SUSTAINABLE FINANCE LAB

HOW MUCH OF A HELP IS A GREEN CENTRAL BANKER?

Quantifying the impact of green monetary and supervisory policies on the energy transition

In this paper

Green central bank intervention can reduce the cost of capital of green economic activities.

The contribution in achieving climate goals is on average a 5%-12% of the needed climate action.

Thus, the role of central banks in the transition is complementary to that of the government.

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The Sustainable Finance Lab (SFL) is an academic think tank whose members are mostly professors from different universities in the Netherlands. The aim of the SFL is a stable and robust financial sector that contributes to an economy that serves humanity without depleting its environment. To this end the SFL develops ideas and provides a platform to discuss them, thus bridging science and practice.

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Working Paper

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Quantifying the impact of green monetary and supervisory policies on the energy transition

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Abstract

To quantify the impact of "green" monetary and supervisory policies of central banks we develop a dynamic General Equilibrium Model for Sustainable Transitions (GEMST-1). This enables us to make a distinction between green and brown final sub-sectors and fossil and renewable power sectors and take into account the feedback loops across sectors through energy prices until 2050. We identify four instruments (capital requirements, collateral frameworks, Asset Purchase Programmes, and Refinancing Operations) of central banks that can lower the cost of capital for climate friendly investments and thus accelerate the energy transition and lower climate risks. We run three scenarios of different green central bank policies where the cost of capital of green final sub-sectors and/or renewable power sectors is lowered by an ambitious 100 basis points. Our analyses shows that the maximum impact of such policies is achieved when it is implemented on both green final sub-sectors and renewable sub-sectors at the same time. Moreover, our study finds that green central bank policies can substantially accelerate the transition with a climate contribution that amount to 5% -12% of the needed emission reductions under an ambitious climate action scenario. Whereas this is a substantial figure, it also indicates that green central bank policy should be seen as a complement, not a substitute for, fiscal and regulatory efforts.

Executive summary

This report investigated the potential effects of green central bank policies on the energy transition, considering inter-sectoral and general equilibrium effects. We identified one supervisory and three monetary tools at the disposal of central banks that can be used for a green purpose, namely: Capital Requirements, the Collateral Framework, Asset Purchase Programmes (APPs), and Refinancing Operations (ROs). We specified the link and described the mechanism by which these instruments affect the cost of capital of different investments. Moreover, we surveyed available empirical evidence to quantify the effects these tools have on the cost of capital. We find the following upper and lower bounds for the effects of the corresponding central bank instruments:

CB instrument	**Lower bound effect**	**Upper bound effect**
Capital Requirements (1% increase in risk weighted assets)	2.5 basis points	20 basis points
Collateral Frameworks	7 basis points	76 basis points
Asset Purchase Programs (APPs)	0 basis points	20 basis points
Refinancing Operations (TROs)	20 basis points	More than 20 basis points

Based on this we estimated the effects of an ambitious, yet possible central bank green intervention to be a reduction in the cost of capital of 100 basis points for the targeted (sub)sectors. The quantification of the impacts of such a green central bank intervention is done using our General Equilibrium Model for Sustainable Transitions (GEMST-1). These impacts were evaluated across sectors and between transition scenarios. Our results show that:

- Green central bank intervention reduces emissions and speeds up the transition as it channels investments towards targeted sectors.
- Central bank green intervention can substantially accelerate the transition with a climate contribution that amount to 5%-12% of the needed emission reductions under an ambitious climate action scenario.
- The quantitative impacts of green central bank intervention depend on the sectoral coverage of such intervention. Our analysis shows that the maximum impact of the intervention is achieved when it targets both green final sub-sectors and renewable power sectors at the same time.
- Across sectors the quantitative impacts differ according to their dependencies on different production factors.

- An intervention that targets renewable sectors only induces spillover effects that could hinder the transition for most final sectors. Thus, the coordination between Central bank green intervention and other fiscal climate policies is essential for a timely and cost-effective transition.

Our study concludes that green monetary and supervisory policies can accelerate the energy transition and reduce emissions. However, this effect is limited, and since the simulated differentiation in the cost of capital of 100 bps can already be considered ambitious, our results indicate that whereas central banks can play a substantial role it should be seen as complementary, supportive, to fiscal and regulatory policies.

Finally, as a general policy conclusion, our study identified four options that central banks could use to change the capital costs between green and brown sectors. It is important to choose one or more combinations of these instruments that would yield the maximum impact on capital costs. A relevant question for future research would be: how should central banks design a policy or policy combination that triggers the maximum change in capital cost? And what instruments can be used in good economic times when there is no monetary stimulus needed? Additionally, a future research agenda could focus on integrating the financial sector in a general equilibrium setup as this would capture the full mechanism by which these tools propagate in the economy.

1 Introduction

There is a growing consensus on the need to transition our economies towards a low carbon future. The fight against climate change is gaining momentum with many policy proposals, clean innovative technologies, and an increase in people's awareness to the problem. There are many trajectories for the transition that are associated with policy interventions and technological breakthroughs. When talking about transition policies, one would first think about regulation and fiscal climate policies, like emission standards, carbon taxes, traded emission permits, or "green" subsidies [Pigato (2018)]. However, in the past few years, climate related risks to the financial sector have been identified and discussed thoroughly within the finance community. Increasingly, the financial industry and the central banking community discuss the role supervisory and monetary policy can play to reduce climate risks and accelerate the transition process. This trend is manifest, for example, by the increase in the membership of the Network for Greening the Financial System (NGFS). Central banks have at their disposal many tools that can be structured to include sustainability concerns and thus accelerate the transition process. Recently, the European Central Bank (ECB) presented its reviewed monetary strategy with climate change being on top of the agenda.

Many argue that central banks could play a vital role in accelerating the transition process to complement governments regulatory and fiscal efforts. Many have argued for greening of supervisory policy tools, such Capital Requirements (CR) and monetary instruments like the Collateral Frameworks (CF), the Refinancing Operations (RO), or the Asset Purchasing Programmes (APP) [Campiglio (2016), Dikau et al. (2020), Dafermos et al. (2020), van't Klooster and van Tilburg (2020), Philipponnat et al. (2020), Schoenmaker (2021), Böser and Colesanti (2021)]. However, there is a lack of studies and models that allows us to simulate the effects and get a sense of the quantitative impacts of such green central bank policies on the transition towards a low carbon economy. This is where the contribution of this study lies.

More precisely, the objective of this paper is two-fold. First, we list the supervisory and monetary tools (others have proposed) that could be adapted and greened, so that they reduce climate related risks and accelerate the transition toward a low carbon economy. Moreover, we identify the mechanisms by which these tools could drive a wedge in the cost of capital between green and brown investments, along with the available empirical evidence of their quantitative effect.

Second, using our Dynamic General Equilibrium Model for Sustainable Transitions version 1.0 (GEMST-1) we quantify the economic and transition effects of differentiating the cost of capital between "green" and "brown" sub-sectors on the transition process. Unlike partial equilibrium sectoral analyses, our model catches the energy-related feedback loops across sectors between transition scenarios which gives a more consistent picture of the economy-wide impacts and spillovers after specific interventions. Moreover, the model deviates from the CGE literature by distinguishing between green and brown final sub-sectors, which allows for identifying transition risk and opportunities between scenarios. Additionally, the model employs sector-specific capital stocks which permits the differentiation between the return and cost of capital across (sub)sectors and between scenarios.

In this study, we analyze scenarios for green central bank intervention that result in a reduction of the cost of capital for green and/or renewables (sub)sectors. We analyze the transition, sectoral and economy wide impacts of such intervention. Furthermore, we compare the impact on emissions of our green central banking scenarios with what is needed to achieve the global climate goals, thus identifying how close green central bank intervention could bring us to reach climate objectives. Like any model based analysis, general equilibrium models make some strong assumptions on behavior and necessarily have to simplify the complexity of the real world. Therefore, our numerical results should be considered as a first estimation of the direction and order of magnitude of policy impacts, not a precise prediction of what green central bank policies will bring. Our study makes the case that it is very worthwhile to start experimenting with these tools at the disposal of central banks. The changing climate makes this urgent, and our results show that the effects of such interventions are promising.

The remainder of this paper is organized as follows: Section 2 outlines different monetary and supervisory instruments and how they might be geared towards greening the real economy. In this section we will explain and quantify from empirical evidence the link between these instruments and the cost of capital. Section 3 describes the model and its main mechanisms. Section 4 presents the results of our scenario analyses. In section 5 we conclude and discuss questions for further research.

2 Green supervisory and monetary instruments

The energy transition is an unprecedented investment program. We need to invest in new technology, build up renewable generation capacity, invest in infrastructures and adaptation to the new energy paradigm. Effective climate policy is therefore directing and accelerating investment. Central banks can contribute to and accelerate the energy transition through lowering the cost of capital of climate friendly investments. Here we discuss four instruments that central banks can use to this end. For each of these instruments, we describe the link and mechanism by which they affect the relative cost of capital. We also survey the available empirical evidence to quantify this link.

