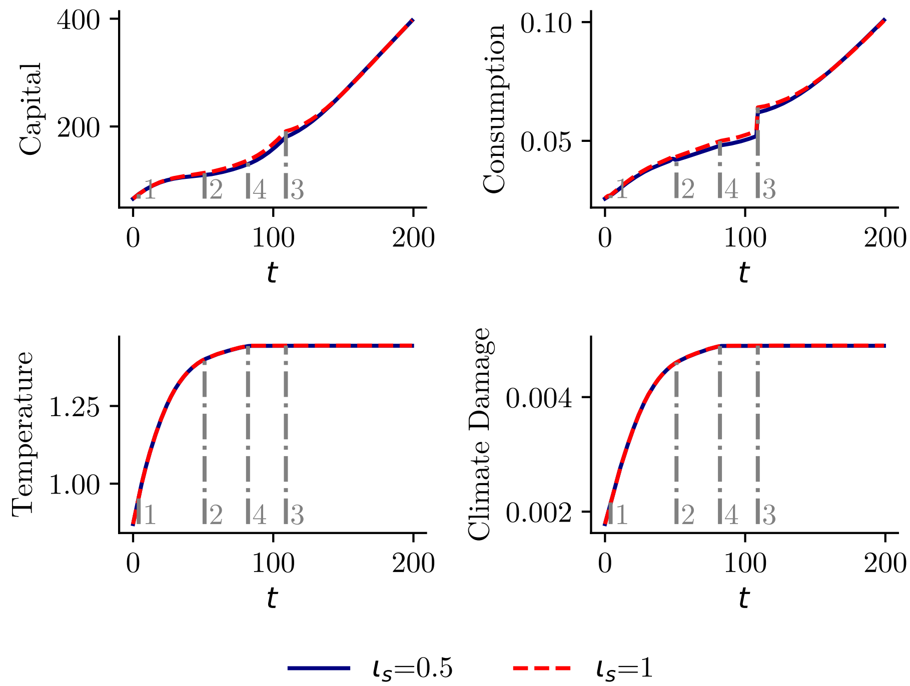

Figure 4.5: Expected capital accumulation, consumption, temperature and climate damage evolutions for a 5 percent emission reduction target and an innovation impact factor of $\iota_s = 0.5$ and $\iota_s = 1$.

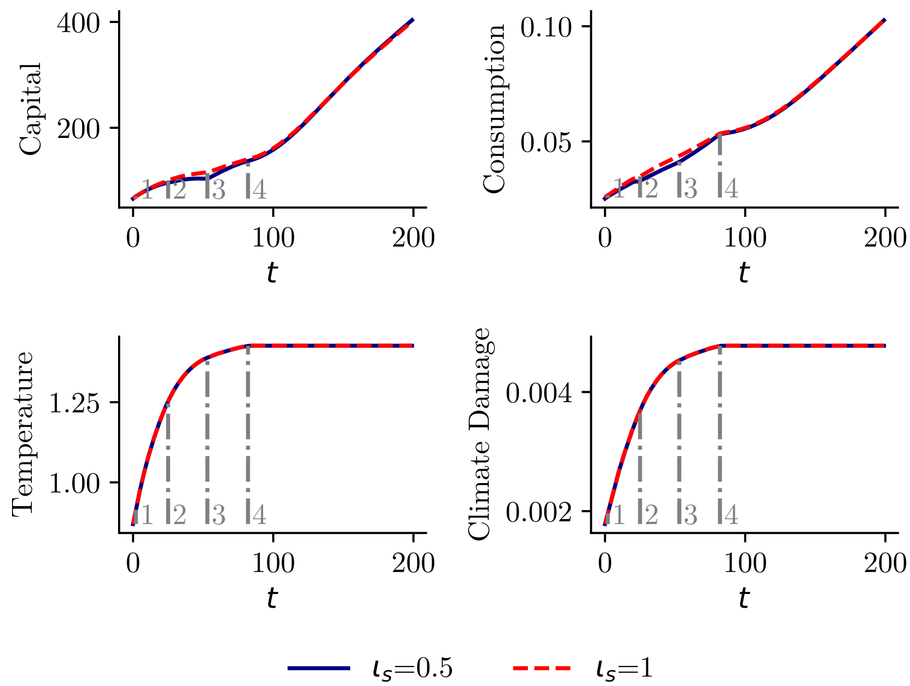

Figure 4.6: Expected capital accumulation, consumption, temperature and climate damage evolutions for a 10 percent emission reduction target and an innovation impact factor of $\iota_s = 0.5$ and $\iota_s = 1$.

4.7 Conclusion

Policies aiming at fostering the adoption of clean technologies and thus reducing the negative impact of carbon emissions have so far mostly taken the form of fiscal instruments, such as carbon taxes and cap-and-trade system for emission certificates. Although these instruments have been shown to be effective in reducing carbon emissions and promoting clean innovation, their viability has been questioned, mostly due to lack of political acceptability and distributive effects. This paves the way for the introduction of new instruments, which ensure that sufficient resources are allocated to sustainable projects. On this account, a more active role of the financial sector and specifically of central banks has been advocated by politicians, academics and central bankers themselves, as pioneered by the speech on "The Tragedy of the Horizon" held by the governor of the Bank of England in 2015. Through their impact on banks' investment decisions, central banks can indeed steer liquidity towards low-carbon activities and discourage production in more polluting sectors. Moreover, by adjusting their own investment guidelines central banks can have an even larger impact with regard to the decarbonization of the economy, as their portfolios currently overweight carbon-intensive compared to low-carbon assets. There is no unique solution for a climate-oriented monetary policy and several options have been proposed. These range from green quantitative easing, in the form of purchases of low-carbon assets by central banks, to green reserve requirements, namely minimum reserve holdings of banks depending on the carbon footprint of the assets held by the individual institution, and to the integration of sustainability criteria into the collateral framework of central banks.

In the present Chapter, we focus on an alternative, yet unexplored approach. Specifically, we study the introduction of an emission-based interest policy adopted by the central bank, which aims at increasing the financing costs for dirty production activities. Indeed, such a monetary policy leads to higher liquidity costs for banks holding more carbon-intensive asset portfolios, so that banks have an incentive to favor low-carbon assets. The adoption of the climate-oriented monetary policy is justified by the presence of damage on output caused by temperature increases, which, in turn, are due to carbon emissions generated in the course of production activities. Firms can devote a share of their inputs to the adoption of a cleaner technology reducing the emission intensity of the sector. This gives rise to a trade-off for the individual firm between lowering financing costs and reducing production capacities. The central bank aims at reducing the expected emission intensity of banks' loan portfolio. We calibrate our model using data from the Euro Area. Our findings show that the applied monetary policy is able to induce the adoption of cleaner technologies across the entire economy and reduces the expected emission intensity of the economy from 0.26 kilogram carbon dioxide per USD in 2018 to 0.001 in 2127 (2071), when applying a 5 (10) percent target for the annual reduction of the expected emission intensity of banks' loan portfolio.

To the best of our knowledge, this work represents the first attempt to integrate a climate-oriented monetary policy in a theoretical model. Accordingly, many extensions of the current framework can and need to be pursued. A key priority is to derive the optimal second-best policy adopted by the central bank. The integration of a more sophisticated climate module, as, for example, described in Nordhaus and Sztorc (2013), and the adoption of alternative damage function specifications, as shown in Bretschger and Pattakou (2019) is also desirable. Moreover, the diffusion process of clean technologies should be improved. On this account, the heterogeneous innovation possibilities across sectors should be taken into account. In addition, alternative climate policies must be embedded in the current framework to provide a realistic assessment of the actual impact of a climate-oriented monetary policy. Finally, we aim to integrate the traditional goals of monetary policy, represented by price and economic stability, as objectives of the central bank.

Chapter 5

Appendices

5.1 Appendix for Chapter 2

5.1.1 Parameters and variables

Parameters / Variables	**Explanation**
Indexes	
t	Time index
i	Sectoral index; c=clean, d=dirty
Production	
Y	Final output
γ	Distribution parameter (final output)
σ	Elasticity of substitution (final output)
Y_i	Intermediate output
K_i	Input factor: knowledge-capital
α	Output elasticity (intermediate sector)
A_i	Sectoral productivity (intermediate sector)
L_i	Input factor: labor
δ	Depreciation rate of capital

Table 5.1: Summary of parameters and variables used in the model.

Parameters / Variables	**Explanation**
Production	
p_i	Price of intermediates
B_i	Spillover intensity
ϕ_i	State-dependence (Cobb-Douglas spillovers)
ζ	Share of capital to the clean sector
ψ_i	Relative weight (perfect substitute spillovers)
Households	
C	Consumption
I	Capital investment
β	Discount factor
θ	Relative risk aversion
q	Rental rate of capital
w_i	Wage rate
Policies	
T	Government transfers
s	Subsidy provided to the clean sector

Table 5.2: Summary of parameters and variables used in the model (continued).

