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Financial markets and green innovation

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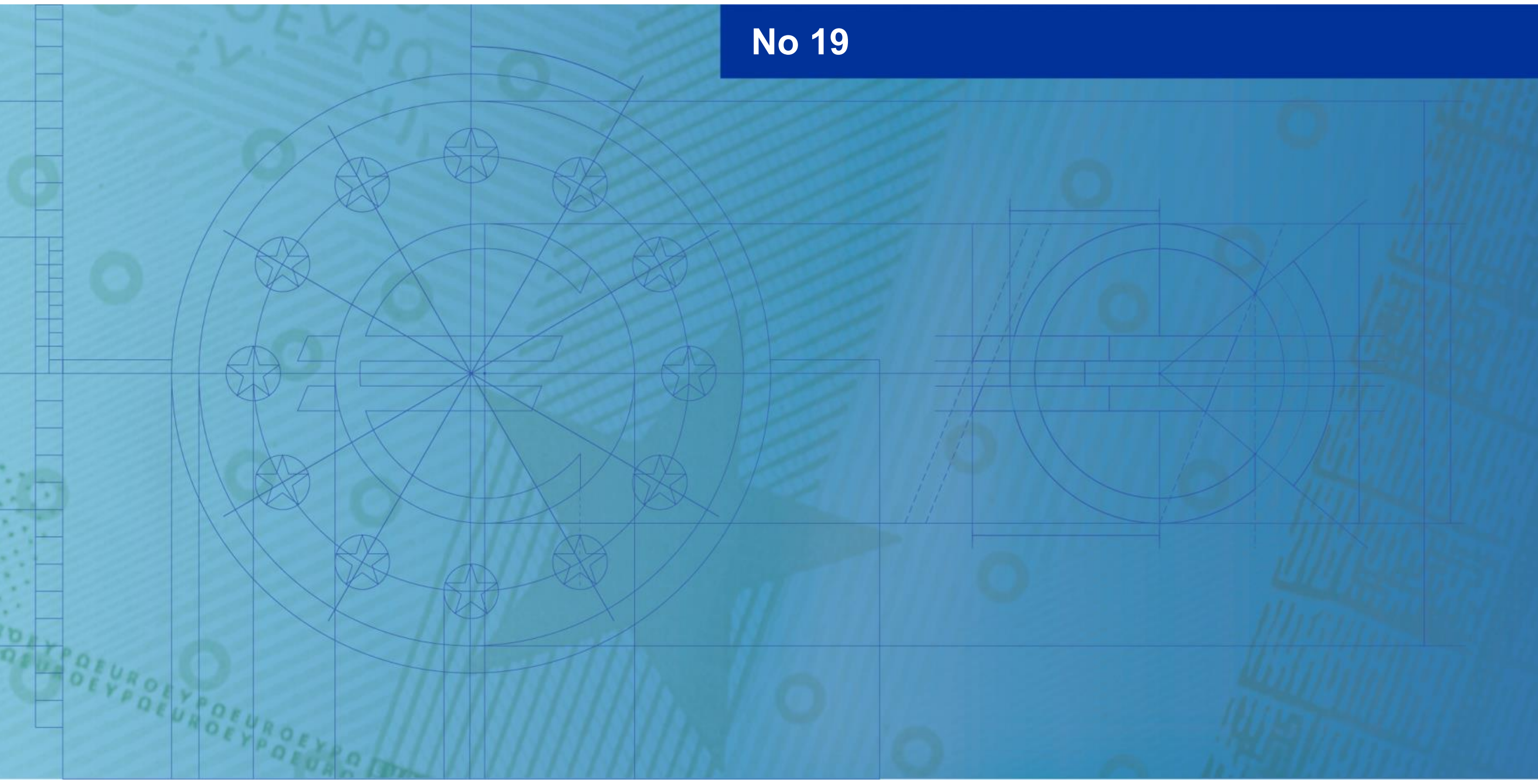

Discussion papers

Discussion papers are research-based papers on policy relevant topics, offering a broader and more balanced perspective. While being partly based on original research, they place the analysis in the wider context of the literature on the topic. They also consider explicitly the policy perspective, with a view to develop a number of key policy messages. Their format offers the advantage that alternative analyses and perspectives can be combined, including theoretical and empirical work. The selection and distribution of discussion papers are subject to the approval of the Director General of the Directorate General Research.

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Abstract

Fulfilling the commitments embedded in the Paris Agreement requires a climate-technology revolution. Patented innovation of low-carbon technologies is lower in the EU than in selected peers, and very heterogeneous across member states. We motivate this fact with an endogenous model of directed technical change with government policy and financial markets. Variations in carbon taxes, R&D investment, and venture capital investment explain a large share of the variation in green patents per capita in the data. We discuss implications for policy, concluding that governments can play a catalytic role in stimulating green innovation while the role of central banks is limited.

JEL classification: E5, G1, O4, Q5.

Keywords: Climate change, financial markets, directed technical change, public policy, central banks.

Non-technical summary

The reduction in carbon emissions necessary to limit global warming to at most 1.5°C above pre-industrial levels requires the application of climate technologies that are not available, yet. In this paper, we describe the state of "green" innovation and identify the set of factors necessary for the development of new low-carbon technologies in manufacturing, transportation, agriculture, and energy generation on a large enough scale to tackle the climate crisis. We then describe the state of these factors in the EU and discuss the role government and monetary policy can play to facilitate "green" innovation.

The main conclusions of the analysis are the following:

First, the long-run rate of patenting of "green" technologies in the EU lags behind selected peers: it is three times lower than in the US, and four times lower than in Japan. Moreover, there is substantial heterogeneity across EU member states: some are global leaders in patented "green" technologies, while one-third of the EU member states have less than one "green" patent per million population per year.

Second, we develop a model of directed technical change to identify the financial and policy factors that are necessary for a healthy rate of "green" innovation. The model concludes that variation in the level of green innovation can be explained by variation in three main factors: carbon taxes, investment in research and development (R&D), and the mix between equity and debt investment.

Third, we show that there is large scope in the EU to improve upon all factors that promote "green" innovation. Relative to selected peers, EU countries on average have low levels of R&D investment and low levels of early- and later-stage Venture Capital financing.

Moreover, as of end-2021, only 11 EU member states have some form of carbon tax, and those that do tax carbon below the levels recommended by economists.

Fourth, and given these observations, we argue that stimulating green innovation falls squarely in the realm of government policies. Among these are higher carbon taxes and more stringent environmental policies, higher R&D subsidies for “green” applied science, and a Capital Markets Union with a strong equity component to promote venture capital.

Fifth, we consider the effectiveness of central bank policies to stimulate “green” innovation. We argue that the ECB’s monetary policy tools have limited effectiveness because they face legal and economic obstacles. For one, green monetary policies by the ECB need to be consistent with the primary mandate of price stability, and its operations need to comply with the concepts of market neutrality and the application of appropriate risk controls. More importantly, central bank policies that transmit to the real economy through the bank lending channel have no effect on the development of patented “green” technologies because banks do not materially contribute to innovation in new technologies. To the extent that bond financing is a form of debt and not of equity, purchasing green bonds is unlikely to contribute significantly to green “innovation,” either. We conclude that facilitating the development of new low-carbon technologies in Europe requires bold government action to support green innovation, and that the ECB can at best play a supportive role.

1. Introduction

In 2015, the signatories of the Paris Agreement pledged to enact policies aimed at keeping temperatures below 1.5°C degrees above pre-industrial levels. Achieving this goal necessitates a reduction of at least 7.6% in greenhouse gas emissions per year, each year until 2030 (UNEP, 2019). There are two options for how to fulfil this pledge. The first one is to dramatically reduce their consumption of goods whose production, processing, and delivery are associated with emissions of greenhouse gases in the atmosphere. The necessary reduction in annual economic activity exceeds that recorded during the covid-19 pandemic.[2] The second is to continue consuming those same goods, but to make sure that they are produced and delivered using low-carbon technologies, a process known as the “green transition."

Given the challenges to the first option, and to limit the necessary reduction in consumption, policy makers have trained their focus on policies that will generate a rapid and large-scale shift from carbon-intensive to low-carbon technologies. It is widely assumed that with the right policies in places, this can be done. After all, humanity has in the past solved similar problems by similar means, as witnessed by the timely replacement during the 1980s and 1990s of chlorofluorocarbons in industrial processes, with technological alternatives that did not deplete the Earth's ozone layer (see Dugoua, 2021). Moreover, a number of low-carbon technologies, like personal electric vehicles, renewables in energy generation, and lab-grown meat, are already widely availability. This creates the impression that the obstacles to the green transition are not technological, but rather political, and that

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[2] Estimates put the decline in greenhouse gas emissions during 2020 between 5.4% and 6.4% (Liu et al., 2020; Global Carbon Project, 2021).

once the right government policies are put in place, the diffusion of green technologies in the economy will arrest the climate crisis.

This optimism overlooks a grim reality: for a substantial share of the global economy, low-carbon technological alternatives either do not exist or are at early stages of development.[3] For example, metallurgy, which generates around 8% of global carbon emissions, relies on an industrial process whereby iron ore is melted at temperatures of around 1,800 degrees Celsius. At present, the only way to do that at a large enough scale is by burning fossil fuels. The same goes for cement production which generates around 7% of global carbon emissions and which is based on a technological process whereby flame temperatures of about 2,000 degrees Celsius are required to convert a mix of clay and limestone into cement. Similarly, the electric batteries that can power relatively lightweight personal vehicles at present cannot be used in freight transportation, air transportation, and water transportation, which collectively generate around 11% of global carbon emissions. While green technological alternatives to marine and aviation fuel exist, they are not commercially viable yet (e.g., Al-Enazi et al., 2021). And rising energy requirements demand breakthrough developments in a range of primary energy sources, such as solar power satellites, biomass, and nuclear fission and fusion (Hoffert et al., 2002; Barrett, 2009).

Achieving the green transition in time requires a climate-technology revolution in manufacturing, transportation, agriculture, and energy generation. The alternatives are not

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[3] This reality is recognized by policy makers. John Kerry, the US climate envoy, argued that "50% of the reductions [in carbon emissions] we have to make to get to net zero by 2050 are going to come from technologies that we don't yet have." https://www.bbc.com/news/av/science-environment-57134655 The Government of Denmark has vowed to make domestic flights fossil fuel free by 2030 while acknowledging that achieving this target "would be difficult, but researchers and companies were working on solutions." https://www.bbc.com/news/world-europe-59849898

viable. For example, if the US was to fulfil the commitments embedded in the Paris Agreement only by reforming energy generation with existing renewable technologies, it would need to build an equivalent to the biggest solar farm and the biggest wind farm currently in operation, each week for the next 15 years (Stock, 2021).

In this paper, we discuss the factors that need to be in place for the kind of rapid green technological innovation that the "green transition" requires. In particular, we discuss how financial markets and climate policies interact to promote the development of green technologies. To that end, we analyse comprehensive global data on green patents since the 1970s.

We show that on average, green patents per capita in the EU are rather low relative to selected peers: three times lower than in the US, and four times lower than in Japan. Moreover, there is substantial heterogeneity across countries: some countries (e.g., Denmark) are global leaders in patented green technologies, while one-third of the EU member states have less than one green patent per million population per year.

We motivate the relatively low level of green innovation in Europe with a model of directed technical change. We model a world where consumers derive utility from a clean environment and from a final consumption good. The latter is produced using high- and low-carbon intermediary goods. Successful innovation in the intermediary goods sector leads to the replacement of mature with new, more energy-efficient technologies. Intermediary goods production is funded by relationship lenders (banks) who have comparative advantage in monitoring mature technologies, and by transaction lenders (Venture Capitalists, or VCs) who have comparative advantage in monitoring new technologies. We show that in this world, low levels of green innovation can be explained by suboptimally low carbon taxes, inadequate research and development (R&D) investment, and the relative undersupply of equity, as opposed to debt, financing.

We then take the model to the data and study which of the drivers identified in the model explains the observed relatively low levels of green innovation in Europe. We document two primary empirical facts. First, relative to selected peers, EU countries on average have low R&D investment and low levels of VC activity. Second, higher R&D and higher VC investment predict strongly future green patent counts. These two factors therefore explain well the low levels of innovation in low-carbon technologies in the EU. We show that if all EU countries had the VC investment levels and the R&D investment levels of the top EU member state (Sweden and Finland, respectively), average green patents per capita in the EU today would be at levels comparable with the US and Japan.

Moreover, as of end-2021, only 11 EU member states have some form of carbon tax, and those that do tax carbon below the levels recommended by economists. We show that countries with a carbon tax tend to generate more green patents. Combined with evidence at the firm level (e.g., Aghion, Dechezleprêtre, Hémous, Martin, and Van Reenen, 2016), this supports the notion that carbon taxes stimulate green technological innovation by aligning market participants' private incentives with social environmental goals.

The analysis strongly supports the idea that stimulating green innovation falls in the realm of government policies. Among these are higher carbon taxes and more stringent environmental policies, higher R&D subsidies for green applied science, and a Capital Markets Union with a strong equity component to promote venture capital. These insights are fully consistent with the views of members of the broad research and policy making community, according to whom carbon taxes, government subsidies, and venture capital are the three most important perceived forces for change when it comes to the green transition (Stroebel and Wurgler, 2021).