2.1 Capital requirements

Capital requirements are one of the main supervisory tools of central banks. Higher capital requirements require banks to hold more capital (equity) for the associated assets (the specific bank loans). As equity is a relative expensive source of capital, this increases the cost of particular forms of lending. Capital requirements can be set from both a micro-supervisory point of view, the level of the individual bank. Or from a macro-supervisory view, considering the systemic risk [Schoenmaker and Van Tilburg (2016) , Bolton et al. (2020)].

As a main macro prudential policy aiming at fighting and mitigating financial instability, and to the extent that green and brown assets are in a relevant distinction in micro- and macro risk, capital requirement could be used to steer funds and capital flows towards financing green parts of the economy or drive it away from brown ones [Berenguer et al. (2020)]. Higher capital requirements increase lenders' cost of capital, and as the banking sector is oligopolistic and this type of cost increase affects all banks in the same way, the pass-through will be near 100% and so higher costs of capital for the bank translate into higher costs of capital for investors. Philipponnat et al. (2020) argue for the European Union to use prudential regulation as a tool to combat climate-related financial instability. Moreover, In its "Guide on climate-related and environmental risks", the ECB published its "understanding" of the prudential management of climate-related and environmental risks, in which the ECB expects related institutions to consider climate-related transition and environmental risks in the formulation and implementation of their business strategy, governance and risk management frameworks. Accordingly, increasing capital requirements for brown assets to reflect their climate related and environmental risks would entail a differentiation in the cost of capital between green and brown assets making green ones relatively more competitive.

With regard to the quantitative evidence linking the change in capital requirements to the cost of capital, Baker and Wurgler (2015) estimated an annualized 85 bps increase in the weighted average cost of capital in competitive lending markets following a binding positive shift in core risk weighted capital requirements by 10% (for example, from 8% to 8.8%) under a benchmark case of riskless debt, no subsidy and segmented markets. Using a model that is based on the Modigliani-Miller framework with conservation of risk premise, Kashyap et al. (2010) reported a modest estimate for the long-run increase of loan rates which ranged between 2.5 to 4.5 basis points following a 1% increase in minimum capital ratio. Basten (2020) investigated the effects of the activation of the Counter-cyclical Capital Buffer (CCB) by Switzerland in 2013 as the macro-prudential tool of Basel III. Under this activation banks were asked to hold extra equity capital worth 1% of their risk-weighted assets secured by domestic residential property. They reported higher mortgage rates charged by banks and insurance companies after the CCB's activation. More precisely, banks were found to charge on average 17-18 bps more. Slovik and Cournède (2011) reported that an increase of 1% in equity capital applied to all risk-weighted assets would induce an increase in lending spreads by 14.4 bps on average across major OECD economies, with 8.4 bps for Japan, 14.3 bps for the Euro14 area and 20.5 bps for the USA. Differences across countries are mainly due to the differences in the return on equity, the share of risk-weighted assets, and the share of lending assets in the balance sheets of banks.

In light of above estimates from different studies, a 1% increase in risk weighted assets would induce a rise in the cost of capital between 2.5 bps and 20.5 bps, with an increase of 14.4 bps on average depending on the country and context. The study of Banque de France (2021) help us to link these estimates in capital requirement to those needed to account for climate related transition risks. More precisely, Banque de France (2021) estimated the annual average cost of credit transition risk for 6 French banks to increase by 12.9 bps and 15.8 bps in 2025 and 2050 respectively under the "orderly" transition scenario, and by 13.44 bps and 17.8 bps in 2025 and 2050 respectively under the more abrupt "sudden" transition scenario. However, such estimates do not take into account the effect on financial stability of certain investments. Nevertheless, such estimates in climate related risks entail a needed increase of the risk weighted capital requirements of around 1% along the transition process to account for these risks. In a more extreme argument that is motivated by the high risk of being stranded sooner than their normal exploitation cycle, along with their expected impact on accelerating global warming and the consequent effect on financial instability, Philipponnat et al. (2020) argues for an equity based financing for new fossil fuel exposure. Under their estimation, such proposal implies a debt prohibitive risk weight on exposures to new fossil fuel extracting and producing activities of 1250%.

2.2 Collateral framework policy

Central banks routinely give loans to banks against assets that serve as collateral. CBs determine the terms and criteria required for different assets to be eligible and accepted by

CB as a collateral. What CBs accept as a collateral, and how much credit it gives on the basis of it, affects the refinancing costs of such assets for banks and financial intermediaries directly. Accordingly, assets that give access to central bank money are valued more by banks and get a differential treatment that increases their price and therefore lowers their yield compared to other assets. Under this tool, banks and other financial institutions do not get access to the full value of their assets in central bank money, rather CBs apply "haircuts" on these values determined mainly by associated risk. Therefore, assets with higher haircuts have lower liquidity and their issuers face higher cost of capital to finance different investment opportunities [Ashcraft et al. (2011)].

Collateral frameworks could be used to favor the financing conditions of green assets. A central bank can define eligibility and haircut criteria for its collateral framework that include a sustainability dimension. The latter could be based on climate related risks and thus results in higher haircuts for brown sectors. This way, green sectors would enjoy lower refinancing costs relative to brown sectors. Consequently, from the perspective of a bank, green assets will have a higher value, which they will pass through as a lower cost for firms. Dafermos et al. (2021), Schoenmaker (2021) , and Banque de France (2020) show that the current Eurosystem collateral rules for corporate bonds are not aligned with the European Union's climate goals.

Bindseil and Papadia, 2006 describe the mechanism by which the collateral premium translates into better funding for firms issuing eligible assets. They distinguish between several premia associated to collateral operations. One premium is the eligibility premium where assets that become eligible witness an increase in their demand and price and a decrease in their yield relative to non-eligible assets [Monnin and Guo (2019), Bindseil and Papadia (2006)]. Several studies were conducted to estimate this eligibility premium based on events by which central banks extended the eligibility criteria to different assets. Van Bekkum et al. (2018) used the ECB's extended collateral eligibility criteria for Class 2 and 3 Residential Mortgage-Backed Securities (RMBS) that took place in December 2011 and June 2012. They find an interest rate reduction of 76 bps in annualized interest on mortgage origination in banks that were actively issuing Class 2 and 3 RMBS. Mésonnier et al. (2017) compared the interest spread between firms with rating 4 and 4+ before and after the implementation of the Additional Credit Claim (ACC) frameworks. They find that this spread decreased by 7 bps when loans with a rating of 4 became eligible as a collateral. In a recent study, Macaire and Naef (2021) reported a spread incease of 46 bps between green and non-green bonds as a reform by the Public Bank of China (PBoC) in which the bank started to accept green bonds as collateral for its medium-term lending facility in 2018.

Another premium associated to collateral operations is referred to as the haircut premium where assets with higher haircuts provide less liquidity services and are consequently valued less by financial institutions [Monnin and Guo (2019)]. Their demand will be lower compared to similar assets with lower haircuts. This will reduce their market price and thereby increase their yield and cost of capital to the issuers. The haircut premium is the difference in yield between two similar assets that differ only in their haircuts. There are no direct estimation studies for haircuts premium. There are indirect estimates based on simulations by theoretical models or by conducting surveys among market stakeholders to bid a value for assets with different haircuts. For example, using a survey based evidence focused on the Term Asset Backed Securities Loan Facility (TALF) program which supplied loans with longer maturity and lower haircuts than was prevailed, Ashcraft et al. (2011) reported that the reduction in yields could exceed the long term 40 bps as a result of lowering haircuts during crises.

In light of the above estimates, the effects on the cost of capital associated to collateral frameworks could range from 7 bps to 76 bps for eligible assets. Noting that there are several proposals to make the collateral frameworks of central banks more consistent to climate targets. For example, Dafermos et al. (2021) propose three policy scenarios to green the Eurosystem bond collateral framework, which aim at incentivizing banks to invest in greener corporate bonds. Their scenarios are based on bonds' carbon footprint and differ in either the eligibility criteria, the adjustment of bonds' haircuts, or both. They show that under the scenario where the bonds of carbon intensive companies are replaced by the bonds of companies that are not carbon-intensive which satisfy the eligibility criteria fully or partly could reduce the weighted average carbon intensity of the Eurosystem collateral framework from around 243 tCO2e/$m to 71 tCO2e/$m. Under the same objective, Banque de France (2020) argues for an aggregate collateral pools alignment with climate targets pledged by central bank's counter-parties instead of aiming for assessing the alignment on an asset-by-asset rule. Mcconnell et al. (2020) investigated the impacts of adding carbon intensity based haircuts to the central bank's collateral framework using an extended general equilibrium transition model with a simple banking sector. They find that such instrument would be effective in steering investments towards carbon neutral ones, along with playing a promising role in reducing the transition burden on governments.