5.1.2 Equilibrium

Cobb-Douglas spillovers

In equilibrium we can substitute the expressions for production by the two intermediate sectors as given by (2.6) into the first-order conditions of the intermediate firms, so that the price ratio for clean versus dirty energy reads

$$\frac{p_c}{p_d} = \frac{K_c}{K_d}\frac{Y_d}{Y_c} = \left(\frac{\tilde{B}_c}{\tilde{B}_d}\right)^{\alpha-1}\left(\frac{\zeta}{1-\zeta}\right)^{2(1-\Theta)}, \tag{5.1}$$

showing that a higher relative spillover intensity $\tilde{B}_c/\tilde{B}_d$ leads to lower relative prices. This follows from the fact that higher relative spillover intensity increases production in the clean sector, thus lowering the price of clean energy. A larger share of capital allocated to the clean sector implies the same effect. By substituting (2.6) into the price ratio for clean versus dirty energy derived from the optimization problem of the final output producer, we obtain

$$\frac{p_c}{p_d} = \frac{\gamma}{1-\gamma}\left[\left(\frac{\tilde{B}_c}{\tilde{B}_d}\right)^{1-\alpha}\left(\frac{\zeta}{1-\zeta}\right)^{2\Theta-1}\right]^{-\frac{1}{\sigma}}, \tag{5.2}$$

meaning that a larger relative spillover intensity and the capital share allocated to the clean sector lower the price ratio as before. By equating (5.1) and (5.2), we can find the share of capital ζ_{CD} allocated to the clean sector in the decentralized economy with the Cobb-Douglas specification, as reported in Proposition 2.2.2. Using the description of intermediate energy generation in (2.6), final good production is given by

$$Y = \left[\gamma\left(Z_c(\zeta)K\right)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\left(Z_d(\zeta)K\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} =: V(\zeta)K.$$

Thus, using the first-order conditions from the final sector optimization, we can express prices for clean energy p_c and for dirty energy p_d as

$$p_c = \gamma \left(\frac{Z_c(\zeta)}{V(\zeta)} \right)^{-\frac{1}{\sigma}} \qquad \text{and} \qquad p_d = (1-\gamma) \left(\frac{Z_d(\zeta)}{V(\zeta)} \right)^{-\frac{1}{\sigma}} .$$

From firms' optimization in the intermediate sector we can finally derive the real rental rate of capital as

$$q = \gamma\alpha \left(\frac{\tilde{B}_c^{(1-\alpha)(1-\sigma)} \zeta^{\Theta(1-\sigma)+\sigma} (1-\zeta)^{(1-\Theta)(1-\sigma)}}{V(\zeta)} \right)^{-\frac{1}{\sigma}} .$$

Perfect substitutes spillovers

With perfect substitutability, the ratio of prices for energy intermediates reads

$$\frac{p_c}{p_d} = \left(\frac{\zeta}{1-\zeta} \right)^{1-\alpha} \left(\frac{\tilde{B}_c}{\tilde{B}_d} \right)^{\alpha-1} \left(\frac{\psi_c\zeta + (1-\psi_c)(1-\zeta)}{(1-\psi_d)\zeta + \psi_d(1-\zeta)} \right)^{\alpha-1} , \tag{5.3}$$

showing that relative spillover intensity has the same impact on relative prices as in the Cobb-Douglas case. From the final sector optimization, we obtain

$$\frac{p_c}{p_d} = \frac{\gamma}{1-\gamma} \left[\left(\frac{\zeta}{1-\zeta} \right)^{\alpha} \left(\frac{\tilde{B}_c}{\tilde{B}_d} \right)^{1-\alpha} \left(\frac{\psi_c\zeta + (1-\psi_c)(1-\zeta)}{(1-\psi_d)\zeta + \psi_d(1-\zeta)} \right)^{1-\alpha} \right]^{-\frac{1}{\sigma}} . \tag{5.4}$$

To find the share of capital allocated to the clean sector with perfect substitute spillovers, we equate (5.3) and (5.4); the result is reported in Proposition 2.2.2.

No spillovers

In the absence of spillovers, we can express the price ratio derived from the intermediate firms problem as

$$\frac{p_c}{p_d} = \frac{K_c}{K_d}\frac{Y_d}{Y_c} = \left(\frac{\zeta A_d L_d}{(1-\zeta)A_c L_c} \right)^{1-\alpha} . \tag{5.5}$$

A larger share of capital allocated to the clean sector implies higher relative prices, whereas higher productivity of the clean sector entails a lower price ratio, as higher production in the clean sector lowers the price of clean energy. From the final sector it follows

$$\frac{p_c}{p_d} = \frac{\gamma}{1-\gamma}\left(\frac{Y_d}{Y_c}\right)^{-\frac{1}{\sigma}} = \frac{\gamma}{1-\gamma}\left(\frac{\zeta^{\alpha}(A_d L_d)^{1-\alpha}}{(1-\zeta)^{\alpha}(A_c L_c)^{1-\alpha}}\right)^{-\frac{1}{\sigma}}. \tag{5.6}$$

By equating (5.5) and (5.6), we can find the steady-state share of capital allocated to the clean sector as in Proposition 2.2.2.

Assuming perfectly mobile labor, we proceed as in the fixed labor case, but impose the additional condition that the capital-labor share is the same in the two sectors, as in (2.7). Hence, we find the closed form expression for the equilibrium capital share allocated to the clean sector as given in Proposition 2.2.3.

5.1.3 Perfect substitutes for $\psi_i \neq 0.5$

Equating the price ratio in the intermediate (5.3) and final (5.4) sectors with the perfect substitute specification, we obtain

$$\left(\frac{\zeta}{1-\zeta}\right)^{\frac{(\sigma-1)\alpha-\sigma}{\sigma}}\left(\frac{\psi_c\dfrac{\zeta}{1-\zeta}+(1-\psi_c)}{(1-\psi_d)\dfrac{\zeta}{1-\zeta}+\psi_d}\right)^{\frac{(1-\alpha)(\sigma-1)}{\sigma}} = \left(\frac{\gamma}{1-\gamma}\right)^{-1}\left(\frac{\tilde{B}_c}{\tilde{B}_d}\right)^{\frac{(1-\alpha)(\sigma-1)}{\sigma}}.$$

By defining $\varphi = \zeta/(1-\zeta)$, $f = [(\sigma-1)\alpha-\sigma]/\sigma$ and $g = (1-\alpha)(\sigma-1)/\sigma$, we can write the expression above as

$$\psi\varphi^{\frac{f}{g}+1} + (1-\psi)\varphi^{\frac{f}{g}} - h^{\frac{f}{g}}(1-\psi)\varphi - h^{\frac{f}{g}}\psi = 0,$$

where for any σ and α, f/g is generally a real number. Taking logarithms, we obtain

$$\psi e^{\left(\frac{f}{g}+1\right)\log\varphi} + (1-\psi)e^{\left(\frac{f}{g}\right)\log\varphi} - h^{\frac{f}{g}}(1-\psi)e^{\log\varphi} - h^{\frac{f}{g}}\psi = 0,$$

which is a polynomial exponential equation, which has generally no analytical solution. However, assuming $\psi_i = 0.5$ or f/g to be a positive integer, the equation becomes a standard polynomial, for which we can easily find a solution. In the Chapter we adopt the approach $\psi_i = 0.5$.

5.1.4 Constant capital-labor share

From the first order conditions of firms, we obtain

$$\alpha p_d \frac{Y_d}{K_d} = q = \alpha p_c \frac{Y_c}{K_c} \qquad \text{and} \qquad (1-\alpha) p_d \frac{Y_d}{L_d} = w = (1-\alpha) p_c \frac{Y_c}{L_c}.$$

Given $L = L_c + L_d$ it follows that

$$\frac{p_c}{p_d} = \frac{\zeta}{1-\zeta} \frac{Z_d(\zeta)}{Z_c(\zeta)} \qquad \text{and} \qquad \frac{p_c}{p_d} = \frac{L_c}{L-L_c} \frac{Z_d(\zeta)}{Z_c(\zeta)}.$$

Hence, we obtain a constant capital-labor share given by

$$\frac{\zeta}{L_c} = \frac{1-\zeta}{L-L_c}.$$

5.1.5 Regime shift

For the sake of brevity, we only analyze the Cobb-Douglas specification. The shares for the perfect substitute and no spillover case reported in Proposition 2.2.4 can be obtained following the same procedure.

Cobb-Douglas spillovers

We assume that the government sets a target ratio $x \in [0, \infty)$ of energy generated from the clean sector, that is,

$$x = \frac{Y_c}{Y_d} = \left(\frac{\tilde{B}_c}{\tilde{B}_d}\right)^{1-\alpha} \left(\frac{\zeta}{1-\zeta}\right)^{2\Theta-1},$$

where we use the structure of the intermediate production functions. Hence, the capital share is given by $\bar{\zeta}_{CD}$, as stated in Proposition 2.2.4. Denoting the subsidy by s, the first-order conditions in the clean energy generation sector become

$$qK_c = \alpha(p_c + s)Y_c \qquad \text{and} \qquad w_c L_c = (1-\alpha)(p_c + s)Y_c.$$

Relative prices in the final sector are still given by (5.2), while relative prices in the intermediate sector now read

$$\frac{p_c}{p_d} = \frac{K_c}{K_d}\frac{Y_d}{Y_c} - \frac{s}{p_d} = \left(\frac{\zeta}{1-\zeta}\right)^{2(1-\Theta)} \left(\frac{\tilde{B}_c}{\tilde{B}_d}\right)^{\alpha-1} - \frac{s}{1-\gamma}\left(\frac{Z_d(\zeta)}{V(\zeta)}\right)^{\frac{1}{\sigma}}, \tag{5.7}$$

where p_d follows from the optimization of the final good producer. By equating (5.2) and (5.7), and plugging in the capital share $\bar{\zeta}_{CD}$ needed to achieve the target x, we can find the relevant subsidy.