We then consider the effectiveness of central bank policies to stimulate green innovation, focusing on the European Central Bank (ECB). Central banks have recently come into focus because of their large footprint in financial markets through asset purchases and lending operations, and there have been growing calls for central banks to support the green transition. Central banks have in principle several tools at their disposal to stimulate green innovation, including through banking supervision, collateral policy, and asset purchases. However, we conclude that these tools have limited effectiveness because they face legal and economic obstacles. First, green monetary policies are legally limited by existing central bank mandates and operational frameworks. In the case of the ECB, any monetary policy action needs to be consistent with the primary mandate of price stability, and central bank operations need to comply with the concepts of market neutrality and the application of appropriate risk controls. This implies that an active tilting of central bank interventions toward green assets, either through lending operations or asset purchases, is severely limited. Second, central bank policies that transmit to the real economy through the bank lending channels have no material effect on the development of patented green technologies because banks do not materially contribute to innovation in new technologies. Examples of such policies include penalizing fossil-heavy assets in bank supervision, changing the carbon mix of assets that banks use as collateral in liquidity operations, and targeted lending operations (“green TLTRO”). Third, to the extent that bond financing is a form of debt and not of equity, according to the model purchasing green bonds would also achieve little in the way of stimulating green innovation. This notion is supported by recent evidence which does not point to an unequivocal positive effect of green bond issuance on firm-level pollution (e.g., Ehlers, Mojon, and Packer, 2020; Flammer, 2021). In practice, this leaves little room for an active green monetary policy whereby the central bank would intervene disproportionately in private asset markets to promote green innovation.

We conclude that facilitating the development of new low-carbon technologies in Europe requires bold government action to support green innovation. Governments should actively promote venture capital markets, raise carbon taxes, and subsidize R&D investments to promote green innovation. Contrary to government policies, central bank actions face obstacles from both a legal and an economic perspective. Central bank policies that operate by supporting bond financing or encouraging bank lending are not effective in stimulating innovation. Still, the ECB can reinforce government actions to promote the "green transition" by modifying supervisory standards and adjusting the implementation of monetary policies to the extent that such policies are consistent with the ECB's legal and operational framework. Examples of such policies include enhancing disclosure requirements of climate risks by banks and firms eligible for asset purchases, adjusting prudential frameworks to reflect climate risks, and purchasing green sovereign bonds through the ECB's asset purchase programme.

The paper proceeds as follows. In Section 2, we review the related literature. In Section 3, we summarize the state of patented green innovation in the EU. In Section 4, we summarize the Model, which is formally spelled out in the Appendix. In Section 5, we summarize the empirical evidence. In Section 6, we discuss implications for government and monetary policy. Section 7 concludes.

2. Financial development, financial structure, and growth: Literature review

Recent surveys have typically concluded that financial development is supportive of economic development, and that this applies both to bank finance and to market finance.[4] That these two, independent components of the financial system individually shape growth is one of the most remarkable insights from the finance-and-growth literature. More recent work has focused on the question, does the financial structure—or the mix of financial markets and intermediaries operating in an economy—affect economic growth? Put alternatively, are markets or banks better at promoting growth, and does their contribution to growth vary with the country's degree of economic and financial development?

Early research concluded that there was no general rule that bank-based or market-based financial systems were better at fostering growth. What is particularly noteworthy is that this conclusion was reached using both aggregate data (Arestis, Demetriades, and Liuntel, 2001; Levine, 2002), sector-level data (Beck and Levine, 2002; 2004), and firm-level data (e.g., Demirguc-Kunt and Maksimovic, 2002). In all such cases, researchers found that the degree to which countries are bank-based or market-based did not help explain growth. The earlier finance-and-growth literature thus concluded that financial structure was not so important for economic development. If advanced economies had different financial structures, but similar levels of development, then banks and markets mattered equally for economic growth.

More recent research however has suggested that equity markets appear to matter considerably more for growth than banks. For example, in a sample of 48 countries, Shen and Lee (2006) find evidence that only stock market development has a positive effect, and

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[4] See Beck (2008), Levine (2005), and Popov (2018).

that banking development has an unfavorable, if not negative, effect on growth. Focusing on the European experience, Langfield and Pagano (2016) report a negative association between economic growth and the ratio of bank to market-based intermediation. While this result may be due to the outsized development of some European banking systems and adverse effects of large-scale housing financing, the more limited impact of banking on growth as income rises appears to be more general.

While both bank-based and market-based financial systems support economic growth on average, their contribution may vary with the extent of economic and financial development. Early evidence from Tadesse (2002) suggests that while market-based systems outperform bank-based systems among countries with developed financial sectors, bank-based systems are far better among countries with underdeveloped financial sectors. In a more recent empirical contribution, Demirguc-Kunt, Feyen, and Levine (2013) use a large cross-country sample and show that as countries develop economically, the association between an increase in economic output and an increase in bank development becomes smaller, and the association between an increase in economic output and an increase in securities market development becomes larger. Gambacorta, Yang, and Tsatsaronis (2014) study relationships between per capita economic growth and various forms of finance, and document diminishing effects of banking at higher levels of development and increasing effects of securities markets.

Recent research has also found that capital markets induce greater productivity gains, innovation, and technological change than banking markets. For example, Hsu, Tiang, and Xu (2014) use a large data set that includes 32 developed and emerging countries and a fixed effects identification strategy, to identify the economic mechanisms through which the development of equity markets and credit markets affects technological innovation. They show that industries that are more high-tech intensive exhibit a disproportionately higher innovation level in countries with better developed equity markets. Brown, Martinsson, and Petersen (2017) document a strong positive relation between the initial size of the country's high-tech sector and subsequent rates of GDP and total factor productivity growth in a sample of 38 countries. They also find a strong positive connection between a country's equity (but not credit) market development and the size of its high-tech sector. Their estimates show that better developed stock markets support faster growth of innovative-intensive, high-tech industries via higher rates of productivity and faster growth in the number of new high-tech firms. These findings confirm the notion that stock markets and credit markets play important but distinct roles in supporting economic growth, with stock markets uniquely suited for financing technology-led growth.

We can conclude that as economies develop, the services provided by securities markets become more important for economic activity, whereas those provided by banks become less important.[5] As per capita income rises, countries' financial structures tend to move towards non-bank financing. Market-based intermediation has thus grown faster than bank-based one, notably in advanced countries, also due to advances in technology, the greater availability and use of hard information, and more internationalized financial systems.

Closest to our objective, recent evidence has demonstrated that economies which get relatively more of their funding from equity markets as opposed to debt markets, decarbonize faster. De Haas and Popov (2022) use a novel data set of output, carbon

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[5] For a comprehensive review of the literature on the costs and benefits of developing capital markets, see Laeven (2014).

emissions, and green patents for 16 industries in 48 countries during the period 1990—2015 to study how countries' financial structure—i.e., the importance of stock markets relative to bank-based financial intermediation—affects their transition to low-carbon growth. They find that for a given level of economic and financial development and environmental regulation, carbon emissions per capita decline faster in economies that receive a higher share of their funding from stock markets. Industry-level analysis reveals two channels. First, deeper stock markets reallocate investment towards energy-efficient sectors, reducing the share of output generated by carbon-intensive sectors. Second, in countries with deeper stock markets, firms in carbon-intensive sectors engage in more green innovation, which results in lower carbon emissions per unit of output. Relative to this study, we look at the interaction of financial markets and public policy, and we focus on the evolution of green patents.

Our analysis also contributes to the literature that has looked at endogenous technology growth in the presence of limited resources or climate policies. Early contributions include Bovenberg and Smulders (1995), Aghion and Howitt (1998), Barbier (1999), Scholz and Ziemes (1999), Grimaud and Rouge (2003), and Groth and Shou (2007). The main focus of these papers is on whether output growth is bound to stop, or even reverse, and whether market outcomes are optimal. In the same vein, Hassler, Krusell, and Olovsson (2021a) analyse directed technical change in the presence of finite natural resources and find evidence for rapid energy-saving technical change in the wake of the 1970s oil shocks. The conclusion in this literature is that both market forces and climate policies play a role in arresting environmental degradation.

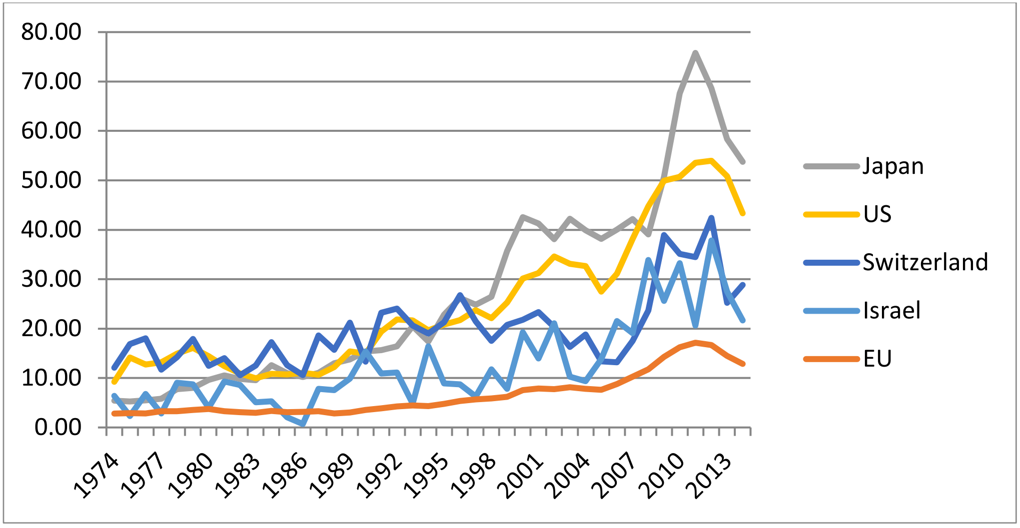
3. State of green innovation in the EU

We document the development of low-carbon technologies by examining data on patents linked to low-carbon technologies ("green" patents). To that end, we use PATSTAT, the Patent Statistical database of the European Patent Office (EPO). Because of a multi-year delays in data processing in PATSTAT, our patent data end in 2015. We follow the methodological guidelines of the OECD Patent Statistics Manual and take the year of the priority filing as the reference year. If a patent does not have a priority filling, the reference year is the year of the application filling. This ensures that we closely track the timing of inventive performance. We take the country of residence of the inventor as the reference country. If a patent has multiple inventors from different countries, we use fractional counts: each country is attributed a corresponding share of the patent. Every patent indicator is based on data from a single patent office and we use the United States as the primary patent office.

PATSTAT classifies each patent according to the International Patent Classification (IPC). We round this classification to 4-character IPC codes and use the concordance table of Lybbert and Zolas (2014) to convert these codes into ISIC 2-digit sectors. We then use these data to construct the variable ‘Green patents’, which counts all patents granted to a particular country, sector, and year and that belong to the EPO Y02/Y04S climate change mitigation technology (CCMT) tagging scheme. CCMTs include all technological inventions to reduce the amount of greenhouse gas emitted when producing or consuming energy. The scheme is the most reliable method for identifying green patents and has become the standard in studies on green innovation (Popp, 2019). “Green patents” thus include technologies related to transportation and waste, industrial production, and energy efficiency of the industrial production or processing of goods.

The first fact we uncover is that the number of green patents per capita increased globally until 2011-2012, after which it started declining (see Figure 1). The reasons for this decline are poorly understood. One prominent explanation by Acemoglu, Aghion, Barrage, and Hemous (2021) is that the fracking revolution in the US reduced market incentives to invest in renewable sources of energy by permanently lowering the market price of liquid gas.

Figure 1. Green patents per million, 1974—2014

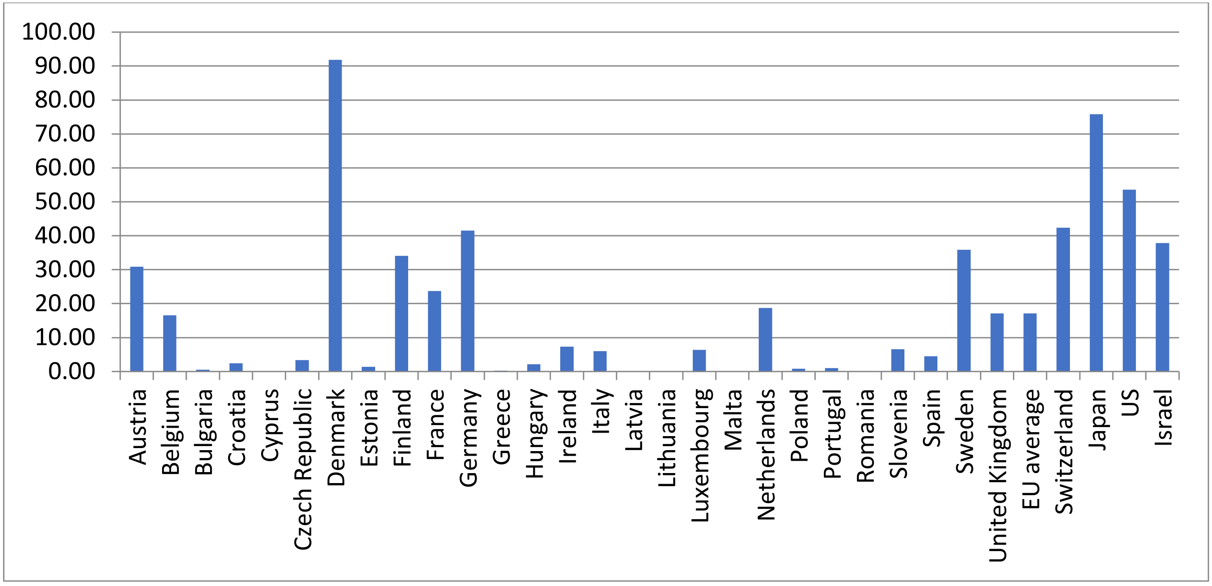


Source: PATSTAT and authors' calculations

The second fact we document is that on average, EU countries lag behind selected peers in patented innovation per capita. As Figure 1 demonstrates, at the peak of green innovation in 2011, there were 16.7 green patents per 1 million in the EU. In comparison, there were more than twice as many green patents in Israel and in Switzerland (37.8 and 42.4, respectively); more than three times as many green patents in the US (54.0); and more than four times as many green patents in Japan (68.6).