2.3 Asset Purchase Programmes

Asset Purchase Programmes (APP) are used as non-conventional monetary policies to stimulate the economy. The main principle of these programmes is to buy corporate bonds in a way that does not distort the market, also known as the market neutrality principle. However, recent evidence shows that the market neutrality is not desirable from a sustainability perspective. For example, the ECB's Corporate Sector Purchase Programme (CSPP) turned out to be biased towards emission intensive firms [Matikainen et al. (2017)]. Schoenmaker (2021) argues that the asset purchases can be tilted towards climate friendly assets thus accelerating the energy transition. This could be achieved by relating the relative share of a firm's securities inversely to its carbon intensity. In the proposed tilting approach, CBs put more weight on low-carbon companies and less weight on high-carbon companies in their portfolio, which results in a relatively lower cost of capital for cleaner green sectors. Moreover, employing a stock-flow fund ecological macroeconomic model, Dafermos et al. (2018) find that a green corporate Quantitative Easing (QE) programme could decrease the induced climate related financial instability and mitigate the increase in global temperature. Furthermore, Dafermos et al. (2020) suggest two low-carbon strategies that the ECB could adopt to replace the market neutrality approach which would reduce the environmental footprint of the ECB's quantitative easing programs and make available finance through such programmes more aligned to Paris goals.

Similar to the mechanism under the collateral framework, the eligibility of certain assets under asset purchases by the central bank is valued by financial institutions as it gives access to central bank money. This increases the demand for, and the market price of, such assets thus reducing its yield and the cost of capital for the original issuers/investors..

Another effect of asset purchases by central banks is to crowd out private investors. These investors will re-balance their portfolio and move to different corporate bonds than those targeted by central banks. This will increase the demand for and prices of such assets and reduce their yield. Accordingly, this might dampen the effect of better funding conditions for firms whose bonds are eligible.

Several studies have aimed to estimate the effects of central bank asset purchases. Studies on the impact of the announcement of eligibility of bonds to the asset purchase programme find a negative effect on the yield of eligible bonds. These studies find that there will be a spillover to non-eligible bonds which witness a reduction in their yield triggered by the re-balancing effect by private investors or banks, that is the general monetary expansion effect. The quantitative effect of the reduction in yield differs per programme. Hancock and Passmore (2014) investigated the effect of holding Mortgage-Backed Securities (MBS) by the Fed. They found that the yield of MBS purchased by the central bank fell by 55 bps relative to a scenario with no purchase. Arce et al. (2017) reported an average decrease of 46 bps in the yield of eligible bonds after the announcement of Corporate Sector Purchase Programme (CSPP) by the ECB. Furthermore, they reported a yield decrease of 46 bps as a re-balancing effect on non-eligible bonds, which yield a net long term effect that equals zero. Zaghini (2019) reported a short term effects of 70 bps in yield reduction of eligible bonds, while in the long term, the difference between eligible and non-eligible bonds decreases to 20 bps driven mainly by the re-balancing effect of 50 bps reduction in the yield of non-eligible bonds. Schoenmaker (2021) simulated a tilting approach for the ECB's CSPP aiming at a higher allocation to low carbon companies with a 25% reduction in medium carbon assets and a 50 % decrease in high carbon assets. He reported a possible 4 bps increase in the spread between low carbon and high carbon companies. Mésonnier et al. (2017) estimated a 7 bps in credit spread for French companies that become newly eligible under the Additional Credit Claims (ACC) programme of February 2012 that extended the Eurosystem's universe of eligible collateral to medium-quality corporate loans.

In light of above estimates, the effects APP could induce a short term direct yield decrease that ranges between 46 bps to 70 bps for eligible assets. However, large part for these yield reductions are offset by the long term re-balancing effect of non-eligible assets, which induce a yield decrease between 46 bps and 50 bps for non-eligible assets. Accordingly, the long term net effect ranges between 0 and 20 bps for eligible assets.

2.4 Refinancing Operations (RO)

In addition to regular open market operations that are guided by the collateral framework, central banks have increasingly been deploying more targeted and longer term refinancing operations for banks (TLTRO). The objective of the TLTRO is to incentivize banks to extend their lending to the targeted sectors in the real economy. The more banks lend to the targeted sectors the more access they have to cheap central bank money, lower interest rates or higher borrowing limits. Using these instruments to achieve climate targets can be done by giving banks favorable interest rates for loans given to finance green projects [van't Klooster and van Tilburg (2020)].

The ECB had two TLTRO programs, while the BoE had its Funding for Lending scheme (FLS). Under these programmes, banks were able to borrow against loans given to the non-financial private sector under certain conditions on the quantity given. The maturity of these loans varied between 2 and 4 years. The rates were lower than prevailing market rates[1].

Monnin and Guo (2019) identify the similarity in transmission channels under this tool compared to the channels under the collateral frameworks. Empirical studies into these operations show that participating banks passed through the low rates in their loans to firms, along with an increase in the volume of these loans. Noting that the design of such programmes matters in explaining possible differences in their effects.

The empirical evidence on the effects of TLTROs on the cost of capital is scarce. To our knowledge, only Benetton and Fantino (2021) quantifies explicitly these effects for TLTRO-I. They reported that participating banks in TLTRO-I passed through a 20 bps reduction in lending rates to the same firms, compared to rates offered to non-participating banks[2]. Most of the remaining evidence is focused on the effects of TROs on either the probability of easing credits credit standards [Andreeva and Garcia-Posada (2019)], tightening margins [Gómez et al. (2019)], the increase in corporate lending [Laine (2020)] or bank credit supply [Afonso and Sousa-Leite (2020)].

Accordingly, available evidence on the effect of TROs on the cost of capital suggests that the reduction in lending rates for targeted sectors relative to non-targeted ones depends on the rate that is given by the CB. Under TLTRO-I, the pass through rate accounted to up to 20 bps reduction in lending rates. However, the empirical evidence on the effects on lending rates under other programmes and schemes is still scares, and as TLTRO-I could be considered a weak version of TLTRO-II and TLTRO-III[3], we argue that the reduction in lending rates has a lower bound decrease of 20 bps.

[1] The borrowing rate under TLTRO-II was equal to the prevailed rate on main refinancing operation, along with a possible rate reduction up to the deposit facility rate (was -0.4%) in case of exceeding a benchmark on bank's net lending. Under BoE's FLS, participants were able to borrow UK Treasury bills against a range of collateral. They could use such bills to borrow from the BoE through its discount window facility or to exchange these bills for central bank money in the buffer for their liquid assets.

[2] The interest rate on TLTRO-I was 10 basis points above the Main Refinancing Operations (MRO) rate (0.15 on the 11th of June 2014, and 0.05 on the 10th of September 2014) at the time of the tender announcement. Under TLTRO-I, the borrowing allowance accounted for 7% of outstanding eligible loans.

[3] The interest rate on TLTRO-II was equal to the MRO rate at the time of the tender allotment. The interest rate on TLTRO-III was originally equal to 10 basis points above the average MRO rate over the lifetime of the TLTRO. The borrowing allowance accounted for 30% under TLTRO-II, and 50% under TLTRO-III, of the outstanding eligible loans.

2.5 Summarizing remarks

In conclusion, the surveyed literature shows that the implementation of different CB's tools would induce a differential in the cost of capital for affected assets relative to other assets (between green and brown assets for example). In light of the specificity of these tools and their implementation circumstances, we argue that some of their effects could become cumulative, at least partly. As APP and TLTRO work through bonds and bank lending respectively, they can be considered complementary to each other. However, both collateral frameworks and capital requirements can be combined with each other or with other instruments.

Under the studied levels of central bank intervention, financing through bonds (combining collateral frameworks with APP) could induce an effect on the cost of capital somewhere in the range between 7 bps and 96 bps[4].

CB instrument	**Lower bound effect**	**Upper bound effect**
Capital Requirements (1% increase in risk weighted assets)	2.5 bps	20 bps
Collateral Frameworks	7 bps	76 bps
Asset Purchase Programs (APP)	0 bps	20 bps
Refinancing Operations (ROs)	20 bps	More than 20 bps

Table 1: Possible reductions in cost of capital induced by different supervisory and monetary instruments

All in all, based on surveyed empirical evidence, and depending on the level and scope of the instruments used, a differentiation in the cost of capital of 100 bps between green and brown assets triggered by one or a combination of a green version of these instruments seems an ambitious, yet possible estimation. In subsequent sections we quantify the effect of such policy on the transition process across sectors and between scenarios.

[4]We acknowledge that in reality there might be feedback effects which would induce a deviation in the aggregated affect from the simple sum of impacts.