When labor is mobile, the capital-labor share is constant across sectors; also in the presence of a target in terms of energy generated from clean compared to dirty sources. The correspondingly capital share is given by Proposition 2.2.5. Following a similar procedure, we can derive the results for the perfect substitutes and no spillover specifications.

5.2 Appendix for Chapter 3

5.2.1 The *monopoly condition*

In Figure 5.1 we show the combination of parameters so that the condition $X = 4(1-\gamma_1^2) - (\gamma_2+\gamma_4)^2 > 0$ is satisfied. Note that the degree of substitutability ($\gamma_1 \in [0,1]$) imposes an upper bound for the network effects, i.e. $\gamma_2, \gamma_4 \in [0,1)$. The set of network effects (γ_2, γ_4) so that the *monopoly condition* is satisfied decreases with a higher substitution between EVs and ICEVs. We also observe that the effect of the substitution parameter is non-linear.

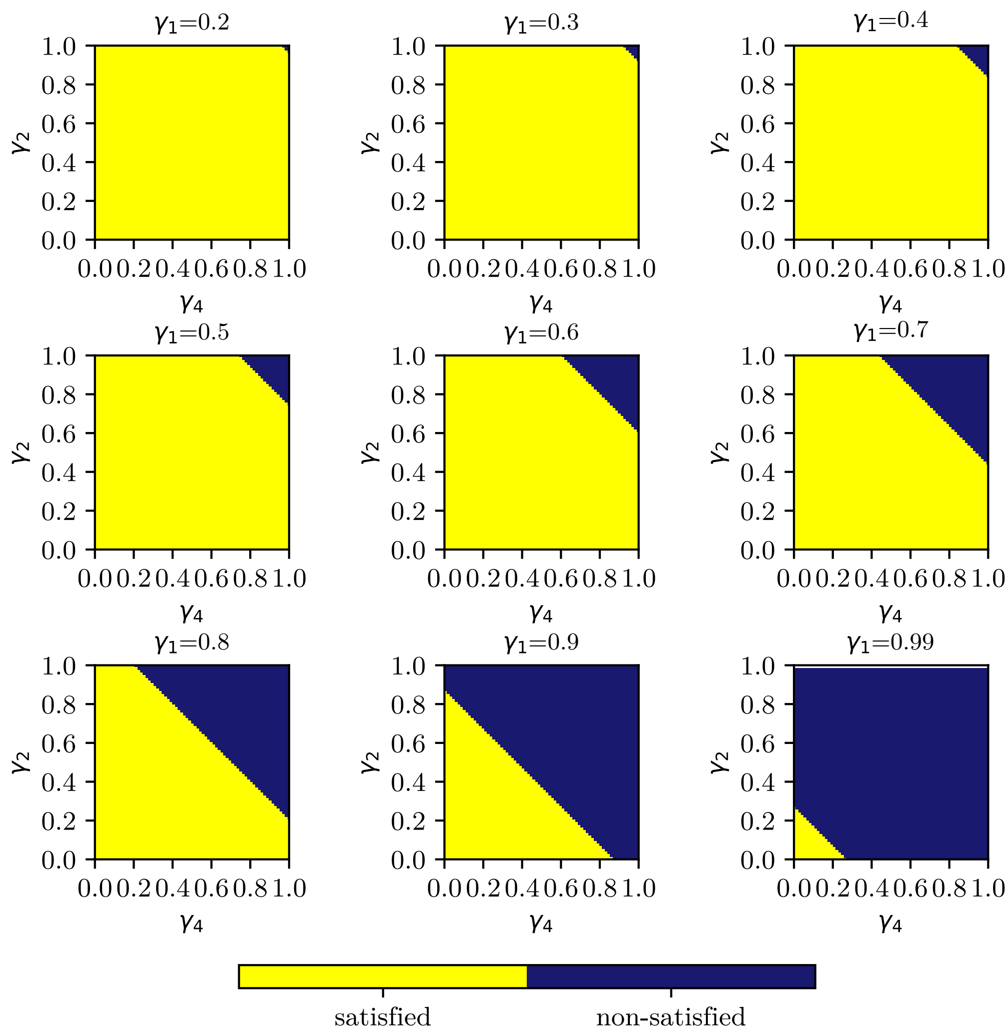

Figure 5.1: Graphical representation of the parameter space (γ_1, γ_2 and γ_4) satisfying the *monopoly condition* (that is, $X > 0$).

5.2.2 Policies

We analytically derive the impacts of policies in the form of subsidies and taxes on quantities and prices, and provide simulations of the effects, for different policy choices. In our framework, the policies take the form of subsidies to EVs and EVCSs (s_c and s_f) as well as a tax on ICEVs (t_d). The policy parameters are chosen so that they take values between zero (no policy intervention) and a maximum value for which the demand for ICEVs vanishes ($q_d = 0$). The latter are given by

$$\begin{aligned} s_c^{max} &= \frac{q_d^* X}{2\gamma_1}, \\ t_d^{max} &= \frac{q_d^* X}{2 - \frac{1}{2}(\gamma_2 + \gamma_4)^2}, \\ s_f^{max} &= \frac{q_d^* X}{\gamma_1(\gamma_2 + \gamma_4)}, \end{aligned}$$

where q_d^* represents the demand for ICEVs in the monopoly case without policy intervention.

Subsidy to EVs ($\mathbf{s_c}$)

When a subsidy is provided to the purchase of EVs, the optimal quantities are

$$\begin{aligned} q_c^{s_c} &= q_c^* + \frac{2}{X} s_c, \\ q_d^{s_c} &= q_d^* - \frac{2\gamma_1}{X} s_c, \\ q_f^{s_c} &= q_f^* + \frac{\gamma_2 + \gamma_4}{X} s_c. \end{aligned}$$

Recalling that $X = 4(1 - \gamma_1^2) - (\gamma_2 + \gamma_4)^2$, larger substitution and network effects increase the magnitude of the change in all the quantities. In the absence of substitution possibilities between EVs and ICEVs ($\gamma_1 = 0$), the subsidy to EVs does not affect the quantity of ICEVs; similarly, q_f is not affected if there are no network effects ($\gamma_2 + \gamma_4 = 0$). Figure 5.2 illustrates the behavior of quantities for different values of the subsidy to EVs.

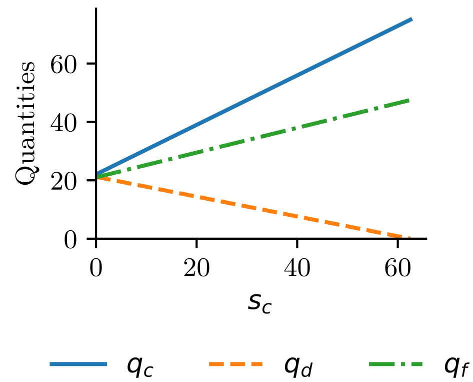

Figure 5.2: Effect on the quantities when a subsidy to EVs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2 + \gamma_4 = 1, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$. In general, the impacts are independent of network effects.

The optimal prices when the subsidy is in place are

$$
\begin{aligned}
p_c^{s_c} &= p_c^* + \frac{2(1-\gamma_1^2) - \gamma_4(\gamma_2+\gamma_4)}{X} s_c, \\
p_d^{s_c} &= p_d^*, \\
p_f^{s_c} &= p_f^* - \frac{(\gamma_2 - \gamma_4)}{X} s_c,
\end{aligned}
$$

showing that if substitution is perfect ($\gamma_1 = 1$) and the network effect is not existing for retailers ($\gamma_4 = 0$), the price of EVs is not affected by the presence of the subsidy to EVs. Moreover, there is no effect on p_f if the network intensities are the same on the two sides of the market ($\gamma_2 = \gamma_4$). Figure 5.3 shows the conditions on the network effects γ_2 and γ_4 for a positive impact of s_c on p_c using different values of the substitution parameter γ_1, focusing on the set of parameters satisfying the *monopoly condition*. High substitutability reduces the parameter space so that s_c has a positive impact on p_c.