The third fact is that there is enormous heterogeneity across EU member states in the propensity to patent green technologies. This is captured by Figure 2. At the one extreme is Denmark, a solid global leader in the field of renewables. At 92 green patents per 1 million population in 2011, it is ahead of all selected peers. There are four other EU member states (Austria, Finland, Germany, and Sweden) that are solid innovators in the field of green technologies, with more than 30 green patents per 1 million population, at par with countries like Israel and Switzerland. At the same time, 1/3 of EU countries registered less than 1 green patent per 1 million population.

Figure 2. Green patents per million, 2011



Source: PATSTAT and authors’ calculations

4. A model of finance, policy, and green innovation

We motivate these findings with a model of directed technical change based on Acemoglu, Aghion, Burzstyn, and Hemous (2012) in which we introduce a financial sector. We present a summary of the model's set-up and findings here; the full-fledged model can be found in the Appendix.

In the model, consumers derive utility from a consumption good and from a high-quality environment. The final good is produced using two intermediary goods, one low- and one high-carbon. Production of the high-carbon good degrades the environment, production of the low-carbon one does not.

Innovation in both sectors is done by scientist-entrepreneurs. At the beginning of every period, each scientist decides whether to direct her research to low- or high-carbon technology. A successful scientist who has invented a better technology in any of the two sectors obtains a one-period patent and becomes the entrepreneur for the current period in the production of machines in this sector. In other words, innovation is based on a quality ladder as in Aghion and Howitt (1990) as opposed to expanding varieties as in Romer (1990). In sectors where innovation is not successful, monopoly rights are allocated randomly to an entrepreneur drawn from the pool of potential entrepreneurs, who then uses the old (mature) technology.

Machine producers can finance their operations by borrowing, either from a relationship lender (such as a bank) or from a transaction lender (such as a VC). There is one representative investor in each sector, and investors are risk-neutral. As in Diamond and Rajan (2001) and Minetti (2010), investors monitor entrepreneurs and by doing so, learn to extract value from the firm's assets. Relationship lenders have a lower cost of monitoring mature technologies with which they have experience. Transaction lenders have a lower cost of monitoring new technologies.[6] Both types of investors direct their investment either to the low- or high-carbon sector and observe if innovation was successful before making their

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[6] This modelling choice is in line with mainstream finance research which argues that venture capitalists have a comparative advantage in funding risky, new ventures, due to the informational and contracting problems associated with debt finance, including bank loans (Leland and Pyle, 1977; De Meza and Webb, 1987).

investment choice. Also, with a certain probability production fails, and the assets are liquidated.

There are three types of policies in the model: taxes, subsidies, and central bank operations. First, governments can impose taxes on intermediary inputs, making the production of the high- or the low-carbon good more expensive. Second, governments can also provide subsidies in one or both the sectors, making innovation in the sector of choice more likely.[7] Finally, central banks can lend to relationship lenders, reducing their cost of monitoring.

In equilibrium, the production of new machines is funded by a transaction lender, and the production of old machines is funded by a relationship lender. Transaction lenders thus fund new machines in both high- and low-carbon sectors, and relationship lenders fund mature machines in both high- and low-carbon sectors.

Tax policy can change the allocation of investment to machines in high- vs. low-carbon sectors. With higher taxes on high-carbon inputs, transaction lenders will have an incentive to invest more in new low-carbon technologies, and relationship lenders will have an incentive to invest more in mature low-carbon technologies. However, tax policy alone cannot incentivize relationship lenders to increase investment in new low-carbon, and reduce investment in new high-carbon, technologies because relationship lenders do not invest in new technologies to begin with.

R&D policy can also affect the allocation of investment to high-carbon versus low-carbon technologies. With higher subsidies for low-carbon R&D, research is redirected

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[7] Howell (2017) shows that government early-stage R&D subsidies increase the likelihood that a firm receives subsequent VC and have a large, positive impact on patenting.

towards the low-carbon sector. As a result, innovation in the low-carbon sector becomes more likely. Similar to the case of taxes, R&D policy alone cannot incentivize relationship lenders to invest in low-carbon machines.

Finally, central banks can engage in a range of policies that can tilt the clean-dirty mix of mature technologies that relationship lenders fund. For example, a central bank can increase the cost to banks of holding carbon-intensive assets on their portfolios, e.g. through haircuts or changes in supervisory requirements. This will increase the cost of monitoring for relationship lenders in the case of high-carbon machines, and in turn sharpen the incentives to adopt mature low-carbon technologies.

At the same time, conventional central bank policy cannot change the mix of new low- versus high-carbon technologies. The reason is that new technologies (both low- and high-carbon) are only funded by transaction lenders, and not by relationship lenders, because new technologies cannot be collateralized. At the same time, by assumption transaction lenders do not have access to central bank liquidity because the true value of transaction loans (equity claims) is difficult to establish, therefore these are not acceptable within existing collateral rules.

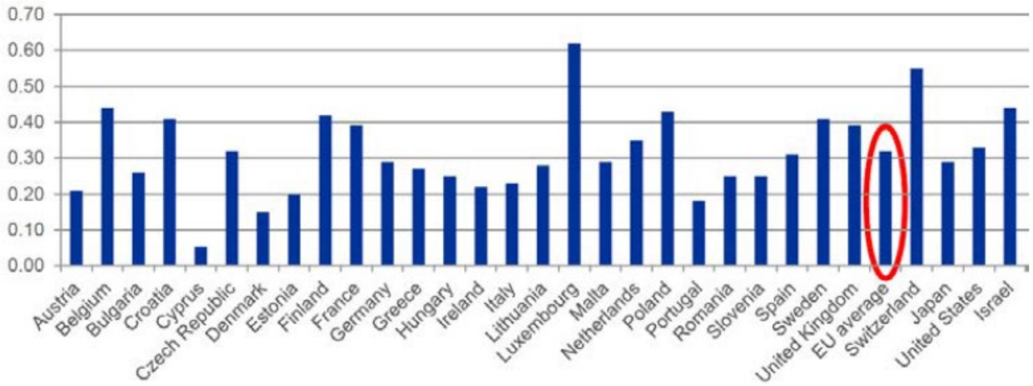
5. Financial structure, climate policy, and green innovation in the EU: Empirical facts

In this section, we provide empirical support for the theoretical mechanisms identified in the previous section, focusing on data from the EU. First, we evaluate the link between financial structure and green innovation. Next, we study the relation between R&D investment and the propensity to green technologies. Finally, we provide some tentative evidence for the effect of carbon taxes on green innovation. Along the way, we also discuss the role that green bonds have played in green patented innovation, as well as the evolution of the mix between high- and low-carbon assets in the European banking sector.

In Figures 3 and 4, we present evidence on financial structure and green patented innovation during the period 2005—2014. Financial structure is defined as the share, out of total financial intermediation, of the country's stock market capitalization. This variable is thus a proxy for how equity-based the country's economy is, or alternatively, for the share of funding that the country's economy received from equity investors.

On average, the EU is not far behind selected peers in terms of the share of equity intermediation. As Figure 3 demonstrates, EU countries get on average around 1/3 of their funding from equity investors, which is more than Japan and almost at par with the United States. In addition, there are a number of countries in the EU which fare very favourably in this respect, getting between 40% and 50% of their funding from equity investors (e.g., Belgium, Finland, and Sweden). At the other extreme, in a number of countries, equity investment is less than 20% of total intermediation (e.g., Cyprus, Denmark, and Portugal).

Figure 3. Equity / (Credit + Equity) in EU, 2005—2014



Source: World Bank’s Financial Structure Database

A higher share of equity investment is associated with higher rates of green innovation. In Figure 4, we plot per-capita green patents against financial structure over the same sample period. A positive correlation readily emerges: higher share of equity investment over the period 2005—2014 is associated with higher per-capita green patents. In a univariate regression sense, moving a country from the 25th to the 75th percentile of financial structure (0.26 to 0.41) increases green innovation by half a sample standard deviation. This effect is significant at the 5-percent statistical level.

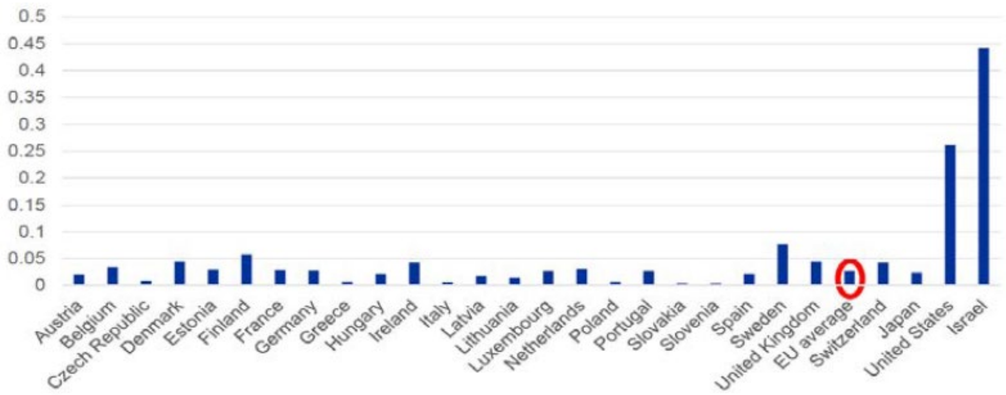
Figure 4. Financial structure and green innovation in EU, 2005—2014

Source: World Bank's Financial Structure Database and PATSTAT

We also record a strong positive relationship between private equity investment and green innovation. In Figures 5 and 6, we revisit the same question, but this time we focus on average annual VC investment, normalized by GDP, in the country over the period 2005—2014. It is a well-established fact in the literature that VC is the type of financing that is best suited to the financing of innovation (e.g., Kaplan and Stromberg, 2003). In a seminal study, Kortum and Lerner (2000) show that the dramatic increase in VC financing during the 1980s and early 1990s in the US was associated with a material increase in the rates of industrial innovation. Controlling for public and private R&D investment, their estimates imply that while the ratio of VC to R&D averaged less than 3% from 1983 to 1992, venture capital accounted for about 8% of industrial innovation in that period. At the same time, more recent studies have questioned whether this result can be transposed to other empirical settings. For example, Popov and Roosenboom (2012) find that the effect of VC on innovation does not hold in a large sample of 21 European countries over a later period (1991—2005), suggesting that the success of the US VC industry during the 1980s and 1990s cannot be easily exported abroad. The effect of VC on green innovation in a European setting thus remains an open empirical question.

Unlike overall equity investment, VC investment is relatively low in Europe. Figure 5 plots VC investment, in percentage points and normalized by GDP, for EU countries and selected peers. Average VC investment in the EU is around 0.025 percent of GDP, which is 10 times less than in the US and 15 times less than in Israel (the global leader in VC investment per capita). At the same time, in a number of EU member states (e.g., Denmark, Finland, Ireland, and Sweden), VC investment is at par or higher, as a share of GDP, than in both Switzerland and Japan.

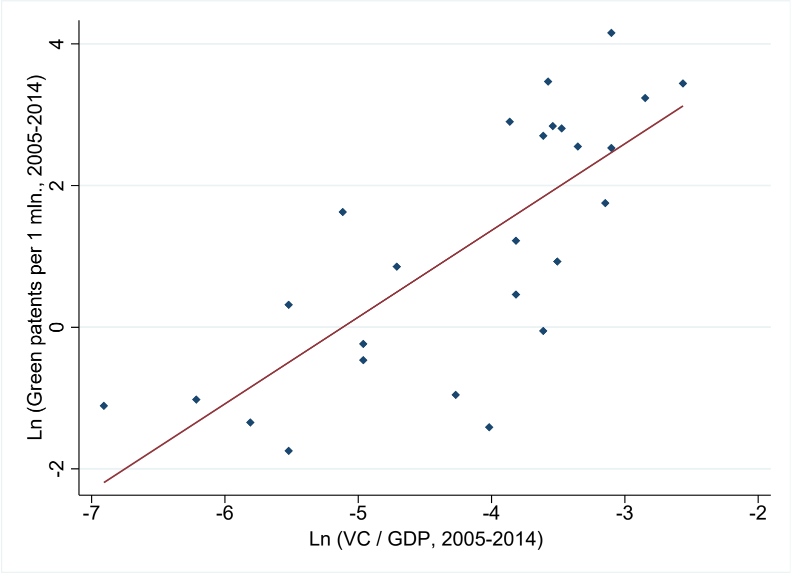
Figure 5. VC / GDP in EU, 2005—2014



Source: European Venture Capital Association and Eurostat

At the same time, higher levels of VC investment are strongly associated with higher rates of green innovation. In Figure 6, we plot per-capita green patents against average VC investment over the period 2005--2014. A positive correlation emerges, and it is much stronger than in the previous case. In a univariate regression sense, moving a country from the 25th to the 75th percentile of VC investment (0.006 to 0.030) increases green innovation by almost one sample standard deviation, which is significant at the 1-percent statistical level.