3 Methodology

In this study we investigate the effects of monetary and supervisory green intervention on the transition process towards a low carbon economy. Our interest lies in quantifying the effects of such policies taking into account the possible feedback loops within and across sectors through energy prices. To this end, we develop our Dynamic General Equilibrium Model for Sustainable Transitions (GEMST-1) model where every final sector has a green and brown sub-sector. In the power sector, the model distinguishes between renewable and conventional fossil fuel power sectors. Moreover, the model features sector-specific capital stocks that allow us to differentiate the cost of capital across different (sub)sectors[5]. We describe in this section the model framework and main mechanism. We also introduce our selected scenarios and their associated assumptions. Annex 1 contains all technical details about our model, along with parameters calibration, sectoral coverage and the main criteria to define green sub-sectors.

3.1 Model description and framework

GEMST-1 is an applied general equilibrium model that has neoclassical foundations, with utility maximizing consumers and profit maximizing producers. Even though these assumptions are greatly debated, we adopt them as our analysis is focused on the supply and demand forces in every market and their effect on endogenous prices. The model envisages 6 aggregated final sectors, namely: Agriculture and Forestry; Real-estate; Manufacturing; Transportation; Utility and Construction, along with an aggregated "Other" sector for the remaining final sectors which are low carbon intensive (for example: Financial and business services; Public administration; Education; Human health and social work). Power can be generated by renewable or conventional sources distinguishing 7 types of power plants.

[5]Note that most CGE-models model the financial markets relatively parsimoniously. Many models have only one cost of capital for all sectors or do not even model the financial markets explicitly. To the best of our knowledge, there are no readily available CGE-models that would allow us to quantify the impact of environmentally differentiated monetary policy in a meaningful way.

Renewable power is generated by Wind, Solar, Hydro, and Other renewables (includes Geothermal and Nuclear) sources. The remaining 3 conventional fossil fuel power sectors include Coal, Gas and Oil representative plants. The model covers one region with no trade channels. This means that leakages between regions in emissions and competitiveness and any dampening or enforcing effects of international trade are not accounted for by construction. As mentioned above, every final sector produces two distinct varieties, one green and one brown with the possibility of substitution between them in consumption. That is, in every final sector consumers can substitute green for brown varieties and do so at a given, constant elasticity of substitution. The criteria for defining green sub-sectors are based on the substitution opportunities between energy sources, efficiency improvements in using different energy sources, and the electrification possibilities in different sectors. These criteria are outlined and detailed in section 2 of Annex 1. Moreover, every brown or green variety is produced using 4 main production factors, namely, labor, capital, energy and an aggregator for other inputs. Labor and other inputs are assumed to be mobile across sectors with exogenous supply, while supply and demand of capital is assumed to be sector-specific and thus every sector has its own Marginal Productivity of Capital (MPK) in equilibrium. Energy is also assumed to be sector-specific. Every sector has its own energy bundle that combines electricity and a fossil fuel bundle. The latter bundle is sector-specific as well, with different substitution possibilities and policies between oil, gas and coal for every final sub-sector. Finally, each of these fossil fuel sources is assumed to be mobile across sectors. Accordingly, the economy-wide price of every energy source (electricity, gas, oil and coal), along with the substitution possibilities between these sources in different sub-sectors will determine the demanded quantities for each energy source by each sub-sector. All sectors buy the lowest cost energy source up to the point where the last unit of energy bought generates just enough extra sales to justify the purchase. Renewables use capital, labor and other inputs as the main factors for their production. Similarly, conventional power relies on these production factors, along with a corresponding fossil fuel source. Power and final output are used for consumption and the production of capital (investment) goods. Figure (1) illustrates the model framework with the main sectoral relations with the arrows indicating the flow of inputs and goods between sectors.

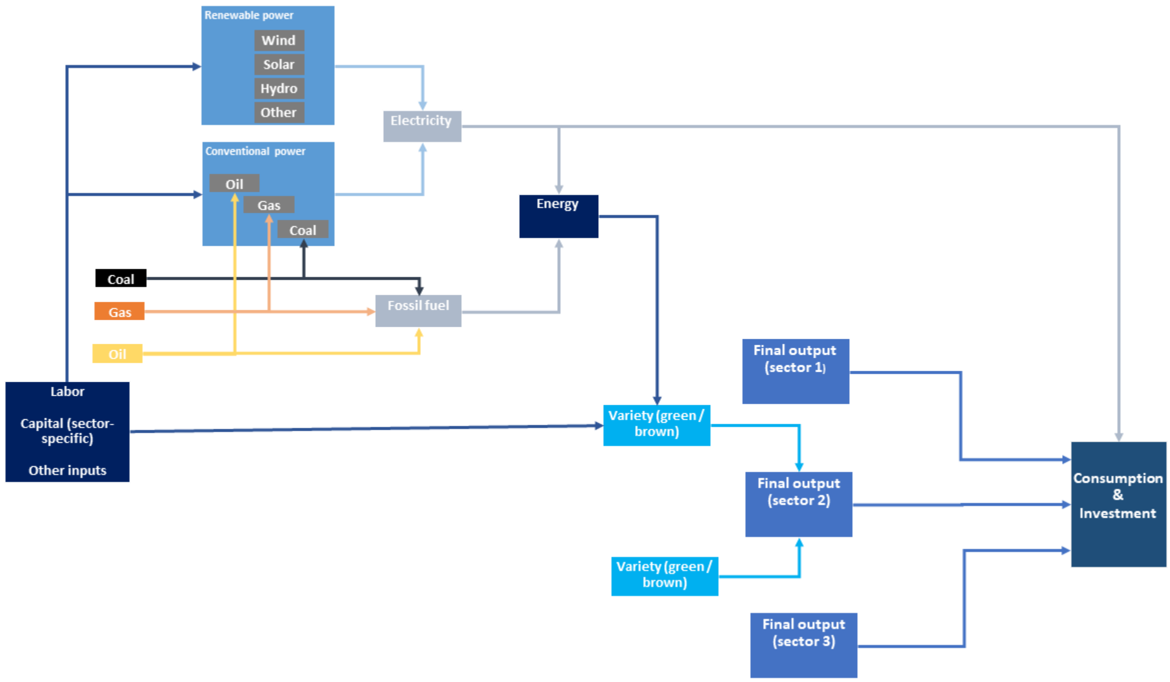


Figure 1: GEMST-1 model framework

We normalize the aggregate price of investment goods in our model to 1 (the numéraire). We assume that the expansionary effect of the green CB's policies is neutralized in contractionary effects on the brown side of the economy, which makes the investment cost constant over time and across scenarios. Alternatively, any inflation in investment goods price is normalized out, even if CBs do not neutralize. That means that reported changes in prices following a certain shock are interpreted relative to the fixed cost of transition. In every period savings are used to buy investment goods, which in turn are allocated across sectors based on their incentives to invest. These incentives are defined as the difference between the endogenous sector-specific Marginal Productivity of Capital (MPK) and the exogenous sector-specific cost of capital. Accordingly, sectors with higher incentives to invest will undertake a higher share of new investments.

The model is calibrated using GTAP10 input-output database along with other sources to calibrate different elasticities and parameters across sectors in the initial period. For a given supply of labor, other input, capital and different fossil fuel sources, the equilibrium is determined by a set of prices that equate the demand and supply in every market. Any shock to the economy will induce changes in the relative price/costs of different inputs/outputs. That induce a change in demand/supply and prices.

For a given fossil fuel supply, that would result in demand driven price changes and no changes in emissions as emissions are assumed proportional to that supply. In order to estimate the ex-post first order effects of the shocks on emissions, we assume a fixed price elasticity of the fossil fuel supply. Following a change in fossil fuel prices, we use these supply elasticities to estimate the change in fossil fuel supply between scenarios. Subsequently, employing the emission intensity of different fossil fuel sources, we can estimate the first order changes in emissions between scenarios. Second order effects, such as dropping fossil fuel prices, lower ETS emission rights prices or laxer regulatory and fiscal policies in response to the greening of central bank policies are not considered here, even if they all may jeopardize the effectiveness of central bank actions. We elaborate on this point when we introduce our results in section 4.

The model is driven over time by the exogenous growth in labor, productivity, and other inputs which is assumed similar across scenarios, along with the endogenous sector-specific accumulation of capital. Green supervisory or monetary policies enter the model through their effect on the cost of capital between sectors.

3.2 Model mechanism

In order to understand the effects of a certain policy intervention, we explain the main mechanisms in our model. Any shock to the equilibrium in our model will induce a change in relative prices of different production factors and translates to change in their demand/supply and the relative price of varieties produced. As the main difference between green and brown production lies in the dependency on different energy sources, a policy shock propagates the economy mainly through changes in energy prices. The relative position of different sectors changes depending on the substitutability between fossil fuels and electricity in high energy intensive and less energy intensive sectors.