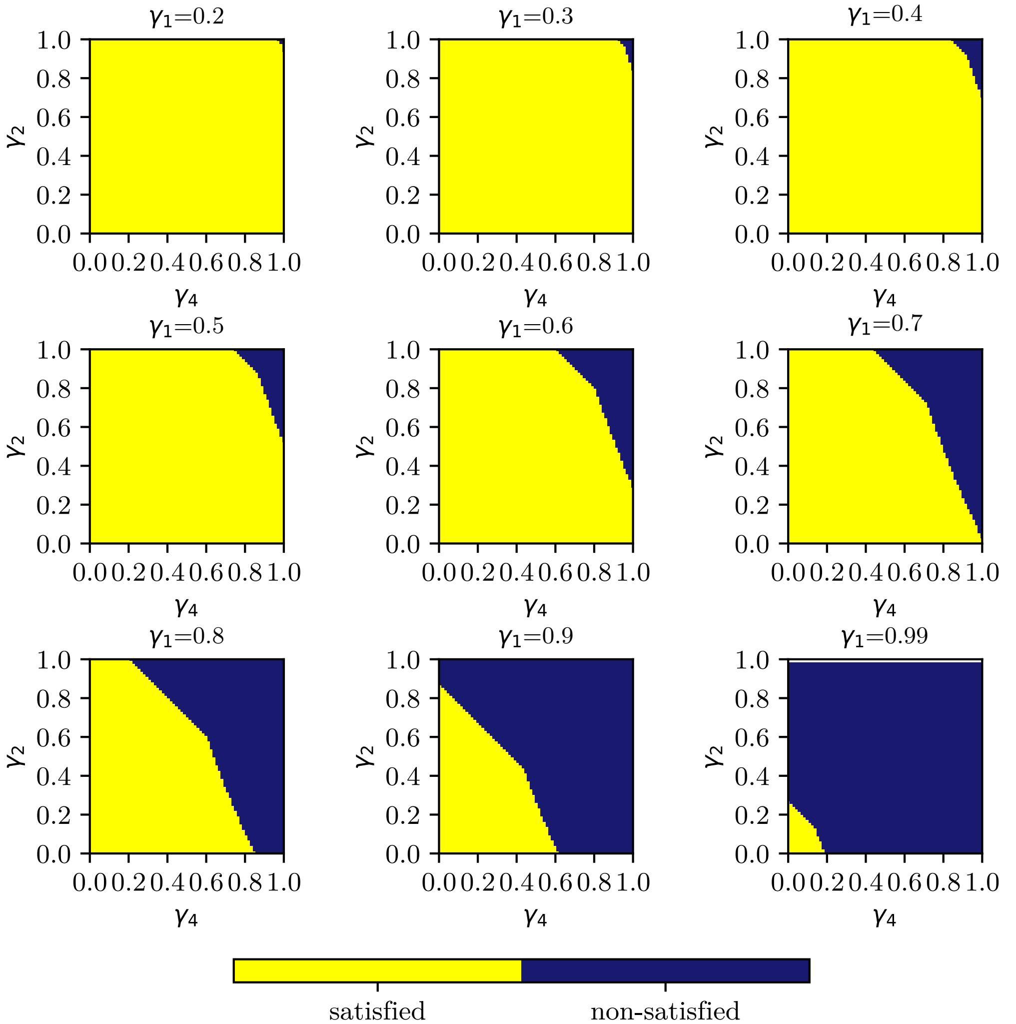

Figure 5.3: Graphical representation of the parameter space $(\gamma_1, \gamma_2, \gamma_4)$ satisfying the *monopoly condition* and leading to a positive impact of an EV subsidy on the price of EVs, that is, $X > 0$ and $2(1 - \gamma_1^2) - \gamma_4(\gamma_2 + \gamma_4) > 0$.

***Taxes on ICEVs* ($\mathbf{t_d}$)**

If a tax is imposed on the demand for polluting cars only, the optimal quantities are

$$
\begin{aligned}
q_c^{t_d} &= q_c^* + \frac{2\gamma_1}{X} t_d, \\
q_d^{t_d} &= q_d^* - \frac{2 - \frac{1}{2}(\gamma_2 + \gamma_4)^2}{X} t_d, \\
q_f^{t_d} &= q_f^* + \frac{\gamma_1(\gamma_2 + \gamma_4)}{X} t_d.
\end{aligned}
$$

The tax on ICEVs affects quantities of EVs and EVCSs, and ICEVs. The impact on the quantity of EVs is higher the stronger the substitution effect. Note that if there is no substitutability between EVs and ICEVs ($\gamma_1 = 0$), nor q_c neither q_f are affected by the tax. Moreover, the quantity of EVCSs is not affected if the network effects are zero ($\gamma_2 + \gamma_4 = 0$). Figure 5.4 illustrates the behavior of quantities for different values of the tax on ICEVs.

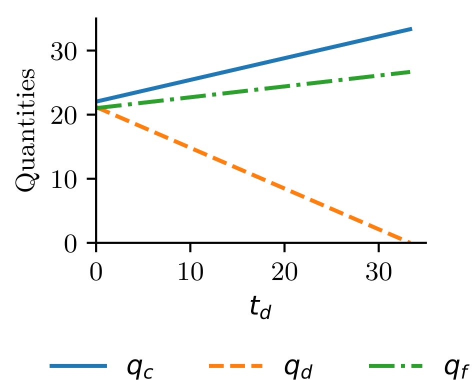

Figure 5.4: Effect on the quantities when a tax to ICEVs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2 + \gamma_4 = 1, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$. In general, the impacts are independent of network effects.

The optimal prices are

$$p_c^{t_d} = p_c^* + \frac{\gamma_1(\gamma_2^2 - \gamma_4^2)}{X} t_d,$$
$$p_d^{t_d} = p_d^* - \frac{1}{2} t_d,$$
$$p_f^{t_d} = p_f^* - \frac{\gamma_1(\gamma_2 - \gamma_4)}{X} t_d,$$

showing that in case of no substitutability or identical network effects, p_c and p_f are not affected by the tax. As discussed in the main text, the effect of the tax on p_c and p_f depends on the relative intensity of network effects.

***Subsidy to EVCSs* ($\mathbf{s_f}$)**

When a subsidy is provided to EVCSs, the optimal quantities are

$$\begin{aligned} q_c^{s_f} &= q_c^* + \frac{\gamma_2 + \gamma_4}{X} s_f, \\ q_d^{s_f} &= q_d^* - \frac{\gamma_1(\gamma_2 + \gamma_4)}{X} s_f, \\ q_f^{s_f} &= q_f^* + \frac{2(1 - \gamma_1^2)}{X} s_f. \end{aligned} \tag{5.8}$$

When the subsidy is applied, EV, EVCS and ICEV purchases are affected. In the absence of network effects ($\gamma_2 + \gamma_4 = 0$) such subsidy has no effect on q_c and q_d. Also, no substitution ($\gamma_1 = 0$) implies that q_d is not affected, whereas perfect substitution ($\gamma_1 = 1$) rules out any effect of the subsidy on q_f. Figure 5.5 illustrates the behavior of quantities for different values of the subsidy to EVCSs.

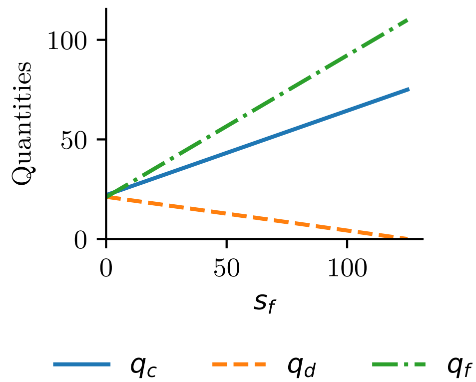

Figure 5.5: Effect on the quantities when a subsidy to EVCSs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2 + \gamma_4 = 1, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$. In general, the impacts are independent of network effects.

The optimal prices when a subsidy to EVCSs is in place are

$$p_c^* = p_c^* + \frac{(1-\gamma_1^2)(\gamma_2 - \gamma_4)}{X} s_f,$$
$$p_d^* = p_d^*,$$
$$p_f^* = p_f^* + \frac{2(1-\gamma_1^2) - \gamma_2(\gamma_2 + \gamma_4)}{X} s_f,$$

showing that p_c is not affected by the policy if there is perfect substitution or the network effects equal. Any effect on p_f is eliminated when EVs and ICEVs are perfect substitutes and if the network effect on the consumers' side is zero. Figure 5.6 shows the conditions on the network effects γ_2 and γ_4 for a positive impact of s_f on p_f using different values of the substitution parameter γ_1, focusing on the set of parameters satisfying the *monopoly condition*.