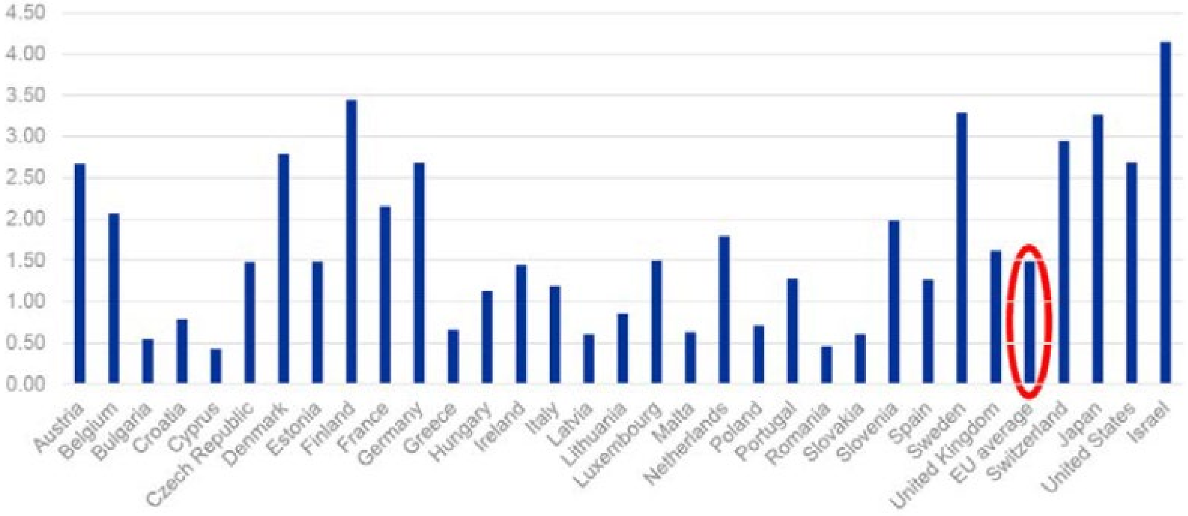
Figure 6. VC investment and green innovation in EU, 2005—2014



Source: European Venture Capital Association, Eurostat and PATSTAT

In terms of R&D investment, it is once again heterogeneous and relatively low in the EU. Figure 7 plots R&D investment, in percentage points and normalized by GDP, for EU countries and selected peers. R&D investment in most EU member states turns out to be relatively low. Average R&D investment in the EU over the period 2005--2014 is around 1.5 percent of GDP, half or less of what Japan, Israel, Switzerland, and the US spend. Once again, a number of EU member states spend as much as the global leaders (e.g., Austria, Denmark, Finland, Germany, and Sweden), but almost half of EU member states devote less than 1% of GDP to R&D investment. This is well below the 3% target set by the Lisbon Strategy.

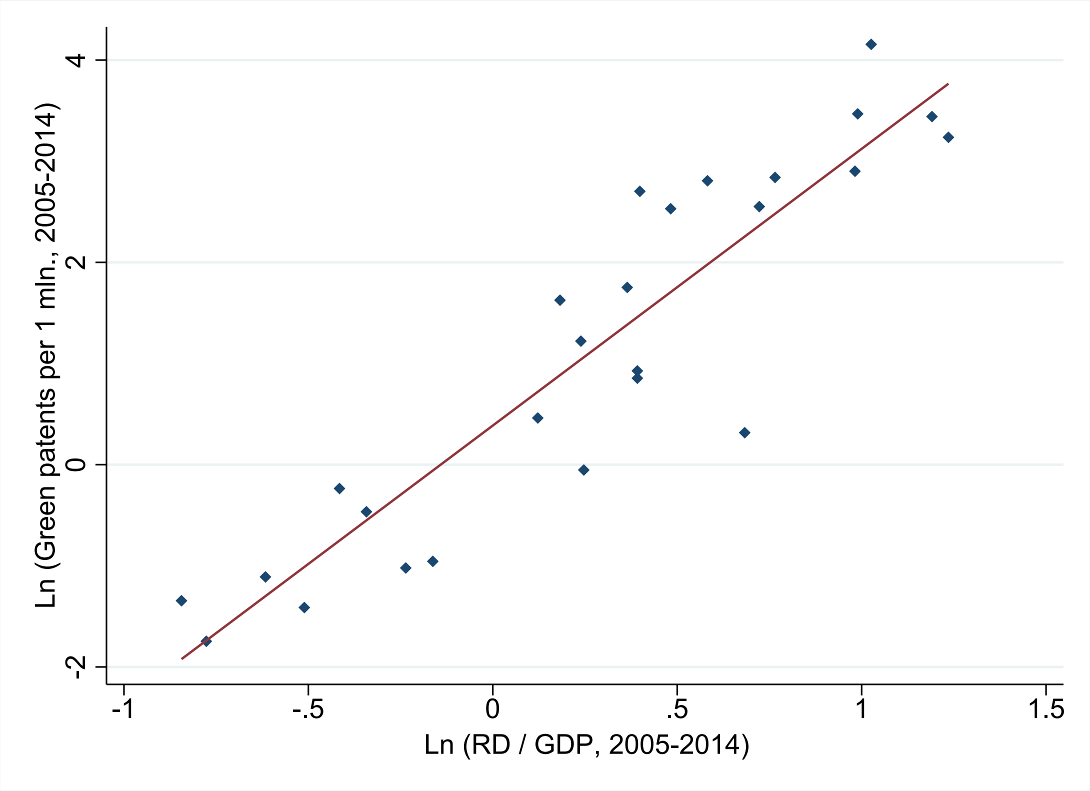
Figure 7. R&D investment / GDP in EU, 2005—2014



Source: Eurostat

Finally, there is an even stronger positive effect of higher R&D investment on green innovation. In Figure 8, we plot per-capita green patents against average R&D investment over the period 2005—2014. The positive correlation between the two series is remarkably strong, with the R-squared of the univariate regression at 0.78. The point estimates imply that moving a country from the 25th to the 75th percentile of R&D investment (0.71 to 1.98) increases green innovation by more than one sample standard deviation. This effect is significant at the 1-percent statistical level.

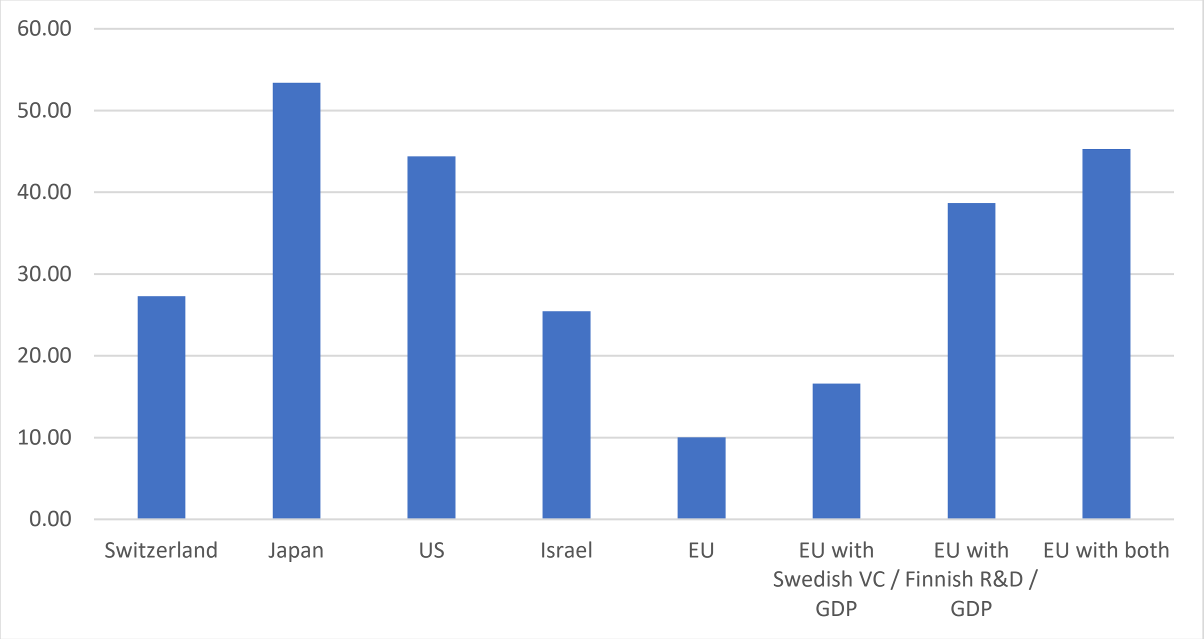
Figure 8. R&D and green innovation in EU, 2005—2014



Source: Eurostat and PATSTAT

The evidence presented so far gives to the natural question: how much higher would green innovation be in the EU if individual members states had higher VC and R&D investment? We evaluate this question based on the point estimates from a regression of green patents on R&D investment and VC investment. Figure 9 summarizes this exercise. The first four bars plot average patents per million for Switzerland, Japan, the US, and Israel over the period 2005—2014. The fifth bar shows the average number of green patents per capita in the EU for the same period. In the sixth bar, we recalculate this number assuming that each EU member state had the level of VC investment in the top country (Sweden). In the seventh bar, we recalculate this number assuming that each EU member state had the level of R&D investment in the top country (Finland). Finally, in the last bar, we recalculate this number assuming that each EU member state had both the level of VC investment of Sweden and the level of R&D investment of Finland. Figure 9 makes it clear that with more VC and R&D investment, EU innovation increases substantially. In the latter case, it is more than 50% higher than in Switzerland or Israel, and at par with the US.

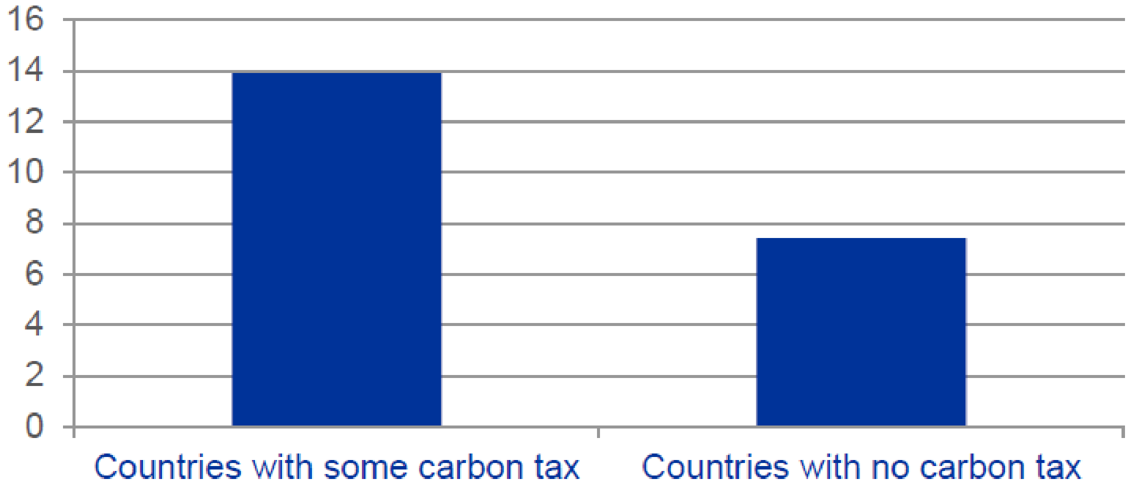
Figure 9. Green innovation in EU under difference scenarios, 2005—2014



Source: European Venture Capital Association, Eurostat, PATSTAT, and authors' calculations

Carbon taxes appear to be weakly associated with higher rates of green innovation in the EU context. In Figure 10, we split the EU member states in those with and those without a carbon tax as of end-2020 and compare the average propensity to produce green patents across the two groups. The data suggest that countries with a carbon tax have almost twice as high green patents per capita than countries without a carbon tax. Clearly, just like the previous exercises, this one does not produce a causal claim. Nevertheless, it supports firm-level evidence that taxes on fossil fuels tend to push firms to improve their energy efficiency and to increase their investment in green technologies (Aghion, Dechezleprêtre, Hémous, Martin, and Van Reenen, 2015).[8]

Figure 10. Carbon taxes and green patents per million in EU, 2005—2014



Source: European Commission and PATSTAT.

One additional consideration concerns the role that green bonds can play in the green transition. Policy makers are placing high hopes in the green bond market. Box 1 discusses the development of this market in recent years and evaluates the evidence regarding the ability of green bonds to finance green innovation. While there is some evidence to that end, it is at this point economically inconclusive, and more research is needed in the future to provide a fuller picture.

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[8] Hassler, Olovsson, and Krussel (2021b) show that the cost of setting carbon taxes too high are dwarfed in the long run by the cost of setting them too high.

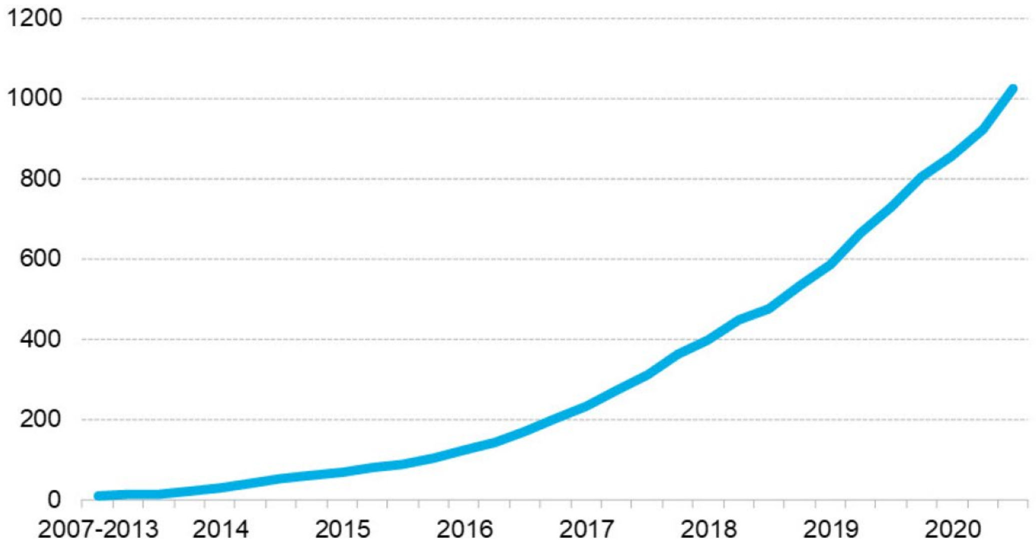
Box 1. Green bonds and green innovation

"Green bonds" are defined as bonds the proceeds from which are committed to financing environmental and climate-friendly projects, such as renewable energy, green buildings, or resource conservation. The first green bond was issued in 2007 by the European Investment Bank. It had a maturity of 5 years and value of €600 million. Since its debut, the market for green bonds has been increasing steadily, as Figure 1 shows. The blue line represents the total cumulative value of green bonds issued. In reaching this cumulative $1 trillion issuance milestone, green bonds have also pushed the wider sustainable debt market—which includes social bonds, sustainability-linked loans, green loans and others—over the $2 trillion mark.