An intervention in the form of (exogenous) lower capital costs in targeted (sub)sectors would increase their competitive position for new investments, and induces a re-allocation of new investments towards these (sub)sectors. This would change the installed capital stocks across (sub)sectors. Targeted (sub)sectors with relatively lower cost of capital will witness more investments and end up with a higher capital stock. The opposite happens in other (sub)sectors. Capital stocks across (sub)sectors could even fall if new investments are not enough to cover the depreciation capital. Consequently, (sub)sectors with higher capital stocks would have a better competitive position and higher market shares. This would cause a chain of price and demand reactions for different production factors, which will be reallocated across (sub)sectors depending on their production dependency (elasticities) for every factor.

Dynamically, after the shock in period 1, the increase in market shares for targeted (sub)sectors would translate in higher demand for goods and their production factors, of which capital, and result in higher MPK for these (sub)sectors in period 2. Furthermore, another effect on MPK in period 1 is channeled through a change in relative energy prices. Such change will have an effect on the demand for different production factors across (sub)sectors, one of which is capital. In turns, new investments in the period 2 will be allocated among different (sub)sectors based on the net effect on the sectoral incentives to invest across sectors. For example, if after the shock in period 1 electricity becomes relatively cheaper than other fossil fuels, the demand and output by (sub)sectors that have higher substitutability between different energy sources or a higher dependency on electricity will rise. Consequently, this will have a positive impact on their MPKs, and thereafter, their shares of new investments in the subsequent period generating a positive growth for these sectors.

We note that our model does not trigger any changes in technologies or emissions/supplies of fossil fuels. However, the model induce changes in relative sector sizes and demands.

3.3 Policy scenarios

In this section we outline our transition scenarios and the assumptions associated to each of them. We assume the same macro drivers for all scenarios in terms of labor, other inputs, and productivity growth rates. In order to allow for comparability with other studies and to make sure that our scenarios reflect a plausible and realistic transition in the power sector, we adopt the IEA's transition scenarios for the power sector. This means that fiscal and regulatory climate policies that drive the transition in the power sector are assumed to correspond to those under IEA's scenarios. Accordingly, our transition period corresponds to that of IEA and has a 2050 horizon. Carbon taxes on final sectors are explicit and their levels are motivated in Annex 1. Moreover, we assume a constant supply of fossil fuel over the transition period and across all scenarios, which means that the change in energy prices will absorb and reflect the entire demand shift.

To get an order of magnitude effect of CB policies, it is best to see how far along the full Paris aligned transition CB policies (ambitious at 100 bps) would take us. So we have a baseline scenario that corresponds to current specified policies, a Paris aligned transition scenario and we compute how far along this transition we would get if CB targets only final (sub)sectors, only power sectors or both. Accordingly, we identify the following transition scenarios for our study:

Specified policies Scenario (SP): this is our benchmark scenario. Under this scenario, we assume the current global level of carbon tax to evolve gradually to a low level of 60 USD/tCO2e in 2050 over the studied period. Moreover, the electricity mix is assumed to evolve according to IEA's Stated Policies Scenario (STEPS). We have no CB intervention under this scenario.

Central Bank Policies (CBP) scenarios: here carbon taxes and the evolution of electricity mix over time are assumed similar to those under SP scenario. The main deviation from SP scenario is the differentiation in the cost of capital (interest rate) between sectors. We assume an active differentiation of 100 basis points over time. This assumption implies the activation of green CB intervention over the whole transition period regardless of the economic cycle. The continuity of central bank intervention over the transition horizon is motivated by the continuity of some of its instruments by design, like capital requirements and collateral frameworks which are in place regardless of the economic cycle. It is questionable whether unconventional monetary instruments like APP and TROs will be applied continuously until 2050. However, they have been applied for 8 years in Europe and over 10 years in both the US and UK. Furthermore, structural developments like slower productivity growth, demographic factors and the legacy of the global financial crisis may very well depress economic development for the years to come [ECB, 2021]. Moreover, the macroeconomic costs associated to the transition following the pricing of externalities and resources that used to be free could add downward macro economic pressure in the coming years [Pisani-Ferry, 2021]. These developments may induce economic conditions that necessitate the continuation of monetary support during most or the whole of the transition process.

As some CBs instruments, could be used to target certain sectors, we distinguish between three sub-scenarios depending on the targeted (sub)sectors under monetary intervention:

- **CBP-all:** under this scenario, we assume that CB intervention induces a lower cost of capital for both green and renewables (sub)sectors.

Central banks could also consider using their policy to support the transition in certain sectors. Accordingly, we construct two hypothetical scenarios under which CB's policy targets final or renewables sectors, and we analyze possible feedback loops that could emerge across sectors of such policy. These scenarios read:

- **CBP-final:** under this scenario, CB intervention induces a lower cost of capital for green sub-sectors only.
- **CBP-renewables:** under this scenario, CB intervention induces a lower cost of capital for renewables sectors only.

Ambitious Climate Action (ACA) scenario: this scenario reflects a sustainable carbon tax scenario. We assume that the electricity mix evolves according to IEA's "Net Zero Emissions" scenario. Furthermore, we assume a progressive carbon tax over time, with tax that reaches 110 USD/tCO2e in 2030, 180 USD/tCO2e in 2040, and 225 USD/tCO2e by 2050. No monetary intervention is assumed under this scenario. This scenario represents an upper bound for climate action that will be used for comparison with other scenarios.

4 Results

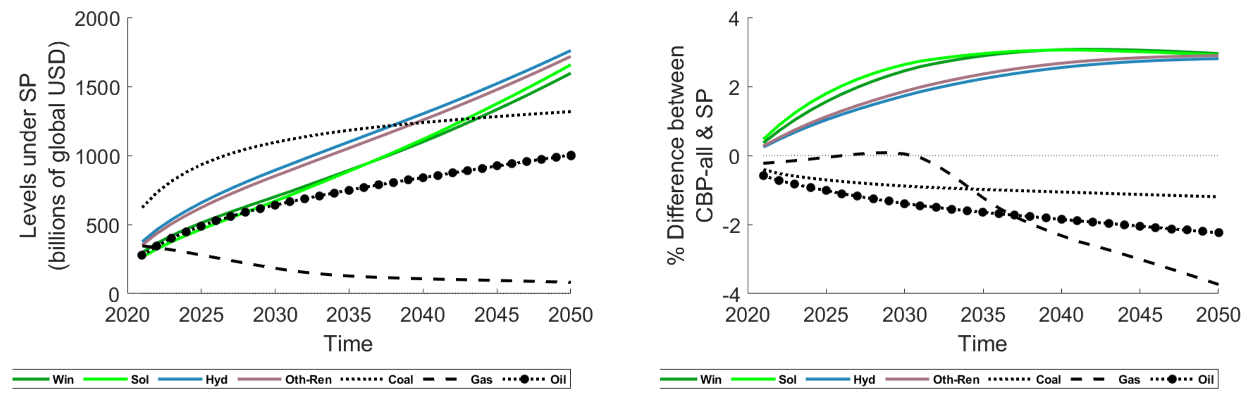
In this section we present the results of our simulations. Our focus will be on the effect on energy prices, capital stocks, emissions, and some distributional effects. In our analysis we assume a differentiation of 100 basis point in the cost of capital between selected sectors. This difference is ambitious, but practically feasible and reflects a relatively high impact of green CB policies as motivated by our literature review. We start this section with the analysis of the CBP-all scenario relative to the SP scenario as a benchmark. We then highlight the main differences in impacts with the CBP-final and CBP-renewables scenarios. Finally, we contrast the obtained results with these under ACA scenario by calculating the total emission reduction gap between SP and ACA. Thereafter, we express the impact of the CBP scenarios on emissions as a share of the total gap to have an indication of the potential contribution of green CB intervention in achieving our climate goals.

4.1 Effects under green CBP-all scenario

We start by analyzing the induced impact on the transition followed by the effect on distributional effects and prices.

4.1.1 Effects on capital allocation across sectors

Under the CBP-all scenario, the CB intervention induces a reallocation of new investments from brown and conventional power (sub)sectors towards green and renewable (sub)sectors. Moreover, the policy triggers a series of chain reactions and substitution between different production factors among (sub)sectors. The net effect of this reallocation can be seen in capital stocks across (sub)sectors.