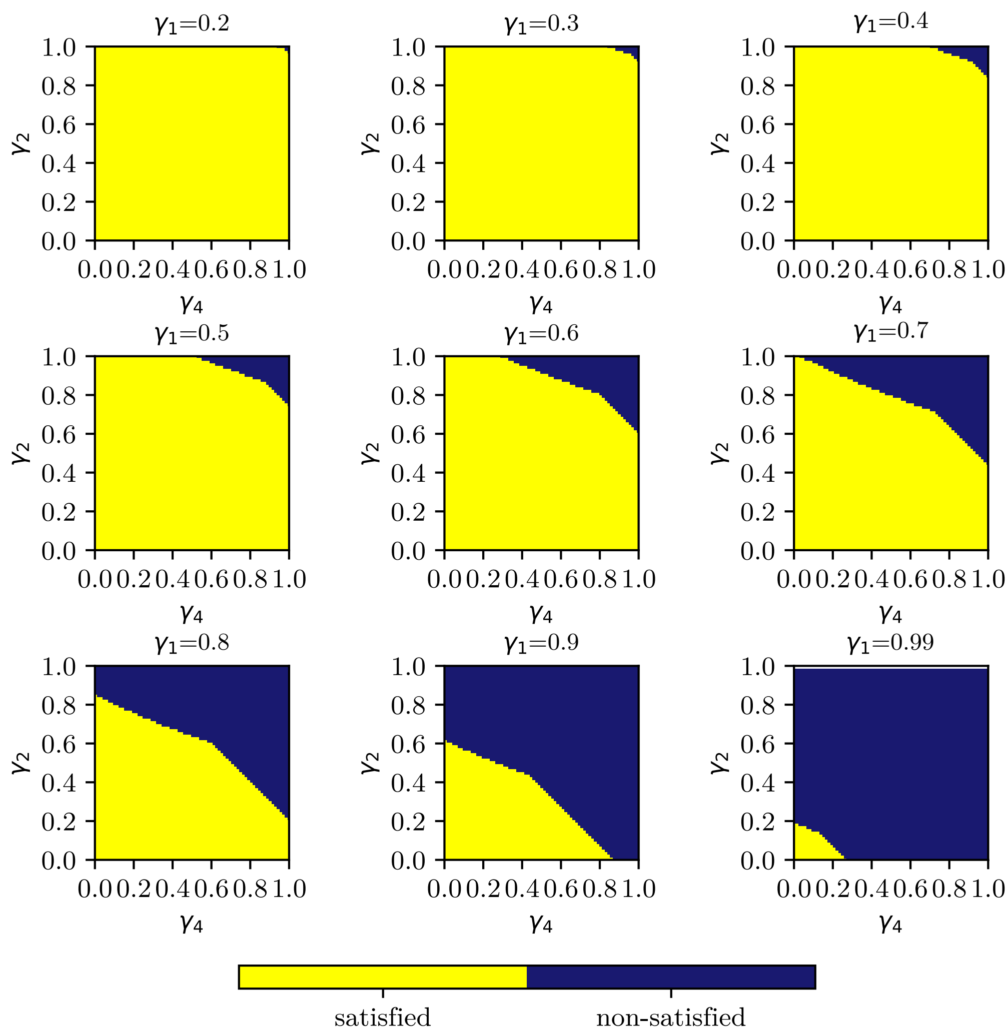

Figure 5.6: Graphical representation of the parameter space $(\gamma_1, \gamma_2, \gamma_4)$ satisfying the *monopoly condition* and leading to a positive impact of a subsidy to EVCSs on the price of EVCSs, that is, $X > 0$ and $2(1-\gamma_1^2) - \gamma_2(\gamma_2 + \gamma_4) > 0$.

Effect of policies on prices

The dependence of prices on the relative intensity of network effects is illustrated in Figures 5.7, 5.8 and 5.9. The graphs show that the price of ICEVs represents an exception thereof as it is solely affected by its own demand parameters (α_d and c_d) and the tax on ICEVs. In contrast, the prices of EVs and EVCSs are generally influenced, both in terms of magnitude and sign by the relative intensity of network effects. Figure 5.7 shows that for the chosen parameters, the price of EVs is always increasing with the subsidy to EVs, whereas the price of EVCSs is increasing for $\gamma_2 > \gamma_4$ and decreasing otherwise. As expected, in Figure 5.8, where a tax is applied, the signs of the impacts are reversed depending on the relative intensities of network effects. For $\gamma_2 > \gamma_4$ the price of EVs is increasing and the price of EVCSs is decreasing. For $\gamma_4 > \gamma_2$, the outcome is reversed. Finally, Figure 5.9 shows that, for the chosen parameters, the price of EVs is increasing with a subsidy to EVCSs for $\gamma_4 > \gamma_2$ and decreasing otherwise, whereas the price of EVCSs is always increasing.

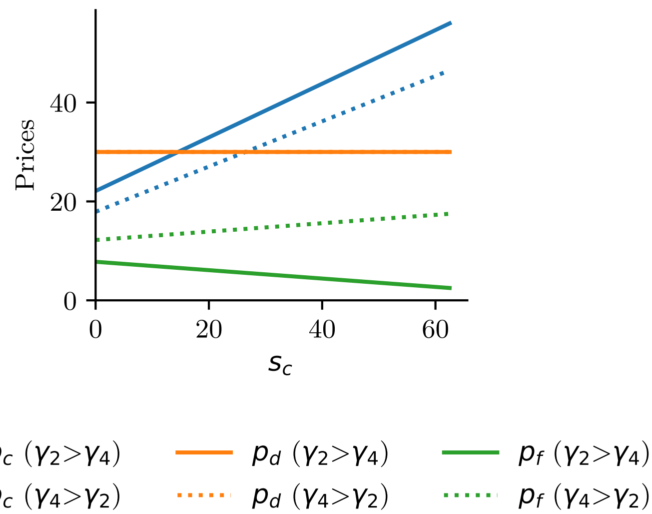

Figure 5.7: Effect on the prices when a subsidy to EVs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2, \gamma_4 \in \{0.4, 0.6\}, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$.

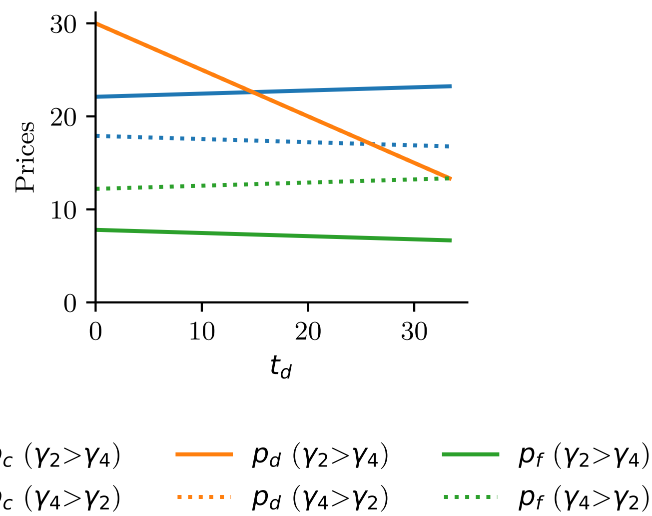

Figure 5.8: Effect on the prices when a tax on ICEVs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2, \gamma_4 \in \{0.4, 0.6\}, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$.

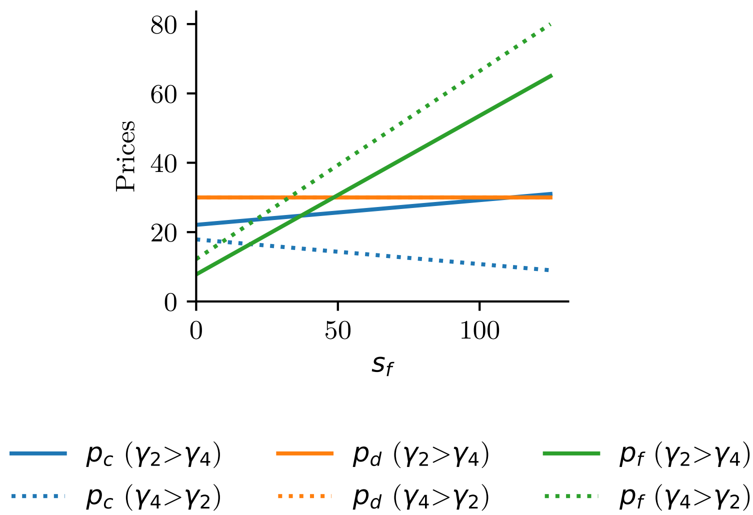

Figure 5.9: Effect on the prices when a subsidy to EVCSs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2, \gamma_4 \in \{0.4, 0.6\}, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$.

***Subsidies to EVs* ($\mathbf{s_c}$) *and EVCSs* ($\mathbf{s_f}$)**

In the following, we study the parameter space of substitution and network effects, $(\gamma_1, \gamma_2, \gamma_4)$, with respect to the price effect of both subsidies s_c and s_f. To simplify the notation we use $\partial p_c/\partial s_c = ds_c > 0$ to denote a positive impact of the subsidy to EVs on the price of EVs and $\partial p_f/\partial s_f = ds_f > 0$ to denote a positive impact of the subsidy to EVCSs on the price of EVCSs. Figure 5.10 provides a graphical illustration of this study separating the parameter space based on the different price effects, taking the *monopoly condition* into account. We can distinguish five different sets: (1) both subsidies have a positive effect on the respective prices ($ds_c > 0$ and $ds_f > 0$); (2) negative effect of the subsidy to EVs on their price and positive effect of the subsidy to EVCSs on their price ($ds_c < 0$ and $ds_f > 0$); (3) positive effect of the subsidy to EVs on their price and negative effect of the subsidy to EVCSs on their price ($ds_c > 0$ and $ds_f < 0$); (4) both subsidies have a negative effect on the respective prices ($ds_c < 0$ and $ds_f < 0$); (5) the monopoly condition not satisfied ($X < 0$). Figure 5.10 shows that the set of parameters so that both subsidies have a negative effect on respective prices is empty, that is ds_c and ds_f can never be jointly negative. This follows from our assumption $X > 0$ and the fact that $ds_c + ds_f = X$. The economic interpretation of this finding follows from the two-sided market structure: as consumers and retailers represent two different sides of the market, the platform will never reduce the price on both sides.