Green bonds were the first sustainable debt instrument to catch investor attention a decade or more ago, but some of the others have been growing rapidly of late. In the first nine months of 2020, green bonds accounted for 47% of the sustainable debt issued worldwide. At the same time, and in relative terms, the market is still quite small in size compared to the market for conventional bonds (around 2.42% in 2018).

Private institutions have developed green bond certifications and standards that grant issuers a green label if individual projects are deemed sufficiently in line with the Green Bond Principles of the International Capital Market Association, and the use of proceeds can be ascertained.

Figure 1. Cumulative green bond issuance by year, 2007—2020, in billion USD

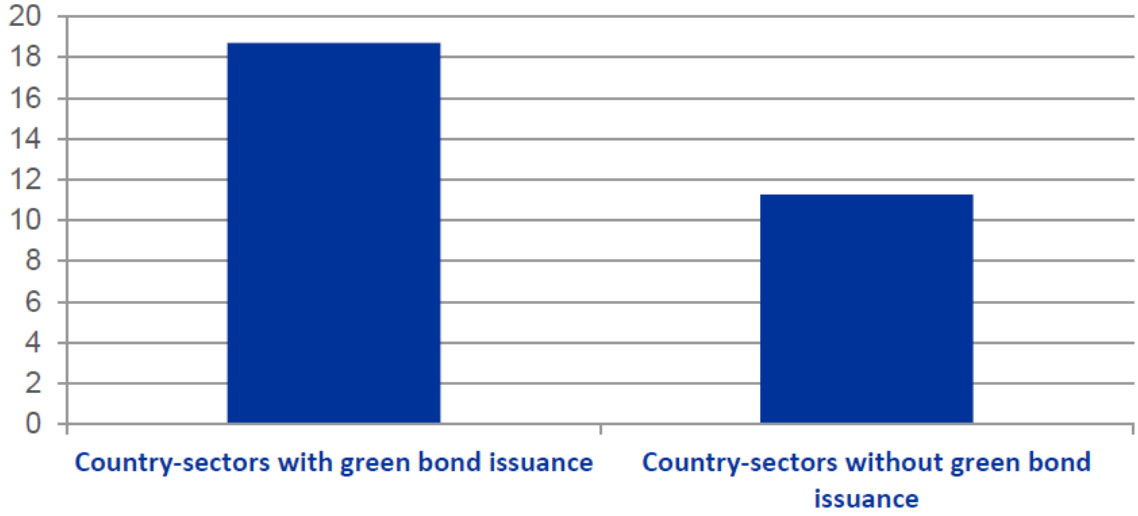


Source: Bloomberg

A key issue for both policymakers and investors is whether existing certifications and standards result in the desired environmental impact, i.e., low and decreasing carbon emissions. The overall effect, according to available evidence, is uncertain, reflecting the very few empirical analyses of this question. For example, Flammer (2021) shows that firms that issue green bonds reduce their emissions by 13%, compared with similar firms that do not, a sizeable effect. At the other extreme, Ehlers, Mojon, and Packer (2020) argue that so far, green bond projects have not necessarily translated into comparatively low or falling carbon emissions at the firm level. The available evidence thus suggests that the impact of green bond financing on firm-level carbon emissions is highly uncertain.

In Figure 2, we compare country-industries with and without green bond issuance, in terms of green patents, over the sample period 2007—2014. The Figure shows that in the EU, country-sectors that issued at least one green bond since 2007 have higher green innovation on average than country-sectors that did not.

Figure 2. Green patents per 1 million in EU, 2007—2014



Source: European Commission and PATSTAT.

The evidence thus points into the direction of green bonds being a viable way to finance green projects. Nevertheless, more future research is needed to establish whether the ability to issue a green bond increases green innovation, or whether firms that are about to invest in a green project find it profitable to do so by issuing a green bond.

Finally, the model predicts that banks will respond to climate policy by increasing the financing of *mature* green technologies, as opposed to that of *new* green technologies. Recent research has identified a slow decline in lending by global banks to fossil-fuel companies, especially after the Paris Agreement (e.g., Delis, De Greiff, Iosifidi, and Ongena, 2018; Altunbas, d'Acri, Marques-Ibanez, Reghezza, and Spaggiari, 2021). In Box 2, we evaluate this hypothesis using data form the ECB's Securities Holdings Statistics. The evidence indeed points to a slow-moving reduction in high-carbon asset holdings by European banks which became more pronounced after 2015.

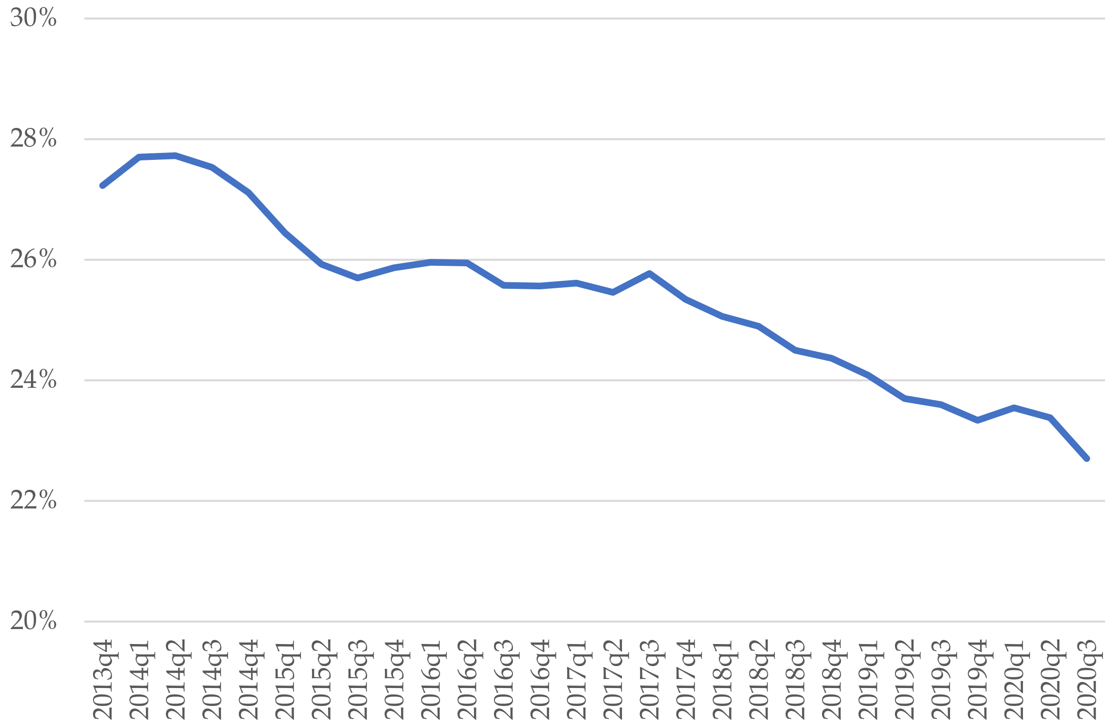
Box 2. High-carbon industry holdings by euro area banks: Evidence from the Securities Holdings Statistics

This box provides evidence on high-carbon industry securities holdings of euro area (EA) banks, based on the Eurosystem's Securities Holdings Statistics over the period from the fourth quarter of 2013 to the third quarter of 2020. The Eurosystem's Securities Holdings Statistics (SHS) data are available since the fourth quarter of 2013 and covers two main types of securities: debt securities and equity securities. The main feature of the data is that holdings information is collected at the level of each individual security, i.e. security-by-security. The SHS sector data provides information on holdings by different investor types. In our analysis, we focus on the holdings by the banking sector, banks for short. Our sample comprises quarterly data from Q4 2013 to Q3 2020.

For the high-carbon industry classification, we consider the following industries as high-carbon (ISIC industry classification in brackets): agriculture (1-5), chemicals (23-25), other non-metallic mineral products, which is primarily cement production (26), basic metals (27), power generation (40-41), and the three types of transportation (land 60, water 61, and air 62).

Figure 1 shows the evolution of high-carbon bank securities holdings as a share of total non-financial securities holdings. Over our sample period, high-carbon securities holdings of EA banks declined from just over 27 percent to just under 23 percent.

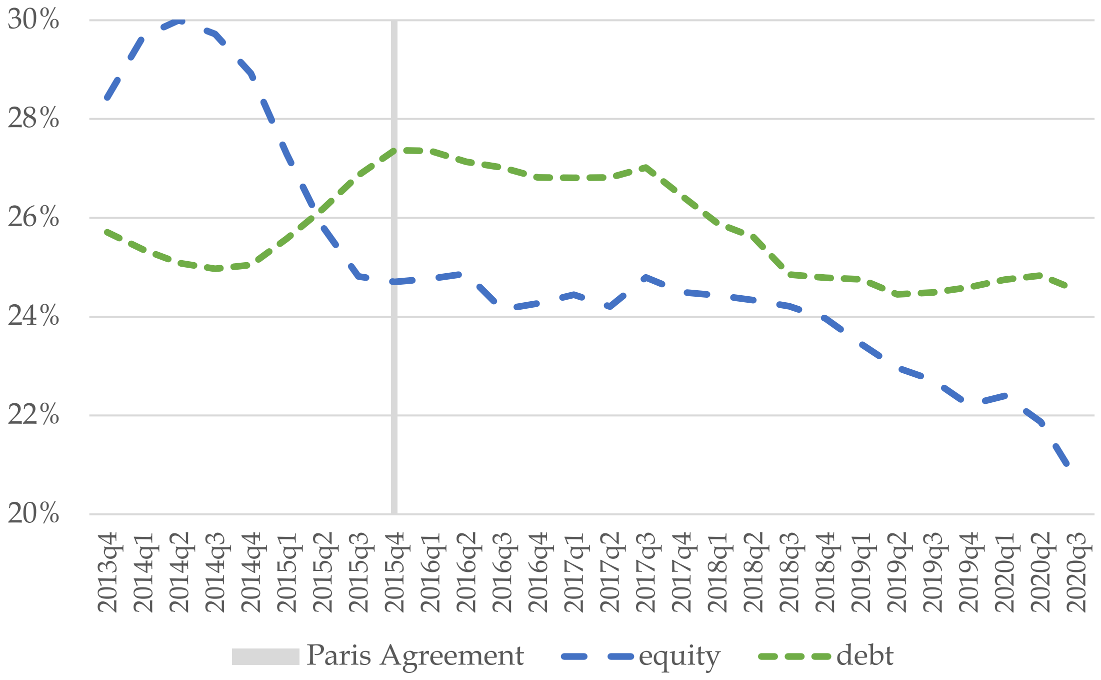
Figure 1: High-carbon bank securities holdings, Q4 2013 – Q3 2020



Notes: This figure shows the evolution of high-carbon bank securities holdings as a share in total non-financial securities holdings (4-quarter rolling window). The data spans Q4 2013 through Q3 2020. Source: Securities Holdings Statistics and authors' calculations.

Figure 2 shows the evolution of high-carbon bank equity and debt securities holdings as a share of total non-financial debt and equity securities holdings, respectively. High-carbon debt holdings increased by about 2 percentage points between 2014 and 2015, from 25 percent to 27 percent. Since the Paris Agreement in 2015, debt holdings declined by 2 percentage point to the levels observed at the beginning of the sample. During the entire sample, high-carbon equity holdings declined from about 28 percent to just under 21 percent. During the same period, high-carbon debt holdings declined by about 4 percentage points.

Figure 2. High-carbon securities holdings by security type, Q4 2013 – Q3 2020



Notes: This figure shows the evolution of high-carbon bank equity and debt securities holdings as a share in total debt and equity non-financial securities holdings, respectively (4-quarter rolling window). The data spans Q4 2013 through Q3 2020. Source: Securities Holdings Statistics and authors' calculations.

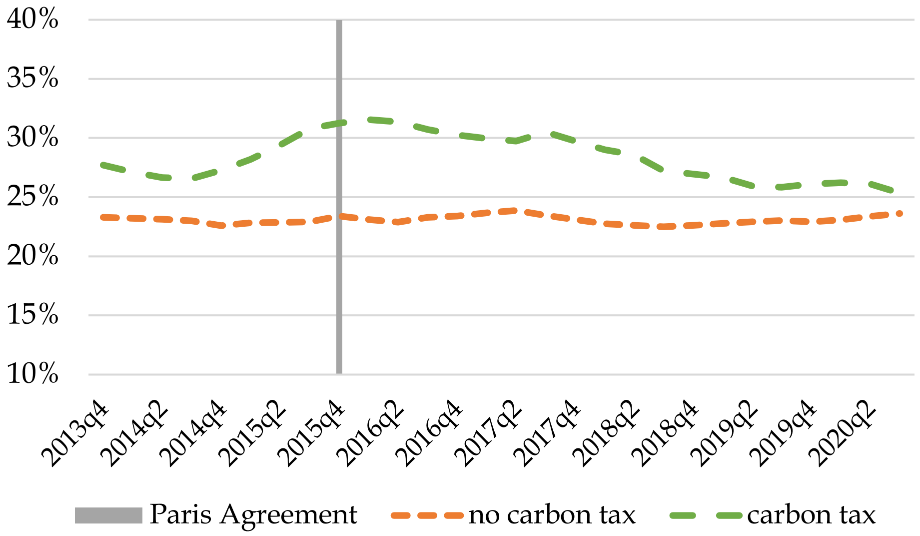
Figure 3, Panel A shows the evolution of high-carbon bank debt securities holdings as a share in total non-financial debt securities holdings in EA countries with and without a carbon tax. Panel B shows the corresponding evolution for equity securities.