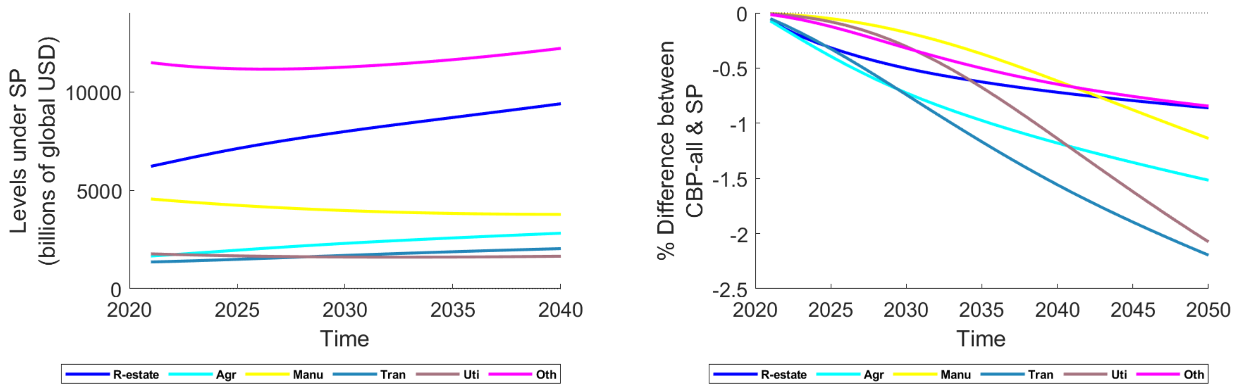
(a) Levels of power capital stocks in SP scenario.

(b) Change in power capital stocks between CBP-all and SP scenarios.

Figure 2: Under CBP-all intervention we invest more in renewables and less in conventional power sources.

Figure (2) summarizes the impacts for power sectors, with Win, Sol, Hyd and Oth-Ren denote Wind, Solar, Hydro and Other renewable power sources respectively. Panel (2a) of this figure shows the paths of power capital stocks over time under the SP scenario. Differences in levels across power sectors reflects their shares in the electricity mix for every period. The unit of the vertical axes in this panel is in billions of global US dollars in the calibrated initial period, while time is depicted on the horizontal axes. The graphs in this panel are driven mainly by the expected evolution of the electricity mix under IEA's "STEPS" scenario which we imposed exogenously on our model such that we make sure that our SP scenario is consistent with the actual expected transition in the power sector. The panel manifest a growth in all power sectors except for gas indicated by the negative slope of its capital stock over time. Such trend for the gas power sector means that the allocated new investments to this sector are not sufficient to cover the depreciated capital. moreover, this panel reflects a faster growth of almost all renewables compared to conventional power sources under the benchmark scenario.

In panel (2b) we see the relative effects of CB intervention between CBP-all and SP scenarios across power sectors over time. The difference between scenarios is expressed as a percentage from the SP scenario in every period. Thus, what is shown in this panel is a cumulative percentage difference between scenarios. The impact curves show a positive impact on all renewables at the expense of conventional power sectors which suffer from lower investments and slower capital growth. Among renewables, Solar witnesses the biggest positive impact over the first two decades of transition, followed by Wind, Other renewables, and Hydro respectively. In contrast, the Oil power sector has a consistent decline over the transition horizon followed by Coal which declines at a lower level. The Gas power sector shows a modest or no decline in capital stock until 2030, after which the decline in this sector become the fastest among conventional power sectors.



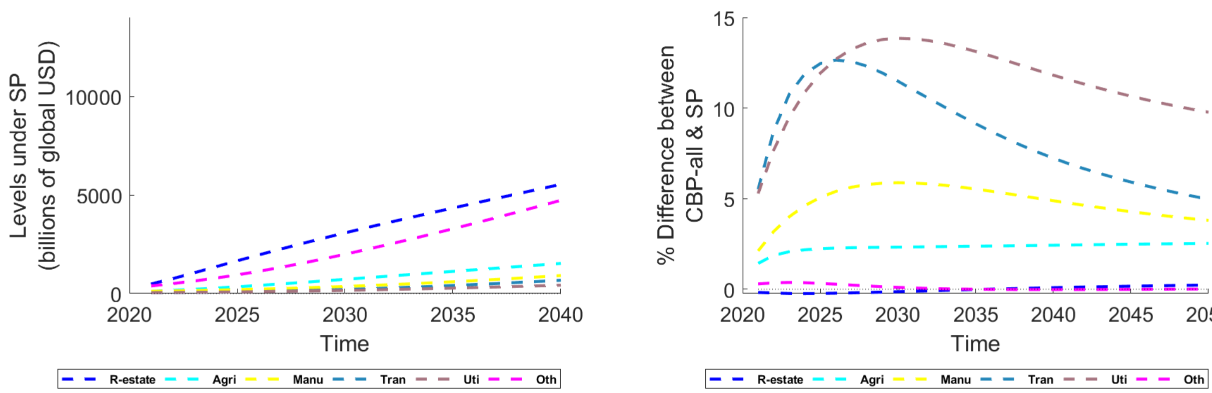
(a) Levels of brown capital stocks in SP scenario.

(b) Difference in brown capital stocks between CBP-all and SP scenarios.

Figure 3: Under CBP-all intervention we invest less in brown sub-sectors.

Figure (3) shows the induced CB intervention impacts among brown sectors, with R-estate, Agr, Manu, Tran, Uti and Oth denote Real-estate, Agriculture and forests, Manufacturing, Transportation, Utilities and Other final sectors respectively. Here again, panel (3a) of this figure depicts the evolution of brown capital stocks over the transition horizon in the SP benchmark scenario. Differences in levels across sectors reflects their market shares in final consumption where Real-estate and the Other sectors have the biggest shares. From this panel we see that some brown sectors witness a growth over the transition period like Real-estate and the Other sectors, while brown Agriculture grows at a lower rate. Brown Transportation and Utility & Construction sectors seem to be constant over time, meaning that new investments in these sectors are roughly equal to the depreciated capital. That is not the case for brown Manufacturing where this sector witnesses a decline over time.

In panel (3b) the relative difference between scenarios for every period are depicted. For example, this panel shows that all brown sectors are affected adversely by the shock. Effects range between 0 in early periods to a maximum of 2.2% in 2050. The largest quantitative relative effect over the transition horizon is on brown Transportation and Agriculture sectors and the lowest effect is on Manufacturing, Other sectors and Real-estate. The effect on the brown Utility & Construction sector is relatively low in early transition periods but becomes stronger starting from 2030. Sectoral effects mainly depend on the substitution towards green sub-sectors, the induced change in energy prices along with the sectoral dependency on different factors.



(a) Levels of green capital stocks in SP scenario.

(b) Difference in green capital stock between CBP-all and SP scenarios.

Figure 4: Under CBP-all intervention we invest more in most green sub-sectors.

Similarly, panel (4a) shows the levels of green capital stocks in the SP-scenario. These stocks are at very low levels in 2021 which follows from their initial market shares. Over the transition period, all green sectors witness a growth with the highest growth in the Real-estate sector. Panel (4b) illustrates the effect of the CB intervention on the transition of green sub-sectors. The highest relative impact over time is seen in the green Utility & Construction sector followed by green Transportation and Manufacturing. The effect on these sectors has a humped shape with higher impacts in the first decade. However, this increase peaks in different years across these sub-sectors. For green Transportation it reaches 12.64% in 2026, while for Utilities & Construction and Manufacturing it reaches 13.85% and 5.88% in 2030 respectively. The humped shape effect is mainly driven by substitution between green and brown sub-sectors. The effect on green Agriculture ranges between 1.4% and 2.6% over the transition horizon. Effects on green Real-estate and the green Other sector are modest in relative terms which fluctuate around zero over the transition horizon.

Taken together, the results show that green and renewable power (sub)sectors are expected to grow stronger than before the shock at the expense of brown and conventional power sectors. With the switch of investments towards green and renewable (sub)sectors, labor and other inputs flow proportionally towards these (sub)sectors as well. The effect on output of different (sub)sectors is negative for brown and conventional power (sub)sectors and positive for green and renewable (sub)sectors. The net impact on output is negative for almost all final sectors (an exception is the Utilities & Construction sector) and positive for the power sector.

In conclusion, a decrease in the cost of capital in targeted (sub)sectors, will result in higher investments for these sectors and higher market shares in subsequent periods. In the period that follows, higher market shares will induce higher demand for goods and thus higher demand for all production factors used for their production, of which capital. Higher demand for capital will increase the MPK and will affect the incentives to invest in that sector positively. As investments switch toward (sub)sectors which are less energy intensive and higher substitution opportunities between electricity and fossil fuel, these sectors will also benefit relatively more from a decrease in energy prices which reinforce their competitive position.

Finally, as the green CB policy induced a reallocation of investments toward green and renewable power sectors, we argue that the effect of the intervention is to speed up the transition as these needed investments are happening sooner than it would be without an intervention.

4.1.2 Effect on energy prices

In the previous section, we have studied the direct effect on investments across different sectors. In this subsection, we analyze the effect on energy prices.