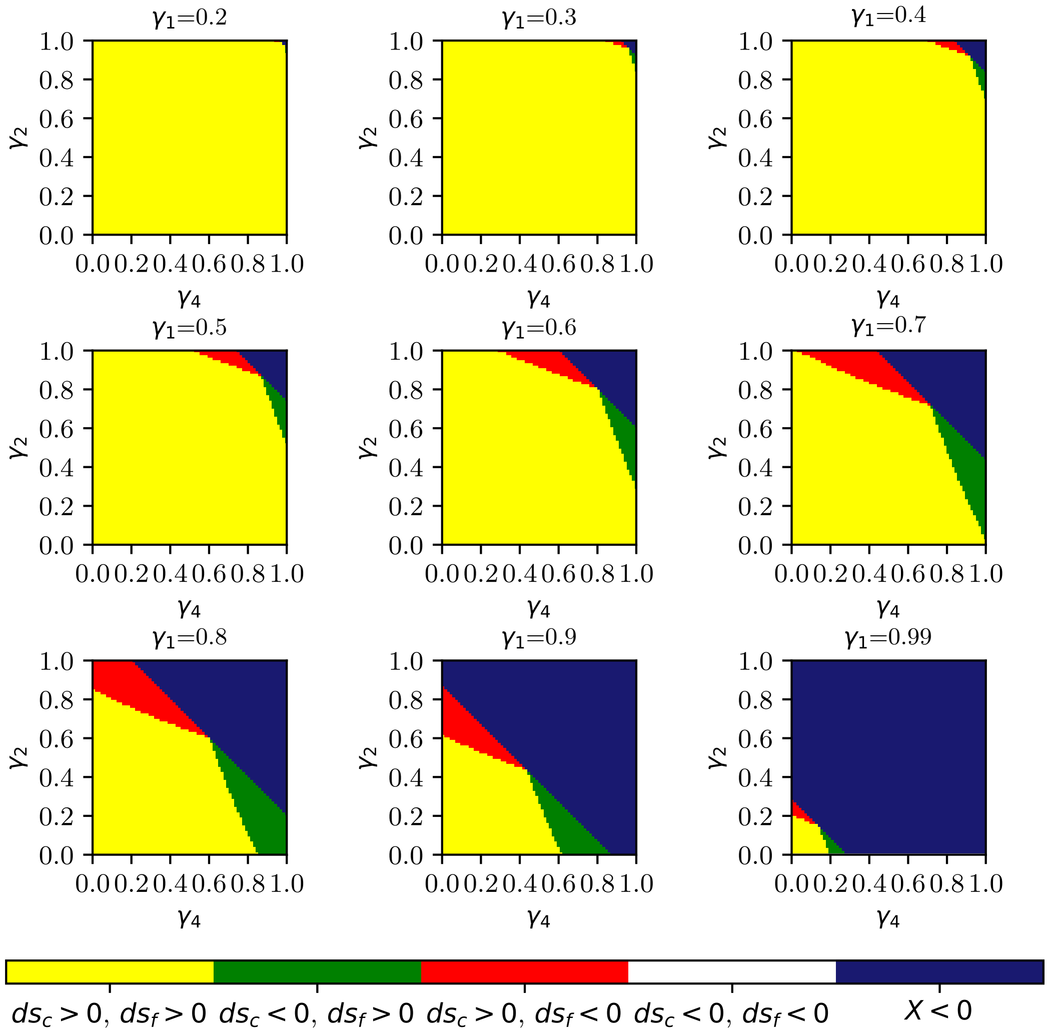

Figure 5.10: Graphical representation of the parameter space $(\gamma_1, \gamma_2, \gamma_4)$ satisfying the *monopoly condition* and determining the sign of the impact of the subsidy on the respective price, provided that $X > 0$.

5.2.3 First-best solution

The social planner takes into account the negative externality due to pollution and solves

$$\max_{q_{0,h},q_{0,a},q_c,q_d,q_f} W^P \quad s.t. \quad q_{0,h}+q_{0,a}=m_h+m_a-p_cq_c-p_dq_d-p_fq_f,$$

where $W^P = U + F + \pi - \phi q_d$. The first-order conditions of the social planner problem are

$$\begin{aligned}
\alpha_c - q_c - \gamma_1 q_d + (\gamma_2+\gamma_4)q_f - c_c &= 0,\\
\alpha_d - q_d - \gamma_1 q_c - c_d^P &= 0,\\
\alpha_f - q_f + (\gamma_2+\gamma_4)q_c - c_f &= 0,
\end{aligned}$$

where $c_d^P = c_d + \phi$ is the cost of producing ICEVs when pollution is taken into account. For an interior solution, the welfare-maximizing quantities are

$$\begin{aligned}
q_c^{fb} &= \frac{1}{\tilde{X}}\left[\alpha_c - c_c - \gamma_1(\alpha_d - c_d^P) + (\gamma_2+\gamma_4)(\alpha_f - c_f)\right],\\
q_d^{fb} &= \frac{1}{\tilde{X}}\left[-\gamma_1(\alpha_c - c_c) + \left[1-(\gamma_2+\gamma_4)^2\right](\alpha_d - c_d^P) - \gamma_1(\gamma_2+\gamma_4)(\alpha_f - c_f)\right],\\
q_f^{fb} &= \frac{1}{\tilde{X}}\left[(\gamma_2+\gamma_4)(\alpha_c - c_c) - \gamma_1(\gamma_2+\gamma_4)(\alpha_d - c_d^P) + (1-\gamma_1^2)(\alpha_f - c_f)\right],
\end{aligned}$$

where $\tilde{X} = 1 - \gamma_1^2 - (\gamma_2+\gamma_4)^2$. The condition $\tilde{X} > 0$ is stricter than $X > 0$ in the monopoly case and will be referred to as the *first-best condition*. The set of parameters satisfying the *monopoly condition* includes the one satisfying the *first-best condition* as

$$X = \tilde{X} + 3(1-\gamma_1^2),$$

where the second term can only be non-negative due to $\gamma_1 \in [0,1]$. In Figure 5.11, we plot all the combinations of parameters satisfying the *first-best condition*.

The set of γ_2 and γ_4 such that the condition holds shrinks with the substitution parameter γ_1. The economic intuition is that if two goods are good substitutes it is more likely that one of the two disappears.

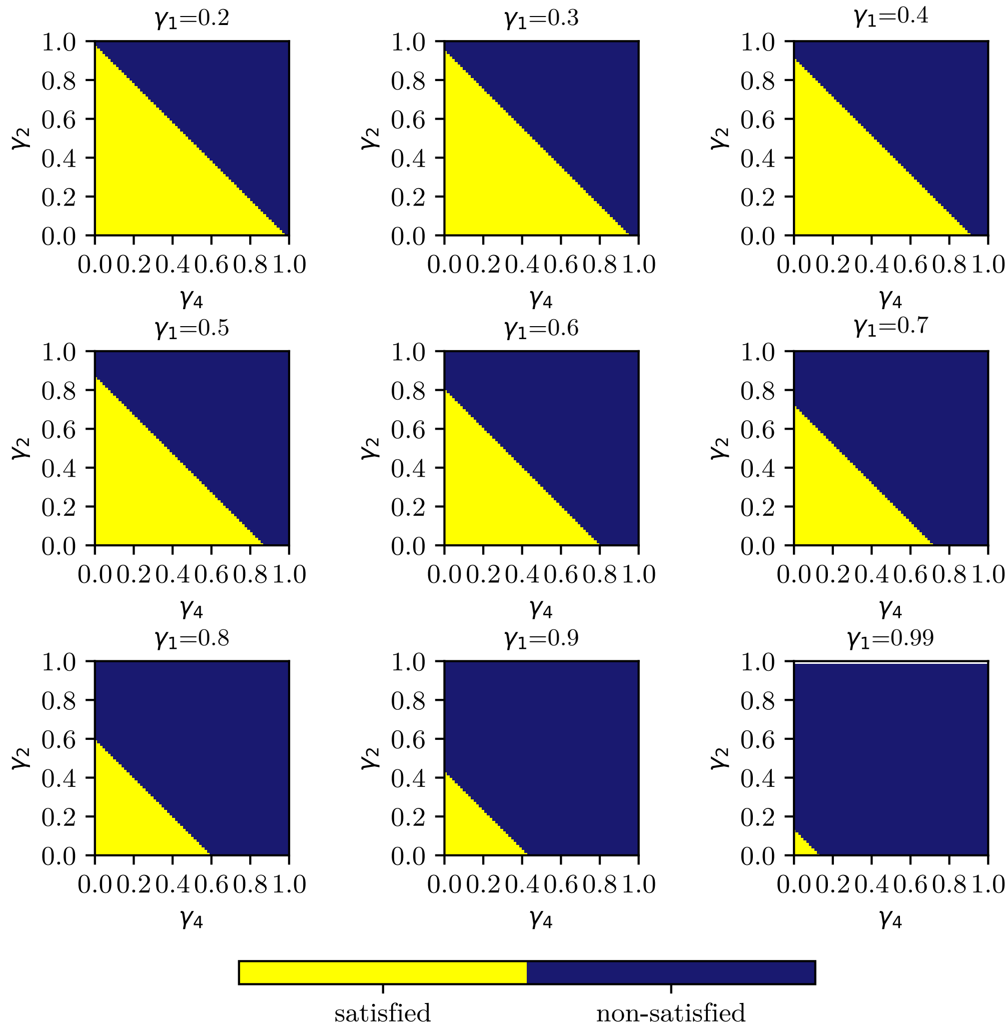

Figure 5.11: Graphical representation of the parameter space (γ_1, γ_2 and γ_4) satisfying the *first-best condition* (that is, $\tilde{X} > 0$).