The countries included in the "with carbon tax" group are Estonia (EE), Spain (ES), Finland (FI), France (FR), Ireland (IE), Latvia (LV), Portugal (PT), and Slovenia (SI). Note that FR and ES introduced a carbon tax in the second observation of our sample and are included in the "with carbon tax" group throughout the sample period. PT introduced a carbon tax in the middle of our sample and is excluded (including it would not change the results). DE only introduced a carbon tax after the end of our sample period and is therefore not included in the "with carbon tax" group.

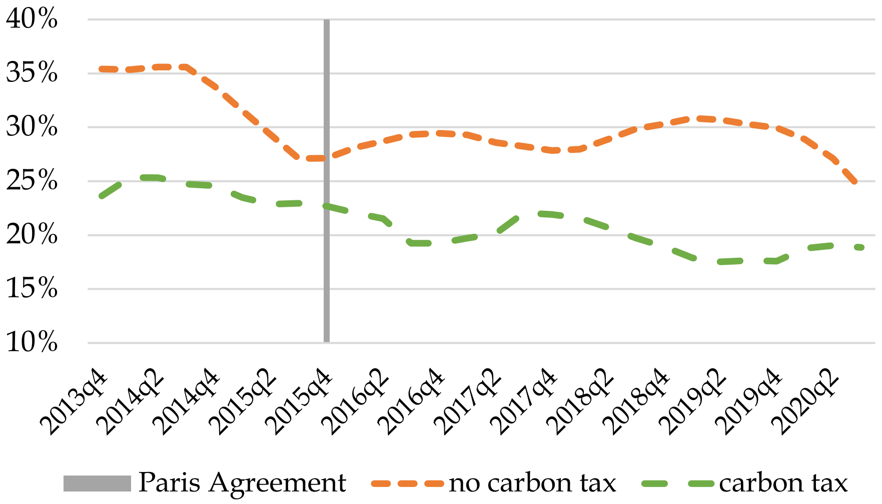
During the period under consideration, all banks reduced their high-carbon securities holdings. Figure 3, Panel A shows that high-carbon debt holdings in countries without a carbon tax are somewhat lower overall compared to those in countries with a carbon tax and remain nearly unchanged from the beginning to the end of our sample. Prior to the Paris Agreement, there is an increase in high-carbon debt holdings of banks in countries with a carbon tax. Thereafter, these holdings decline by about 5 percentage points compared to banks in the other group. By contrast, Figure 3, Panel B shows that high-carbon equity holdings of banks did not decline by more in countries with a carbon tax. In general, high-carbon equity holdings are lower in countries with a carbon tax. We note that focusing solely on the most carbon-intensive industry, the energy sector (electricity, gas and water supply), yields similar patterns (unreported).

Figure 3: High-carbon bank securities holdings in countries with and without a carbon tax, Q4 2013 – Q3 2020

Panel A: debt securities



Panel B: equity



Notes: Panel A shows the evolution of high-carbon bank debt securities holdings as a share in total non-financial debt securities holdings in EA countries with and without a carbon tax (4-quarter rolling window). Panel B shows the corresponding evolution for equity securities. Countries with a carbon tax are: EE, ES, FI, FR, IE, LV, PT, SI. The data spans Q4 2013 through Q3 2020. Source: Securities Holdings Statistics and authors' calculations.

In conclusion, over this period, EA banks reduced the share of high-carbon securities in their portfolios. Distinguishing between debt and equity issued by high-carbon industries, we find that bank holdings of both types of securities declined since the adoption of the Paris Agreement in 2015. We also compare the evolution of bank securities holdings in EA countries with a carbon tax to those in EA countries without a carbon tax. We document that all banks reduced their high-carbon asset holdings our sample period. However, since the Paris Agreement, banks in countries with a carbon tax reduced their high-carbon debt securities holdings by about 5 percentage points more compared to banks in EA countries without a carbon tax. By contrast, high-carbon equity holdings of banks did not decline by more in countries with a carbon tax. At the same time, Laeven and Popov (2021) show that in response to carbon taxes, banks reduce fossil lending in the affected markets, but increase it in unaffected foreign ones. This evidence points to the limitations of a unilateral carbon taxes.

6. Discussion and policy implications

6.1. Implications for government policy

A Capital Markets Union (CMU) with strong emphasis on stimulating the development of private equity, and in particular VC markets, has the potential to stimulate green innovation. Innovation is a complex process that frequently ends in failure and rarely generates tangible assets (Gompers and Lerner, 2006). As a result, neither credit nor stock markets may promote innovation sufficiently. Banks may be reluctant to fund innovation because they lack the expertise to screen risky projects which cannot be collateralized and which erode the value of collateral that underlies existing loans (Ueda, 2004; Hall and Lerner, 2010; Minetti, 2010). Stock market investors may focus excessively on short-term profits and undervalue firms with long-term investments, such as R&D, which create strategic options for a firm and are a major source of competitive advantage (Stein, 1988; Hall, 1993). Therefore, from the point of view of long-term innovation-based growth, it is critical to stimulate private equity, and especially VC, investment.

The EU produces one third of the top 10 per cent most cited scientific publications worldwide,[9] **but it is home to only 12% of the world's unicorns.**[10] This strongly suggests that Europe has not managed to convert its scientific excellence into innovations and commercial success as quickly as its main competitors. One of the main reasons for this failure to bring applied science to the marketplace is a relatively inefficient VC industry. Europe attracts around 10% of the global VC investment; in comparison, North America attracts 42%, and China 36% of global VC investment.[11] The European VC industry is characterized by small funds, too little late-stage investment, and a funding mix tilted towards governments and away from institutional investors like pension funds.[12] The success of countries like Israel and Sweden in building up VC markets through close collaboration between governments and business testifies to the potential for developing such markets also in Europe. Both countries used government funds and public-private partnerships to scale up the start-up economy and create

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[9] https://sciencebusiness.net/news-byte/eu-has-fewer-unicorns-us-and-china

[10] https://www.statista.com/statistics/1092626/number-of-unicorns-in-the-world-by-region/

[11] https://capitalfinance.lesechos.fr/analyses/dossiers/will-europe-eventually-catch-up-with-the-us-and-china-127148

[12] https://medium.com/speedinvest/8-reasons-why-the-european-vc-industry-is-lagging-behind-b93770ae1e70

a VC culture, suggesting that there is a catalytical role for the government in developing such markets.

A "green" CMU with a strong equity component would thus serve two purposes. It would boost the supply of financial instruments which are naturally associated with innovation in low-carbon technologies. It would also increase the number of green assets in the European economy. As a result, the ECB will over time acquire "greener" portfolios even without departing significantly from its current operational principles.

Second, R&D investment in the EU, both public and private, needs to be increased significantly. The Lisbon Strategy invited EU member states to spend at least 3% of their GDP on R&D by 2010.[13] Yet, in 2010, only two EU countries (Finland and Sweden) had achieved this target (Pelikanova, 2019). At present, the overall R&D investment shortfall in the EU is €110 billion each year. The EU has recently increased funding for R&D, and especially for "green" projects, and yet the levels of funding remain well below target. For example, Horizon Europe will fund R&D to the tune of around 13.5 billion per year,[14] are the European Green Deal includes €1 billion for R&D per year.[15] Therefore, while the direction of more R&D funding is the right one, the scale of the commitments falls short of the economy's total funding needs.

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[13] https://ec.europa.eu/invest-in-research/action/history_en.htm.

[14] https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en#:~:text=What%20is%20Horizon%20Europe%3F,budget%20of%20%E2%82%AC95.5%20billion.&text=The%20programme%20facilitates%20collaboration%20and,policies%20while%20tackling%20global%20challenges.

[15] https://ec.europa.eu/info/research-and-innovation/strategy/strategy-2020-2024/environment-and-climate/european-green-deal_en.

Finally, while the EU is among the global leaders in green laws and policies, its member states could adopt even stricter environmental standards and regulations. As of end-2020, only 11 EU countries have adopted some form of carbon tax. Moreover, no EU country has adopted a carbon tax at levels necessary to stimulate a substantial economy-wide reallocation towards green assets (see Barrage, 2020). The recently imposed EU carbon border tax is a step in the direction of imposing carbon taxes at the required levels and scope. Being a large and wealthy economic area, the EU cannot be ignored by firms when they make technological decisions. For example, if a car manufacturer faces lax environmental standards in the US, but very strict ones in the EU, it may find it cheaper to only produce cars that comply with the EU standards, rather than two types of cars fit for two separate markets with very different environmental standards. This will in turn also stimulate the development of new technologies necessary to comply with environmental regulation in the EU.

A historical analogy is the role that California played during the 1990s with respect to the rest of the US. At the time, California had the toughest pollution standards in the US. Manufacturer of various products made in different parts of the US often found it made sense to comply with the Californian pollution standards even if the products were not made for the Californian markets. Some researchers have credited California's strict pollution standards during the 1990s with the re-emergence of critical green technologies, such as the electric car, together with a range of other energy-saving technologies (e.g., Aghion, Dechezleprêtre, Hémous, Martin, and Van Reenen, 2015). The intuition is that technology use is global, and so it is enough if a new technology is produced in one country, after which it is disseminated to all markets. In this sense, the EU does not need to fund the development of green technologies domestically. Instead, it could facilitate their development abroad through stringent domestic standards on carbon usage and efficiency.

6.2. Implications for monetary policy

Can central banks enact policies that support green innovation? We have argued that both in theory and in practice, there are three main factors that are key to the development of new green technologies: carbon taxes, green R&D subsidies, and (private) equity investment. Choosing a tax-subsidy mix and tweaking regulation to change the debt-equity funding mix in the economy are policies that lie squarely in the domain of government. However, there has been a growing call for central banks to do their part. We now discuss and evaluate qualitatively the effectiveness and limitations of several policy options of central banks.[16]

6.2.1. Conventional monetary policy

In accordance with the logic of the model presented here, conventional monetary policy tools that work through the bank lending channel cannot stimulate green innovation. This is because by default, relationship lenders do not meaningfully engage in the funding of innovation. This argument applies to a range of conventional monetary policies, such as changes in the policy rate, to the extent that they mostly affect real economic activity via the channel of bank lending, rather than through changes in asset prices. This also applies to adjusting the haircuts in the collateral framework, depending on whether banks are pledging low- or high-carbon assets, to the extent that it is only banks that can pledge collateral at the

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[16] See Drudi et al. (2021) for a comprehensive discussion of potential Eurosystem actions to address climate change.

central bank.[17] The same holds for a targeted “green” lending operations, whereby banks would receive longer term refinancing conditional on using the proceeds to invest in green activities. Finally, this also applies to bank supervision, where in principle micro-prudential tools can be used to incentivize banks to green their lending portfolios. In all of these cases, our model predicts no material effect on green innovation, because banks by construction do not fund new technologies.[18] More generally, the same prediction holds as long as markets have a comparative advantage over banks in aggregating information and funding new technologies, which is true in most theories of banking (e.g., Allen and Gale, 1999).

Stimulate green innovation by accepting credit claims collateralised by intangible assets in central bank operations is a theoretical possibility but is inconsistent with existing operational frameworks and established risk management practices. Innovation is typically accompanied by the production of intangible capital, such as copyrights, patents, and trademarks. To the extent that banks' incentives to fund the development of new technologies by firms will increase if they can obtain central bank liquidity against the kind of assets that such new technologies produce, accepting intangible capital in liquidity operations may lead to higher green innovation. In principle, the ECB accepts credit claims as collateral in liquidity operations. However, such claims will come with haircuts to reflect credit and liquidity risk, and those haircuts will be steeper if such collateral consists of hard to evaluate

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[17] Central banks collateral rules can and should be adjusted to reflect clear physical and transition risks related to climate change embedded in liquidity operations of the central banks. The point is that if these liquidity operations support banks, then they are unlikely to promote the development of new green technologies.

[18] This is not to say that supervision cannot play an important role in encouraging banks to fund the adoption of existing green technologies, and more generally play an important role in supporting the financing of the green transition. The point is that the reach of banking supervision is limited to banks, which have a comparative disadvantage in funding new technologies. Banking supervision therefore can only play a limited role in the development of new green technologies.

assets and illiquid assets such as intangible assets. Moreover, established risk management practices would not permit a preferential treatment of (green) intangible assets as collateral relative to tangible assets.

In practice, therefore, there is therefore limited scope to promote green innovation through conventional central bank policies.

6.2.2. Unconventional monetary policy

The first unconventional monetary policy that would come closer to the logic in our model is buying publicly or privately traded equity claims in private companies. While the ECB has no experience with equity purchases, other central banks (like the Bank of Japan) have been engaged in such operations for a while now, in an attempt to stimulate general economic activity (see Charoenwong, Morck, and Wiwattanakantang, 2021). In terms of our model, equity is the right type of financial instrument to finance innovation, and so increasing the supply of equity funding in the economy should stimulate the development of new green technologies.

There are two downsides to central banks purchasing equity. The first is that equity also funds new high-carbon technologies. By purchasing equity claims, the central banks may ultimately increase the funding of inferior and/or high-carbon technologies. The second is that the gold standard in funding innovation is private equity financing, such as VC. At the same time, this is a very sophisticated form of financing, and it requires the type of human capital and industry-specific know-how which central banks typically do not possess.[19]

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[19] Venture Capital typically requires active management involvement for which central banks do not possess the expertise and such equity investments can give rise to conflicts of interests that central banks would want to avoid.