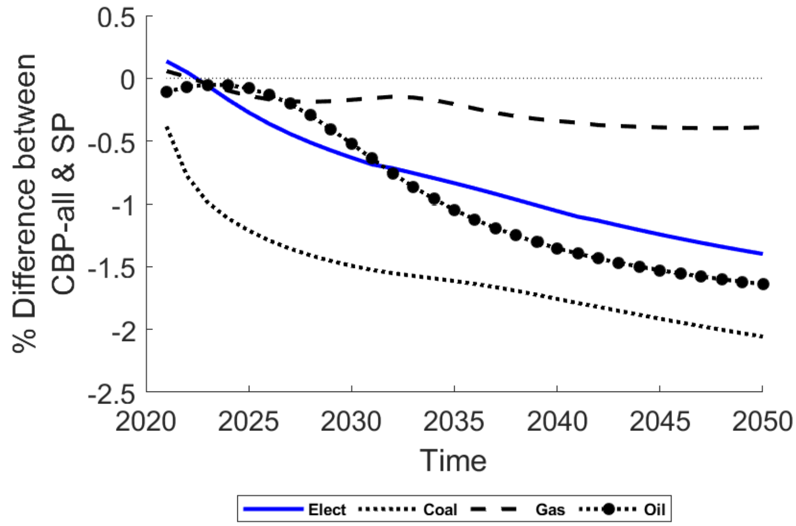


Figure 5: Difference in energy prices between CBP-all and SP scenarios. Under CBP-all induces lower prices for all energy sources.

Figure (5) reports the relative difference in the price of different energy sources in the model under CBP-all relative to SP scenario, with Elect denoting the Electricity price. We see from this figure a reduction in prices of almost all energy sources over time. The effect on the prices of fossil fuels is mainly driven by the decrease in the overall demand, since we have a fixed supply of these resources over time and across scenarios. On the one hand, the reallocation on investments away from conventional power sectors would reduce the demand for coal, gas, and oil used in the production of conventional power, inducing lower prices for coal, gas and oil. On the other hand, the reallocation towards green sub-sectors on the expense of brown ones would reduce the demand for different fossil fuels as brown sub-sectors are more energy intensive. These two channels reduces the total demand of fossil fuels and triggers a reduction in their prices. The reduction in coal and gas prices tops -2.05% and -0.39% respectively in 2050. Finally, oil price seems to have a relative slower decrease between the two scenarios in the first 4 years, where the lowest relative reduction of -0.05% is reached in 2024. After that, the reduction in oil price become stronger and tops a maximum of -1.64% in 2050. This effect is driven by the afro-mentioned humped shape switch in new investments towards green sub-sectors (Transportation, Utilities & Construction), which are less oil dependent than its brown counterpart. The demand for oil from these sub-sectors decreases along with a reduction in demand from conventional oil power plant. However, this reduction in price trigger a rebound effect by other (sub)sectors where lower oil prices make it relatively cheaper than other production factors to be used by brown Real-estate and Other sectors. Quantitatively, the reduction in demand dominates over the transition horizon.

The electricity price seems to increase a little in the first two years, followed by a steep decrease over time which reaches a highest relative decrease of 1.4% in 2050. That is, lower cost of capital on green and renewable (sub)sectors makes electricity cheaper by 1.4% compared to an electricity price that prevails under SP in 2050. The reduction in the electricity price means that the policies triggered a growth in power supply that outweighs the growth in demand from final sectors. From the supply side, more resources are channels from final sub-sectors and conventional power and towards renewables. Thus, the shock reduces electricity supply by conventional power and increases that coming from renewable sources. The net effect on total electricity supply is positive, inducing a higher supply of electricity in the economy. From the demand side, we have an increase in demand by all green sub-sectors.

We note here that the overall reduction in energy prices allows some brown sub-sectors, like Real-estate and the Other sector to substitute the capital investments lost by the intervention with higher demand for energy in their production process.

4.1.3 Effect on emissions

As emissions are proportional to fossil fuel supply in our model, which is assumed exogenous to our model, we cannot capture the policy effects on emissions. We acknowledge the limitations of not modeling the endogenous response of supply integrally, but given the current model, we aim in this subsection to show what the first order impacts will be. First order effects on emissions are straightforward to calculate. These effects follow from the above mentioned impacts on energy prices.

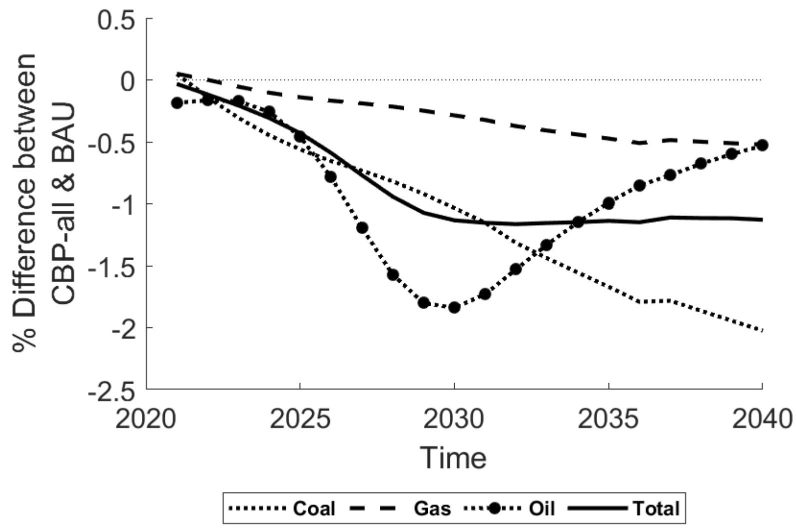


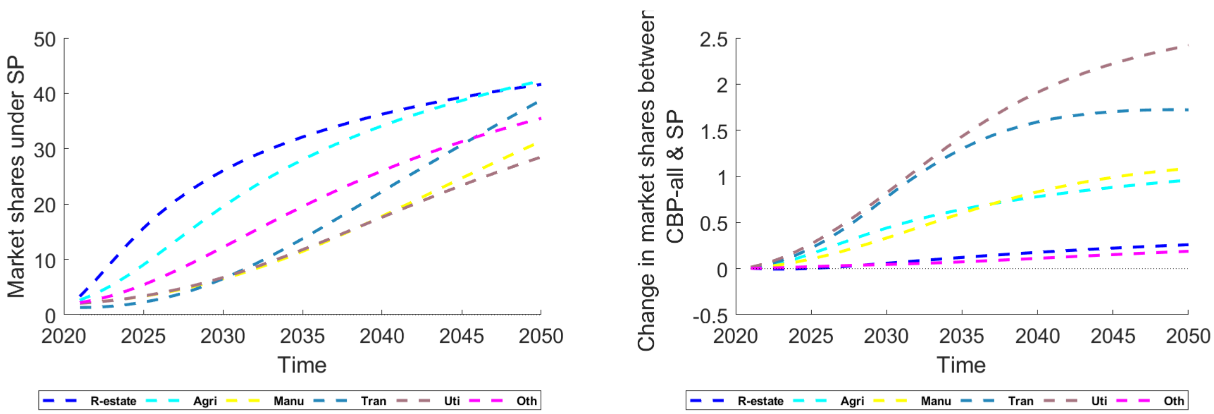
Figure 6: Difference in CO2 emissions by source between CBP-all and SP scenarios. Under CBP-all CO2 emissions are lower from all fossil fuel sources.

Effects on emissions are calculated using estimated average price elasticities of the supply of fossil fuel sources. These elasticities translate fossil fuel price changes between scenarios to changes in fossil fuel supply, and depending on emission intensity of fossil fuels, result in first order changes in emissions. These relative changes in emissions between scenarios are illustrated in figure (6). The curves for emissions by source are strictly proportional to those for energy prices. Resulting in a negative aggregate effect on total emissions which peaks at 2% cumulative reduction in 2050.

In a full model with a responsive endogenous fossil fuel supply, a reduction of supply of fossil fuels would have another round of second/third order effects. It would induce an increase in fossil fuel price which would trigger a decrease in demand from final sub-sectors especially brown ones. Green varieties become more competitive and output is reallocated from brown to green sub-sectors. Accordingly, we get a reduction in emissions but not a full reduction in output in terms of varieties and services. However, to some extent, it will also reduce fossil fuel supply, and therefore, create a chain reaction of price and quantity adjustments in the model. This could even bring the price of fossil fuels further down which could trigger an increase in their demand as a third order effect. However, we argue that the impact on emissions of these latter effects would be quantitatively small in comparison to the first and second order effects.

4.1.4 Effect on market shares

In every period, the shock of lower cost of capital is mainly absorbed in the current period by a reallocation of investments towards green and renewable (sub)sectors. However, this shock could propagate over time through changes in market shares between green and brown sub-sectors. In this subsection, we quantify the effects on green market shares over time.



(a) Green market shares under SP scenario.

(b) Change in green market shares between CBP-all and SP scenarios.

Figure 7: Under CBP-all market shares shifts towards green sub-sectors.