In what follows, we show that in the presence of network effects and pollution externality, the ratio of EVs to ICEVs in the first-best is always higher compared to the monopoly outcome; this result does not depend on the actual values of the demand parameters and network externalities. We define $\zeta_{fb} = \zeta_{fb}^N/\zeta_{fb}^D$, and $\zeta_m = \zeta_m^N/\zeta_m^D$. Using the ratios of EVs to EVCSs in the in the firs-best and decentralized economy, we can write

$$\begin{aligned}
\zeta_m &= \frac{2\zeta_{fb}^N - (\gamma_2+\gamma_4)(\alpha_f - c_f)}{2\zeta_{fb}^D + \gamma_1(\gamma_2+\gamma_4)(\alpha_f - c_f) + \frac{3}{2}(\gamma_2+\gamma_4)^2(\alpha_d - c_d)}, \\
&= \frac{\zeta_{fb}^N - \frac{1}{2}(\gamma_2+\gamma_4)(\alpha_f - c_f)}{\zeta_{fb}^D + \frac{1}{2}\gamma_1(\gamma_2+\gamma_4)(\alpha_f - c_f) + \frac{3}{4}(\gamma_2+\gamma_4)^2(\alpha_d - c_d^D)},
\end{aligned} \tag{5.9}$$

which implies $\zeta_m^N \leq \zeta_{fb}^N$ and $\zeta_m^D \geq \zeta_{fb}^D$. Hence, for any parameter values $\zeta_m \leq \zeta_{fb}$.

5.2.4 Oligopoly

In an oligopolistic market structure, the inverse demand functions faced by firms become

$$
\begin{aligned}
p_c &= \alpha_c - Q_c - \gamma_1 Q_d + \gamma_2 Q_f, \\
p_d &= \alpha_d - Q_d - \gamma_1 Q_c, \\
p_f &= \alpha_f - Q_f + \gamma_4 Q_c,
\end{aligned}
$$

where $Q_j = \sum_{i=1}^{N} q_{i,j}$, with $j = \{c, d, f\}$, is the total quantity of each good produced in the economy and $q_{i,j}$ denotes the quantity of each good produced by firm i. Each firm maximizes individual profits taking into account the quantities produced by the other firms

$$
\begin{aligned}
\pi_i &= (p_c - c_c)q_{i,c} + (p_d - c_d)q_{i,d} + (p_f - c_f)q_{i,f} \\
&= (\alpha_c - Q_c - \gamma_1 Q_d + \gamma_2 Q_f - c_c)q_{i,c} + (\alpha_d - Q_d - \gamma_1 Q_c - c_d)q_{i,d} \\
&+ (\alpha_f - Q_f + \gamma_4 Q_c - c_f)q_{i,f}.
\end{aligned}
$$

Profit maximization yields

$$
\begin{aligned}
\alpha_c - (Q_c + q_{i,c}) - \gamma_1(Q_d + q_{i,d}) + \gamma_2 Q_f + \gamma_4 q_{i,f} - c_c = 0, \\
\alpha_d - (Q_d + q_{i,d}) - \gamma_1(Q_c + q_{i,c}) - c_d = 0, \\
\alpha_f - (Q_f + q_{i,f}) + \gamma_2 q_{i,c} + \gamma_4 Q_c - c_f = 0.
\end{aligned}
$$

From the first-order conditions we can derive the reaction functions of firm i, that is, the optimal quantities of the EVs, ICEVs and EVCSs produced by each firm given production of the three goods by the other firms. The reaction functions are linear because of the assumption of linear demand and cost functions. Moreover, the quantity of each good produced by firm i depends on the quantity of the other two goods produced by the firm itself because of the presence of substitution and network effects. Firms are identical, hence they all produce the same quantities of EVs, ICEVs and EVCSs, that is, $q_{i,j} = q_{-i,j} = q_j$, for all the goods in the economy. For an interior solution, optimal quantities produced by each firm i are

$$
\begin{aligned}
q_c^* &= \frac{1}{X_{olig}}[(n+1)(\alpha_c - c_c) - \gamma_1(n+1)(\alpha_d - c_d) + (n\gamma_2 + \gamma_4)(\alpha_f - c_f)], \\
q_d^* &= \frac{1}{X_{olig}}[-\gamma_1(n+1)(\alpha_c - c_c) + \left[n + 1 - \frac{(n\gamma_2 + \gamma_4)(\gamma_2 + n\gamma_4)}{n+1}\right](\alpha_d - c_d) \\
&\quad - \gamma_1(n\gamma_2 + \gamma_4)(\alpha_f - c_f)], \\
q_f^* &= \frac{1}{X_{olig}}[(\gamma_2 + n\gamma_4)(\alpha_c - c_c) - \gamma_1(\gamma_2 + n\gamma_4)(\alpha_d - c_d) \\
&\quad + (n+1)(1-\gamma_1^2)(\alpha_f - c_f)],
\end{aligned}
$$

where $X_{olig} = (n+1)^2(1-\gamma_1^2) - (n\gamma_2 + \gamma_4)(\gamma_2 + n\gamma_4) > 0$ is defined as the *oligopoly condition*. For $n = 1$, the *oligopoly condition* coincides with the *monopoly condition*; in general, for $n > 1$, we can write

$$X_{olig} = X + 2(n-1)(1 - \gamma_1 - \gamma_2\gamma_4),$$

meaning that for $1 - \gamma_1 - \gamma_2\gamma_4 > (<)0$, the set of parameter satisfying the *oligopoly condition* (*monopoly condition*) is larger than the one satisfying the *monopoly condition* (*oligopoly condition*). Since prices do not affect welfare as in the baseline model, we do not report them in the oligopolistic case. When the optimal policies apply, the optimal quantities become

$$
\begin{aligned}
q_c^{pol} &= q_c^* + \frac{1+n}{X_{olig}} s_c + \frac{\gamma_1(1+n)}{X_{olig}} t_d + \frac{n\gamma_2+\gamma_4}{X_{olig}} s_f, \\
q_d^{pol} &= q_d^* - \frac{\gamma_1(1+n)}{X_{olig}} s_c - \frac{(n+1) - \frac{1}{n+1}(n\gamma_2+\gamma_4)(\gamma_2+n\gamma_4)}{X_{olig}} t_d \\
&\quad - \frac{\gamma_1(n\gamma_2+\gamma_4)}{X_{olig}} s_f \\
q_f^{pol} &= q_f^* + \frac{\gamma_2+n\gamma_4}{X_{olig}} s_c + \frac{\gamma_1(\gamma_2+n\gamma_4)}{X_{olig}} t_d + \frac{(1+n)(1-\gamma_1^2)}{X_{olig}} s_f.
\end{aligned}
$$

Notice that welfare now includes profits from all the n firms in the economy and damage is given by the total amount of ICEVs produced, that is

$$W = U + F + n\pi_i - \phi Q_d,$$

where $Q_d = nq_d$. As in the monopoly case, however, profits are simply redistributed within the economy and they do not matter in the welfare determination.