Moreover, venture capital investments are much less liquid than publicly listed equity, and may therefore pose an unacceptable risk to the balance sheet of the central bank.

Another theoretical possibility at the central bank's disposal that has the potential to stimulate green innovation is green corporate bonds purchases. Monetary authorities around the world have practised some form of quantitative easing at least since the Global Financial Crisis. The ECB has, since 2016, purchased almost €300 billion worth of corporate bonds under its Corporate Sector Purchase Program (CSPP), including green corporate bonds. The Eurosystem is at present one of the largest investors in green bonds issued by euro area corporates. Under the CSPP, the Eurosystem currently holds around 20% of the eligible green corporate bond universe (Drudi et al., 2021). Given the size of the program, there is a case to be made that the CSPP can have an environmental impact, if it were tilted towards greener assets. Moreover, recent evidence suggests that through the CSPP, the ECB is currently overbuying relatively more polluting sectors (Papoutsi, Piazzesi, and Schneider, 2021). A correction which takes the CSPP portfolio closer to the market may be justified (Schnabel, 2021), and in line with what some other central banks, like the Bank of England, have already announced.[20] Recent research has argued that a green CSPP can have a meaningful, although limited effect on the reallocation of resources necessary underpinning the green transition (e.g., Ferrari and Landi, 2020; Abiri, Ferdinandusse, Ludwig, and Nerlich, 2022).

The downside of dropping high-carbon sectors from the ECB's corporate bonds portfolio is that the cost of funding for these sectors will likely increase. Goetz (2019) shows that the Fed's QE program led firms to reduce pollution by reducing their cost of funding and

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[20] The Bank of England has declared its intention to consider how, subject to achieving its inflation target, it might support the transition of the UK economy to net zero emissions by 2050 (Bank of England, 2021).

allowing them to purchase abatement technologies. Grimm, Laeven, and Popov (2021) show that by subsidizing the cost of debt for innovative firms with low levels of debt funding, the ECB's CSPP program has stimulated corporate innovation. To the extent that these effects are symmetric, an increase in the cost of funding for some high-carbon firms generated by their exclusion from the CSPP portfolio may lead them to reduce green innovation and to adopt cheaper, more carbon-intensive technologies. The overall effect on the carbon footprint of high-carbon sectors from greening the CSPP in this way is therefore ambiguous.

An alternative approach is to keep high-carbon firms and sectors in the CSPP portfolio but tie the purchase of bonds from them to a measurable improvement in energy efficiency. This would be tantamount to purchasing green bonds from high-carbon firms, whose proceeds finance climate-friendly projects, and in particular, the development of new green technologies.[21] At the same time, the overall effect of purchasing green bonds, according to the evidence discussed in Box 1, is uncertain, reflecting the very few empirical analyses of this question. For example, Flammer (2021) shows that firms that issue green bonds reduce their emissions by 13%, compared with similar firms that do not, a sizeable effect. At the same time, Ehlers, Mojon, and Packer (2020) argue that so far, green bond projects have not necessarily translated into comparatively low or falling carbon emissions at the firm level.

Another unconventional policy that has in principle the potential to stimulate innovation is the purchase of sovereign bonds linked to investment in green technologies and infrastructure ("green PSPP"). In terms of the model discussed in Section 4, and the evidence discussed in Section 5, ("green") R&D subsidies are a powerful tool to stimulate the

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[21] One implementation challenge for the purchase of green bonds is that there is no generally accepted definition of what constitutes a green bond. To fill this gap, the EU is currently working on an EU green bond standard.

development of new green technologies. When governments issue sovereign bonds that are ring-fenced for climate projects, such as public subsidies for green R&D, the ECB can purchase those in secondary markets, in excess of those already acquired in the context of the Asset Purchase Program (APP) and the Pandemic Emergency Purchase Program (PEPP). The ECB currently already purchases green sovereign bonds under both programs, but it could in principle do so to a greater extent, and in a way that departs from “market neutrality”.[22]

There are a number of downsides to purchasing green sovereign bonds. First, most R&D investment fails. While failure is the sign of an investment strategy that targets radical innovation, green sovereign bonds earmarked for R&D subsidies will often be linked to failing projects. Second, the current universe of green sovereign bonds is limited, with the share of investment grade green bonds still very small compared to the wider global bond market, despite the expansion of the market and surge in investor demand. This makes it difficult to meet operational targets from an implementation point of view. Furthermore, green sovereign bonds still lack a commonly agreed upon standard and definition, posing implementation challenges. EU governments do not currently issue enough green bonds to allow existing programme targets to be met (Drudi et al., 2021).

Finally, the ECB could in principle stimulate green innovation indirectly by introducing firm-level disclosure requirements in its operations. Private investors are much more likely to invest in firms that are embarking on technological greening if they trust the information at the firm-level. Consequently, a requirement for reliable climate disclosures can become part of a range of ECB policies. For example, liquidity provision to banks can be conditional on

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[22] Since January 2021, the Eurosystem also accepts certain sustainability-linked bonds as collateral in its liquidity operations.

comprehensive disclosure of the bank's climate risk exposure in its lending portfolio. Similarly, the ECB can commit to only purchase, under the CSPP, bonds from companies that have disclosed their carbon footprint, in addition to concrete plans for the reduction thereof.

7. Conclusions

The global community has pledged to address forcefully the climate crisis. The Paris Agreement of 2015 affirmed the goal of holding the increase in the global average temperature to well below 2°C above pre-industrial level and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial level. The Glasgow Climate Pact of 2021 further recognized that limiting global warming to 1.5°C required rapid, deep and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45 per cent by 2030 relative to the 2010 level and to net zero around mid-century.

Achieving these ambitious climate goals requires the development of new low-carbon technologies on a grand scale. This development necessitates an increase in private and public R&D investment, and a concurrent increase in market (especially private equity) finance.

The design of a policy mix that would support such development is the purview of government policy. First, optimal carbon taxes need to be imposed, to align the incentives of private market participants with social goals. Second, subsidies for R&D in green applied science need to increase, both at the EU level and by individual member states. This would also help bridge the gap between the overall level of R&D investment in Europe and the target set in the Lisbon Strategy. Third, under the Capital Market Union, all remaining restrictions to the emergence of a vibrant private equity and VC industry in Europe need to be removed.

Under existing mandates, central banks are unlikely to have a material contribution to the development of green technologies. An active tilting of central bank interventions in favour of green technologies is in conflict with the principle of market neutrality and, in any case, central bank policies that operate by supporting bond financing or encouraging bank lending are not effective in stimulating innovation. Still, the ECB can reinforce government actions to promote green technologies by enhancing disclosure requirements of climate risks by banks and firms eligible for asset purchases, by adjusting prudential frameworks to reflect climate risks, by purchasing sovereign green bonds through its asset purchase programme, and by supporting the push for a “green” CMU with a strong equity component.

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Appendix. A Model of Directed Technical Change with Financial Frictions

We now set up a model of directed technical change, a financial sector, and central-bank policy to analyze to what extent central banks can influence the direction of technical change. The framework we set up combines elements of directed technical change as specified in Acemoglu, Aghion, Burzstyn, and Hemous (2012)—AABH from now on—with the financial structure specified in Minetti (2010). We now describe the model formally.

1 The Model

1.1 Aggregate Aspects

There are two sectors, low-carbon, or "clean" ($j = c$) and high-carbon, or "dirty" ($j = d$), and a unique final good is produced in a competitive market by combining clean and dirty inputs, Y_c and Y_d, according to the production function

$$Y = \left[Y_c^{\frac{\varepsilon-1}{\varepsilon}} + Y_d^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}},$$

where ε is the elasticity of substitution.

Clean and dirty inputs are also produced in a competitive market, using labor and a continuum of sector-specific machines; formally

$$Y_c = L_c^{1-\alpha} \int_0^1 A_{ci}^{1-\alpha} x_{ci}^{\alpha} di \quad \text{and} \quad Y_d = L_d^{1-\alpha} \int_0^1 A_{di}^{1-\alpha} x_{di}^{\alpha} di, \tag{1}$$

where $\alpha \in (0, 1)$.

Normalizing the total labor supply to 1, market clearing in the labor market requires

$$L_c + L_d \leq 1.$$

Innovation is done by scientists. Each scientist decides whether to direct her research to clean or dirty technology. This choice involves comparing profits in the two sectors. The researcher is then randomly allocated to at most one machine, and the probability that an innovation is realized in sector j is η_j. A successful innovation increases the quality of a machine by a factor $1+\gamma$, with $\gamma > 0$. A scientist who is successful in inventing a better version of a machine in sector j then obtains a patent and becomes the entrepreneur for the production of the machine. The timing is the same setting as in Minetti (2010), i.e., there are three periods and they are respectively labeled time 0, 1, and 2.

Time 0. Initial conditions are given. The scientist chooses a sector where to carry out R&D. An innovation shock is then realized. If the shock is positive, a new productive machine is now available. The scientist meets with an investor and establishes a relationship or a transactional credit link. They write a contract.

Time 1. The entrepreneur decides whether to produce with the new technology. As in AABH, if the shock is negative the entrepreneur instead receives a monopoly right from a random sector where innovation has not been successful. The entrepreneur can then produce with this old technology instead.

Time 2. All production takes place. Individual projects succeeds or fails. If the project fails, the lender recovers and liquidates the machine. Note that the probability of failure is different and independent of the probability of a successful innovation because with a certain probability, also production using the old technology fails.

Normalizing the measure of scientists s to 1, market clearing for scientists requires

$$s_c + s_d = 1.$$

For the final good, market clearing implies that

$$C = Y - \quad \left(\int_0^1 x_{ci} di + \int_0^1 x_{di} di \right),$$

where C is consumption of the final good, and ψ is the cost in terms of final good of producing one unit of any machine costs. Following AABH, we normalize $\equiv \alpha^2$.

We also define

$$A_j = \int_0^1 A_{ji} di, \quad j \in \{c, d\}, \tag{2}$$

as the average productivity in sector $j \in \{c, d\}$. The specification for the innovation possibilities frontier then implies that A_c and A_d will change in accordance with the following equations

$$
\begin{aligned}
A_c &= (1+\gamma\eta_c s_c)\, A_{c,0} \\
A_d &= (1+\gamma\eta_d s_d)\, A_{d,0},
\end{aligned}
$$

where $A_{c,0}$ and $A_{d,0}$ are the initial levels—at time 0—of the average productivity in sector c and d respectively.

Preferences are given by $u\,(C,S)$, and this utility function is increasing in both C and S, twice differentiable, and jointly concave in (C,S).

The environmental quality is given by

$$S = -\xi Y_d + S_0. \tag{3}$$

As revealed by (3), production of the dirty good degrades the quality of the environment.

1.2 Financial markets

We now modify the setting in AABH to include a financial sector. Following Minetti (2010), we first introduce a probability of production failure. This is needed to ensure that the liquidation value enters in the problem of the investor. The probability of failure is denoted by $1-\rho$. As stated above, the probability of failure is different from the probability of a successful innovation, because with probability $1-\rho$, also production using the old technology fails. Second, we add the repayment R_j^I as an additional cost factor for $(I \in \{O,N\})$ and where N denotes the new technology—used with probability η_j— and O the old technology—used with probability $1-\eta_j$—and L denotes the lender type $L \in \{T,R\}$.

1.3 Machine producers and scientists

The profit-maximization problem of the producer of machine i in sector $j \in \{c,d\}$ can be written as

$$\max_{x_{ji},L_j} p_j L_j^{1-\alpha} \int_0^1 A_{ji}^{1-\alpha} x_{ji}^{\alpha} di - wL_j - \int_0^1 p_{ji} x_{ji} di.$$

The first-order condition w.r.t. x_{ji} and L_j are respectively given by

$$x_{ji} = \left(\frac{p_j \alpha}{p_{ji}}\right)^{\frac{1}{1-\alpha}} A_{ji} L_j, \tag{4}$$

and

$$
\begin{aligned}
(1-\alpha)\, p_c L_c^{-\alpha} \int_0^1 A_{ci}^{1-\alpha} x_{ci}^{\alpha} di &= w, && (5) \\
(1-\alpha)\, p_d L_d^{-\alpha} \int_0^1 A_{di}^{1-\alpha} x_{di}^{\alpha} di &= w. && (6)
\end{aligned}
$$

The profit-maximization problem of the monopolistic producer of machine i in sector $j \in \{c, d\}$ can then be written as

$$
\begin{aligned}
\pi_{ji} &= \max_{p_{ji}, x_{ji}} \rho \left(p_{ji} - \psi\right) x_{ji} \left(1 - R_{Lj}^{I}\right) + (1-\rho)\} \\
&= \max_{p_{ji}} \rho \left(\frac{p_j \alpha}{p_{ji}}\right)^{\frac{1}{1-\alpha}} A_{ji} L_j \rho \left(p_{ji} - \psi\right) \left(1 - R_{Lj}^{I}\right).
\end{aligned}
$$

The first-order condition delivers

$$p_{ji} = \frac{}{\alpha} = \alpha.$$

Hence, the profit-maximizing price is a constant markup over marginal cost $p_{ji} = \psi/\alpha$. We have assumed that $\psi = \alpha^2$, so $p_{ji} = \alpha$.

The equilibrium demand for machines i in sector j is thus

$$x_{ji} = p_j^{\frac{1}{1-\alpha}} A_{ji} L_j. \tag{7}$$

The equilibrium profits of machine producers endowed with technology A_{ji} can then be written as

$$\pi_{ji} = \rho\alpha \left(1-\alpha\right) p_j^{\frac{1}{1-\alpha}} A_{ji} L_j \left(1 - R_{Lj}^{I}\right). \tag{8}$$

Finally, profits of scientists are given by:

$$\Pi_j = \rho\eta_j \left(1+\gamma\right) \alpha \left(1-\alpha\right) p_j^{\frac{1}{1-\alpha}} A_{ji0} L_j \left(1 - R_{Lj}^{I}\right). \tag{9}$$

1.4 Expected return of the investor and monitoring choice

Investors are risk-neutral. Provided that innovation is successful, the new technology can only be produced if funding is available. Relationship lenders are less likely to finance new technologies because of her superior knowledge of the old technology.

M_j^I, $I \in \{O, N\}$, denotes the liquidation value which depends both on the sector and whether or not innovation took place. Recall from the timing assumptions above that the investor decides whether to invest into clean and dirty technology after the shocks η_j realized but before ρ is realized. Because monitoring is costly for the lender, the optimal monitoring intensity is conditional on η_j.[1]

If innovation does not take place and the old technology is used (with probability $1 - \eta_j$) the expected return of the investor is given by

$$P_{Lj}^O = \rho R_{Lj}^O + (1 - \rho) M_j^O \mu_{Lj} - \frac{c_{Lj}}{2} \mu_{Lj}^2,$$

where $(c_{Lj}/2) \mu_{Lj}^2$ constitutes the monitoring cost.

The first-order condition w.r.t. μ_{Lj} gives optimal monitoring conditional on that the old technology is being used:

$$\widehat{\mu}_{Lj} = \frac{(1 - \rho) M_j^O}{c_{Lj}}. \tag{10}$$

If innovation takes place, and the new technology is used instead (with probability η_j) the expected return of the investor is given by:

$$P_{Lj}^N = \gamma \rho R_{Lj}^N + (1 - \gamma) \left[R_{Lj}^O \rho + (1 - \rho) M_j^N \mu_{Lj} \tau_j \right] - \frac{c_{Lj}}{2} \mu_{Lj}^2,$$

where τ_j denotes to what extent information is transferable.

The first-order condition w.r.t. μ_{Lj} now gives optimal monitoring conditional on that the new technology is being used:

$$\widetilde{\mu}_{Lj} = \frac{(1 - \gamma)(1 - \rho) M_j^N \tau_j}{c_{Lj}}. \tag{11}$$

Inserting the optimal monitoring probabilities into the expressions for P_{Lj}^O and P_{Lj}^N, respectively, we get

$$P_{Lj}^O = \rho R_{Lj}^O + \frac{(1 - \rho)^2 \left(M_j^O \right)^2}{2 c_{Lj}}, \tag{12}$$

and

$$P_{Lj}^N = \gamma \rho R_{Lj}^N + (1 - \gamma) R_{Lj}^O \rho + \frac{(1 - \gamma)^2 (1 - \rho)^2 \left(M_j^N \tau_j \right)^2}{2 c_{Lj}}. \tag{13}$$

---

[1] By monitoring the lender learns to extract value from the firm's assets.

1.5 Equilibrium

The relative benefit from undertaking research in sector c relative to sector d can be derived from (9). Specifically, it is governed by the ratio

$$\frac{\Pi_c}{\Pi_d} = \frac{\eta_c}{\eta_d} x \underbrace{\left(\frac{p_c}{p_d}\right)^{1/1-\alpha}}_{\text{Price effect}} \times \underbrace{\frac{L_c}{L_d}}_{\text{Market size effect}} \times \underbrace{\frac{A_{c0}}{A_{d0}}}_{\text{Direct productivity effect}} \times \underbrace{\frac{1-R_{Tc}^N}{1-R_{Td}^N}}_{\text{Financing effect}}, \tag{14}$$

where we used Lemma 1 in Minetti (2010) that states that only transactional lenders finance new innovation. Equation (14) reveals that if the ratio $\frac{1-R_{Lc}^N}{1-R_{Ld}^N}$ is different from one, then financing affects the profit ratio. Apart from the financing term, the determinants of the profit ratio is qualitatively very similar to without financing, i.e., as in AABH. Hence, innovation will favor the more advanced sector when $\varepsilon > 1$ (which, corresponds to $\varphi \equiv (1-\alpha)(1-\varepsilon) < 0$. These effects are now amplified by the ratio $\left(1-R_{Lc}^N\right)/\left(1-R_{Ld}^N\right)$.

Following Minetti (2010), we assume that

$$R_{Lj}^N = \chi \Pi_j,$$

where $\chi < 1$. That $\chi < 1$ implies that only a fraction of the profit generated in a project is verifiable and contractible while the rest can be stolen by the entrepreneur.

Comparing P_{Lj}^N and P_{Lj}^O, investors fund innovation if the following condition holds,

$$\gamma \rho R_{Lj}^N - \gamma R_{Lj}^O \rho + \frac{(1-\rho)^2}{2c_{Lj}} \left[(1-\gamma)^2 \left(M_j^N \tau_j\right)^2 - \left(M_j^O\right)^2\right] \geq 0. \tag{15}$$

The zero profit condition of the lender is $P_{Lj}^O = 1$, i.e.,

$$\rho R_{Lj}^O = 1 - \frac{(1-\rho)^2 \left(M_j^O\right)^2}{2c_{Lj}}. \tag{16}$$

Combining the above two equations, we get a similar participation constraint as in Minetti (2010):

$$R_{Lj,PC}^O = \frac{1-(1-\gamma)^2 (1-\rho)^2 \left(M_j^N \tau_j\right)^2 / 2c_{Lj} - \gamma \rho R_{Lj}^N}{(1-\gamma)\rho}. \tag{17}$$

Lemma 1 in Minetti (2010) states that the entrepreneur never adopts the new technology under relationship funding. The contract with a relationship lender specifies

$$R_{Rj}^{O}=\frac{2c_{Rj}-(1-\rho)^{2}\left(M_{j}^{O}\right)^{2}}{2\rho c_{Rj}}, \tag{18}$$

which follows directly from (16).

Under transactional funding, if the innovatrion shock is positive, the entrepreneur always adopts the new technology. The contract with a transactional lender specifies R_T^N and R_T^O such that

$$\frac{(1-\rho)^{2}}{2\gamma\rho c_{Tj}}\left[(1-\gamma)^{2}\left(M_{j}^{N}\tau_{j}\right)^{2}-\left(M_{j}^{O}\right)^{2}\right]\leq R_{Tj}^{N}-R_{Tj}^{O}, \tag{19}$$

$$\gamma R_{Tj}^{N}+(1-\gamma)R_{Tj}^{O}=\frac{2c_{Tj}-\left[(1-\gamma)(1-\rho)\left(M_{j}^{N}\tau_{j}\right)\right]^{2}}{2c_{Tj}\rho}, \tag{20}$$

and

$$0\leq R_{Tj}^{O}\leq\chi\Pi_{j}^{O},\quad 0\leq R_{Tj}^{N}\leq\chi\Pi_{j}. \tag{21}$$

where the first relation is the incentive compatibility constraint, the second follows from zero profits for new machines, and the third captures limited liability.

2 Implications

We now assume that $M_d\equiv M_d^N=M_d^O$, $M_c\equiv M_c^N=M_c^O$, $M_d\geq M_c>M_d^N\geq M_c^N$, and $c_{Rj}\geq c_{Tj}$.

From (18), we have

$$\begin{aligned}R_{Rc}^{O}&=\frac{2c_{Rc}-(1-\rho)^{2}(M_{c})^{2}}{2\rho c_{Rc}}\\R_{Rd}^{O}&=\frac{2c_{Rd}-(1-\rho)^{2}(M_{d})^{2}}{2\rho c_{Rd}}.\end{aligned}$$

It immediately follows that if $M_d\geq M_c$ then $R_{Rd}^O\leq R_{Rc}^O$.

Now, rewrite (20) as

$$(1-\gamma)R_{Tj}^{O}=\frac{2c_{Tj}-\left[(1-\gamma)(1-\rho)\left(M_{j}^{N}\tau_{j}\right)\right]^{2}}{2c_{Tj}\rho}-\gamma R_{Tj}^{N},$$

and substitute into (19) to arrive at

$$
\begin{aligned}
R_{Tc}^{N} &\geq \frac{1}{2c_{Tc}}\left[\frac{2c_{Tc}-\left[(1-\gamma)(1-\rho)(M_c\tau_c)\right]^2}{\rho(1+\gamma)}-(M_c\tau_c)^2\frac{(1-\rho)^2}{\rho}\frac{1-(1-\gamma)^2}{\gamma(1+\gamma)}\right],\\
R_{Td}^{N} &\geq \frac{1}{2c_{Td}}\left[\frac{2c_{Td}-\left[(1-\gamma)(1-\rho)(M_d\tau_d)\right]^2}{\rho(1+\gamma)}-(M_d\tau_d)^2\frac{(1-\rho)^2}{\rho}\frac{1-(1-\gamma)^2}{\gamma(1+\gamma)}\right].
\end{aligned}
$$

Again, we see that if $M_d \geq M_c$ then $R_{Td}^{N} \leq R_{Tc}^{N}$.

We can now rewrite (14) to get it in the same form as in AABH:

$$
\frac{\Pi_c}{\Pi_d}=\frac{\eta_c}{\eta_d}\left(\frac{(1+\gamma\eta_c s_c)}{(1+\gamma\eta_d s_d)}\right)^{-\varphi-1}\left.\frac{\widehat{A}_{c0}}{\widehat{A}_{d0}}\right)^{-\varphi}, \tag{22}
$$

where $\widehat{A}_{c0} \equiv A_{c0}\left(1-R_{Tc}^{I}\right)$, and $\widehat{A}_{d0} \equiv A_{d0}\left(1-R_{Td}^{I}\right)$. An important difference relative to in AABH is that now these technology terms thus now incorporate financial aspects.

Because (22) is basically identical to equation (18) in AABH, Lemma 1 in that paper still applies; we repeat a modified version of it here.

Lemma 1: *Under Laissez fair, it it is an equilibrium for innovation at time t to occur in the clean sector only when $\eta_c\widehat{A}_{ct-1}^{-\varphi} > \eta_d(1+\gamma\eta_c)^{\varphi+1}\widehat{A}_{dt-1}^{-\varphi}$, in the dirty sector only when $\eta_c(1+\gamma\eta_d)^{\varphi+1}\widehat{A}_{ct-1}^{-\varphi} < \eta_d\widehat{A}_{dt-1}^{-\varphi}$, and in both sectors when $\eta_c(1+\gamma\eta_d s_{dt})^{\varphi+1}\widehat{A}_{ct-1}^{-\varphi} = \eta_d(1+\gamma\eta_c s_{ct})^{\varphi+1}\widehat{A}_{dt-1}^{-\varphi}$* (with $s_{ct}+s_{dt}=1$).

2.1 Policy

2.1.1 Taxes

The government can set a tax on the dirty input so that the price of a dirty machine becomes

$$
p_d^{*}=(1+T)\,p_d.
$$

It is straightforward to show that taxes change the relative prices of the two goods in the following way

$$
\frac{p_c}{p_d^{*}}=\left(\frac{A_c}{A_d}\right)^{-(1-\alpha)}, \tag{23}
$$

where $p_d^{*} \equiv (1+tax)\,p_d$, i.e., p_d^{*} is the price including the tax. This case is analyzed in detail in AABH and it can change the profit ratio in (14) so that innovation becomes directed towards the clean good.

2.1.2 Subsidies

It is straightforward to include R&D subsidies into the analysis. Using 9) and following AABH, a subsidy, q_t, to R&D in the clean sector alters profits in that sector to

$$\Pi_c = \rho\left(1+q_t\right)\eta_c\left(1+\gamma\right)\alpha\left(1-\alpha\right)p_c^{\frac{1}{1-\alpha}}A_{ci0}L_c\left(1-R_{Lc}^I\right),$$

with profits in the dirty sector being unchanged. As in AABH, this implies that a sufficiently high subsidy to clean research can redirect innovation towards the clean sector. The qualitative result is thus the same as in AABH. At the same time, quantitatively speaking, the subsidy may have to be very high for a very long period to actually redirect innovation towards the clean sector (see Meng, 2021).

2.1.3 Monetary policy

To keep the model tractable, we assume as a first pass that central bank policy works by changing the monitoring cost parameter c_{Lj}. Intuitively, this assumes that by expanding the set of eligible capital to e.g. transactional loans, it effectively lowers the monitoring cost for these assets as investors can recycle these assets as collateral. Specifically, we now assume that central banks can lower c_{Tc} relatively more, then they can affect the repayments that are needed.

$$\frac{\partial R_{Tj}^N}{\partial c_{Tj}} = \frac{1}{c_{Tc}}\left(\frac{1}{\rho\left(1+\gamma\right)} - R_{Tc}^N\right) > 0.$$

Hence, a lower c_{Tj} reduces repayments in sector $j \in \{c, d\}$.

At the same time, while accepting credit claims collateralised by intangible assets in central bank operations is a theoretical possibility, it is inconsistent with existing operational frameworks and established risk management practices. Moreover, even if relationship lenders start issuing credit claims collateralized by intangible assets, banks will still be reluctant to fund innovation because they lack the expertise to screen risky projects which cannot be collateralized and which erode the value of collateral that underlies existing loans (Ueda, 2004; Hall and Lerner, 2010; Minetti, 2010).

2.1.4 Summary

Let us now sum up the results. First, financing can affect the direction of R&D. Specifically, if $M_d > M_c$ then $R_{Td}^N < R_{Tc}^N$ and R&D will be biased towards dirty innovation. Second, taxes on the dirty good will bias the direction of technical change in favour of the low-carbon good. Third, subsidies for green R&D will redirect innovaiton towards the clean sector. Finally, if central banks can lower the monitoring costs in the clean sector then they can alter the direction of R&D also in favour of the low-carbon good. However, this is not an operation alternative because credit claims are only accepted as collateral from relationship lenders, and these are unwilling to fund projects collateralized with ingangible assets linked to green innovation.

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