5.3 Appendix for Chapter 4

5.3.1 The optimization problem of firms

Note that the Cobb-Douglas production function of firms satisfies the Inada conditions, so that firms choose positive capital and labor inputs for production, ruling out the extreme case where they only devote capital to the adoption of a new technology, that is, $\gamma_{s,t} < 1$. Thus, when solving the optimization problem of firms, we only need to account for the non-negativity constraint on $\gamma_{s,t}$. The Karush-Kuhn-Tucker (KKT) conditions are then given by equations (4.3), (4.4), (4.5), the non-negativity constraint on the share $\gamma_{s,t}$ and on the KKT multiplier $\mu_{s,t}$, as well as the complementary slackness condition $\mu_{s,t}\gamma_{s,t} = 0$. Equating the first-order conditions with respect to capital (4.4) of two different sectors $s, \bar{s} \in \mathcal{S}$, we obtain

$$K_{\bar{s},t} = \left[\frac{A_s(z_t)}{A_{\bar{s}}(z_t)} \frac{\bar{\gamma}_{s,t}^{\alpha}}{\bar{\gamma}_{\bar{s},t}^{\alpha}} \frac{N_{s,t}^{1-\alpha}}{N_{\bar{s},t}^{1-\alpha}} \frac{R_{\bar{s},t}^{L}}{R_{s,t}^{L}}\right]^{\frac{1}{\alpha-1}} K_{s,t}.$$

Using $R_{s,t}^L = R_{CB,t}^D[1 + \psi_t\kappa_t(\Gamma_{s,t}) - \psi_t]$ and the notation $K_{s,t} = \zeta_{s,t}K_t$, we obtain

$$\zeta_{\bar{s},t} = \left[\frac{A_s(z_t)}{A_{\bar{s}}(z_t)} \frac{\bar{\gamma}_{s,t}^{\alpha}}{\bar{\gamma}_{\bar{s},t}^{\alpha}} \frac{N_{s,t}^{1-\alpha}}{N_{\bar{s},t}^{1-\alpha}} \frac{1 + \psi_t\kappa_t(\Gamma_{\bar{s},t}) - \psi_t}{1 + \psi_t\kappa_t(\Gamma_{s,t}) - \psi_t}\right]^{\frac{1}{\alpha-1}} \zeta_{s,t}.$$

Summing these equations over all $\bar{s} \in \mathcal{S}$, yields

$$1 = \left(\sum_{\bar{s}\in\mathcal{S}} \left[\frac{A_s(z_t)}{A_{\bar{s}}(z_t)} \frac{\bar{\gamma}_{s,t}^{\alpha}}{\bar{\gamma}_{\bar{s},t}^{\alpha}} \frac{N_{s,t}^{1-\alpha}}{N_{\bar{s},t}^{1-\alpha}} \frac{1 + \psi_t\kappa_t(\Gamma_{\bar{s},t}) - \psi_t}{1 + \psi_t\kappa_t(\Gamma_{s,t}) - \psi_t}\right]^{\frac{1}{\alpha-1}}\right) \zeta_{s,t},$$

as given by equation (4.6) in the text. We now turn to the decision of firms to adopt a cleaner technology. Given the loan rate $R_{s,t}^L = R_{CB,t}^D[1 + \psi_t\kappa_t(\Gamma_{s,t}) - \psi_t]$, we obtain

$$\begin{aligned}\frac{\partial R^L_{s,t}}{\partial \gamma_{s,t}} &= R^D_{CB,t}\psi_t \frac{\partial \kappa_t(\Gamma_{s,t})}{\partial \Gamma_{s,t}} \frac{\partial \Gamma_{s,t}}{\partial \gamma_{s,t}} \\ &= R^D_{CB,t}\psi_t \kappa_{1,t}\kappa_t(\Gamma_{s,t})(-\iota_s \Gamma_{s,t-1}).\end{aligned}$$

For any interior solution $\gamma_{s,t} \in (0,1)$, the first-order condition (4.3) reads as

$$\alpha \tilde{A}_{s,t}\bar{\gamma}^{\alpha-1}_{s,t} K^{\alpha-1}_{s,t} N^{1-\alpha}_{s,t} = q_t R^D_{CB,t}\psi_t \kappa_{1,t}\kappa_t(\Gamma_{s,t})\iota_s \Gamma_{s,t-1},$$

as the KKT multiplier $\mu_{s,t} = 0$. Combining this equation with the first-order condition with respect to capital (4.4), we obtain the optimal adoption level chosen by firms. For $\gamma_{s,t} = 0$, the first-order conditions with respect to $\gamma_{s,t}$ and $K_{s,t}$ reduce to

$$\alpha \tilde{A}_{s,t} K^{\alpha}_{s,t} N^{1-\alpha}_{s,t} = q_t K_{s,t} R^D_{CB,t}\psi_t \kappa_{1,t}\kappa_t(\Gamma_{s,t-1})\iota_s \Gamma_{s,t-1} + \mu_{s,t}$$

and

$$\alpha \tilde{A}_{s,t} K^{\alpha}_{s,t} N^{1-\alpha}_{s,t} = q_t K_{s,t} R^D_{CB,t}[1 + \psi_t \kappa_t(\Gamma_{s,t-1}) - \psi_t],$$

respectively, which together yield the KKT multiplier

$$\mu_{s,t} = q_t K_{s,t} R^D_{CB,t}\{1 - \psi_t[1 + (\kappa_{1,t}\iota_s \Gamma_{s,t-1} - 1)\kappa_t(\Gamma_{s,t-1})]\} > 0.$$

Thus, the choice of adopting a cleaner technology is generally described by

$$\gamma_{s,t} = \max\left\{\frac{\psi_t[1 + (\kappa_{1,t}\iota_s \Gamma_{s,t-1} - 1)\kappa_t(\Gamma_{s,t})] - 1}{\psi_t \kappa_{1,t}\iota_s \Gamma_{s,t-1}\kappa_t(\Gamma_{s,t})}, 0\right\},$$

and the KKT multiplier is given by

$$\mu_{s,t} = q_t K_{s,t} R^D_{CB,t} \max\{1 - \psi_t[1 + (\kappa_{1,t}\iota_s \Gamma_{s,t-1} - 1)\kappa_t(\Gamma_{s,t-1})], 0\}.$$

Note that

$$\alpha\bar{\gamma}_{s,t}^{\alpha}K_{s,t}^{\alpha-1}N_{s,t}^{1-\alpha}\tilde{A}_{s,t} = \frac{\alpha\tilde{Y}_{s,t}}{K_{s,t}} \quad \text{and} \quad (1-\alpha)\bar{\gamma}_{s,t}^{\alpha}K_{s,t}^{\alpha}N_{s,t}^{-\alpha}\tilde{A}_{s,t} = \frac{(1-\alpha)\tilde{Y}_{s,t}}{N_{s,t}}.$$

Using this fact, it is straightforward to derive equations (4.8) in the Chapter, from the first-order conditions with respect to capital and labor. The loans provided to sector s are therefore given by

$$L_{s,t} = Q_t K_{s,t} + W_{s,t}N_{s,t} = \frac{P_t\tilde{Y}_{s,t}}{R_{s,t}^{L}},$$

which leads to the conclusion that firms make zero profits.

5.3.2 The optimization problem of households

We show that any nominal output good price satisfies the budget constraint of the household, while imposing market clearing for the single output good. First, note that firms and banks make zero profits, that is, $\Pi_t^F = \Pi_t^B = 0$. The constraint faced by the household, when optimizing, is therefore given by

$$P_t(C_t + K_{t+1}) = R_{CB,t}^{D}(Q_t K_t + W_t N_t) + (1-\delta)P_t K_t + \Pi_t^{CB}.$$

With the central bank seigniorage given by

$$\Pi_t^{CB} = \psi_t R_{CB,t}^{D}\sum_{s\in\mathcal{S}}[\kappa_t(\Gamma_{s,t}) - 1]L_{s,t},$$

and given that the household's income can be rewritten as

$$Q_t K_t + W_t N_t = \sum_{s\in\mathcal{S}}(Q_t K_{s,t} + W_{s,t}N_{s,t}) = \sum_{s\in\mathcal{S}} L_{s,t},$$

the constraint faced by the household reads

$$P_t(C_t + K_{t+1}) = R^D_{CB,t} \sum_{s \in \mathcal{S}} [1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t] L_{s,t} + (1-\delta) P_t K_t.$$

Noting that, as before, loans in each sector can be rewritten as

$$L_{s,t} = \frac{P_t \tilde{Y}_{s,t}}{R^L_{s,t}},$$

where $R^L_{s,t} = R^D_{CB,t}[1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t]$, the constraint of the household is given by

$$C_t + K_{t+1} = \tilde{Y}_t + (1-\delta) K_t,$$

where we used the market clearing condition $\tilde{Y}_t = \sum_{s \in \mathcal{S}} \tilde{Y}_{s,t}$.

5.3.3 Industrial classification system

We have used the statistical classification of economic activities in the European Community (NACE) as adopted by Eurostat, which represents the classification of economic activities adopted in the European Union.[1] The NACE code is subdivided in a hierarchical, four-level structure. The categories at the highest level are called sections. The first two digits of the code identify the division, the third digit identifies the group, and the fourth digit identifies the class. For the scope of our study, however, we only used the most aggregated 1-digit level, as reported below. Given our computations related to the median emission intensity across sectors in the EA, we aggregate in the clean sector the economic activities **M** to **S**, whereas the dirty sector comprises the activities **A** to **I**. The remaining economic activities were excluded from the analysis because of the lack of available data.

[1] The NACE Rev. 2, the mostly recently revised classification whose implementation began in 2007, is available at https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF.

Code	Economic activities: 1-digit
A	Agriculture, forestry and fishing
B	Mining and quarrying
C	Manufacturing
D	Electricity, gas, steam and air conditioning supply
E	Water supply; sewerage, waste management and remediation activities
F	Construction
G	Wholesale and retail trade; repair of motor vehicles and motorcycles
H	Transportation and storage
I	Accommodation and food service activities
J	Information and communication
K	Financial and insurance activities
L	Real estate activities
M	Professional, scientific and technical activities
N	Administrative and support service activities
O	Public administration and defense; compulsory social security
P	Education
Q	Human health and social work activities
R	Arts, entertainment and recreation
S	Other service activities
T	Activities of households as employers
U	Activities of extraterritorial organisations and bodies

Table 5.3: NACE classification.

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