Panel (7a) plots the evolution of market shares across green sub-sectors under our benchmark SP scenario. In every period market shares of brown sub-sectors equals the subtraction of green market shares from 100%. We see that all green sub-sectors witness a growth in their corresponding market share over time. This is logical as these sub-sectors are more energy efficient and have, by definition, higher substitution opportunities between energy sources compared to brown one. Market shares of green Real-estate grows until it dominates

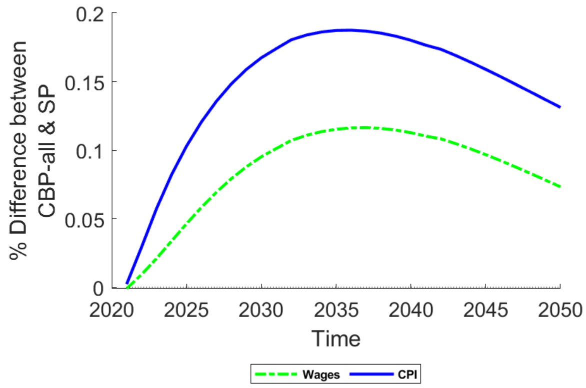
41% of the market by 2050. The lowest growth in green market shares is observed in the green Manufacturing, Utilities and Construction followed by the green Transportation sector respectively.

We quantify the effect of green CB intervention on the market shares of green sub-sectors in panel (7b). This panel reports the difference in market shares between the CBP-all scenario and the SP scenario. All graphs in this panel indicate a positive effect of CB intervention on green market shares. The quantitative effect is modest for some sub-sectors, especially for Real-estate and the Other sectors (around 0.2% in 2050). The highest quantitative effect is seen in the Utility & Construction sector, where the shock induces an increase of 2.42% in green market shares by 2050. Similarly, the increase in green Transportation peaks at 1.72% in 2050. The effect on shares of green Agriculture and manufacturing increases over time to around 1% in 2050.

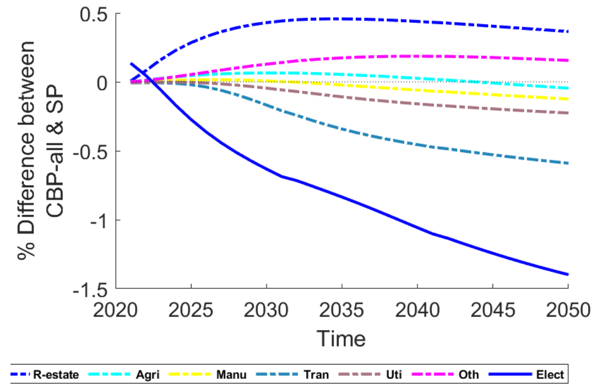
These results manifest the positive impact of green CB intervention on steering funds towards green sub-sectors and boosting the transition for these sectors.

4.1.5 Effects on price levels

Given their primary monetary objective of price stability, one of the model outcomes of high interest to central banks is the effect of their intervention on price levels across sectors in the economy. In this subsection, we report the relative change in prices between scenarios. However, we emphasize that the reported effects are relative to the normalized price of investment goods, which we have fixed and is stable at 1. Accordingly, the reported price changes between scenarios are in addition to the potential price changes for investment goods. Alternatively, the stability of the investment price can be motivated by assuming that the expansionary effect of the green CB's policies is neutralized by contractionary effects on the brown side of the economy, such that on average investment goods, prices remain stable.



(a) Difference in wages and CPI.



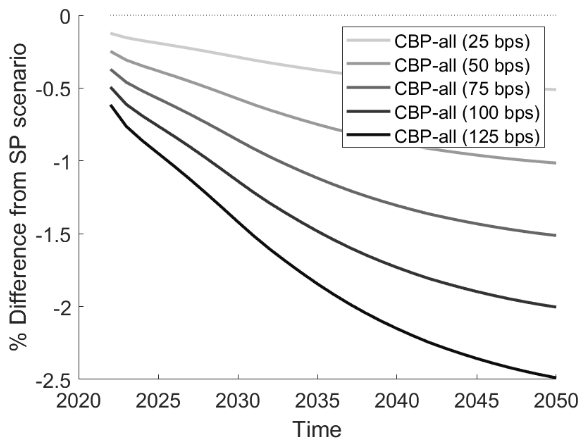
(b) Difference in the price for final consumption.

Figure 8: Under CBP-all intervention there will be an overall rise in price levels in the economy.

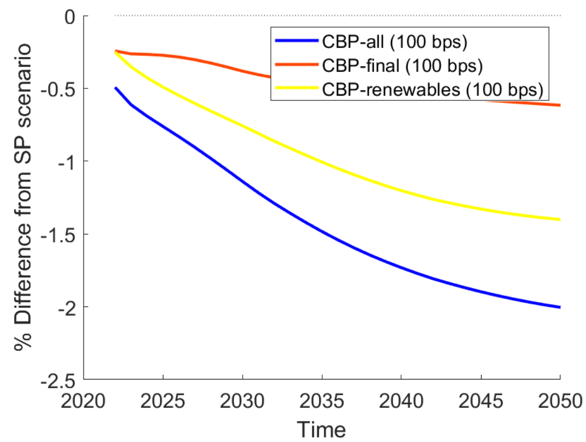
Figure (8) presents the relative effect on Consumer Price Index (CPI) and wages in panel (8a), while panel (8b) depicts the relative effects for final consumption prices across sectors. We see that prices of Transportation and Utilities & Construction witness a relative decrease with the highest decrease in the Transportation price. Real-estate, Other sectors and Agriculture becomes relatively more expensive overtime. The aggregate net effect on the cost of living is reflected by the effect on CPI which echos the budget weighted effect on final consumption prices. This indicator witnesses an increase over the transition horizon. The highest quantitative relative increase in the cost of living materializes around 2036 with 0.187% (or 18.7 basis points) increase in CPI under CBP-all relative to SP benchmark. In conclusion, the effect of CB intervention on price levels in addition to a fixed cost of transition (fixed price of investments) is considerable.

4.2 Different specifications for green Central Bank interventions

In this section we present the main differences in the aforementioned effects under two cases: the first when we assume different levels (lower or higher than 100 bps) of CB intervention under the CBP-all scenario; the second is when the CB intervention does not target all



(a) Difference in emissions between CBP-all and SP scenarios under different policy levels



(b) Difference in total emission under different scenarios relative to SP scenario

Figure 9: Effects on total emissions of CBP-all intervention is stronger with higher policy levels or sectoral coverage.

(sub)sectors in the economy at the same time.

In the preceding section we analyzed different effects under CBP-all scenario relative to SP benchmark assuming a lower cost of capital of 100 bps for green and renewable (sub)sectors compared to other (sub)sectors. We note that the described impacts are qualitatively the same under higher reductions in the cost of capital for green and renewable (sub)sectors. Quantitatively however, these effects are stronger. Panel (9a) of figure (9) reflects how the quantitative effects differ across several policy levels. The figure plots the relative effect on emissions for a 25, 50, 75, 100 and 125 bps policy induced capital cost gap under CBP-all scenario. We see that these effects are proportional to the policy level. That is doubling the policy level would double the effect.

Additionally, in Appendix A we analyze the main differences in effects under two ‘partial’ CBP scenario's: CBP-final and CBP-renewables. Under CBP-final the CB is assumed to reduce the cost of capital of green sub-sectors only, while under CBP-renewables the CB targets renewable power sectors. For both scenarios, the reduction in capital cost is assumed 100 bps. Such analysis would help understanding potential differences and emerging feedback loops between final and power sectors. Moreover, it allows for comparing the effectiveness of different specifications of CB's green intervention. The full policy analysis for these two scenarios can be found in Appendices B and C where we present the main differences in the relative policy impacts under these scenarios compared to the above analyzed impacts under CBP-all scenario.

Under the CBP-final scenario investments are driven away from the power and brown (sub)sectors towards green sub-sectors. Lower capital in conventional power is substituted by higher demand for other production factors of which coal and gas, which in turn increases their prices. The oil price on the other hand follows a similar trend as that described under the CBP-all scenario with a lower oil price mainly because of the demand reduction by the Transportation sector. Using our price elasticities of supply to compute the impact on emissions, the reductions from oil under this scenario are mitigated by the rise in emissions from coal and gas. The aggregate relative effect on emissions is negative as shown in panel (9b). Lower capital stocks in the power sectors reduces the supply of electricity. Electricity demand by brown sub-sectors decreases, while that by green sub-sectors increases. The net effect of the supply and demand forces on electricity price is positive. With regard to distributional effects, a reduction in the capital cost for green sub-sectors by higher investments would induce a reallocation of labor toward power sectors to substitute for lower capital stocks. Finally, the effects on CPI are positive over the transition horizon (highest positive effect is 10.64 bps in 2042).

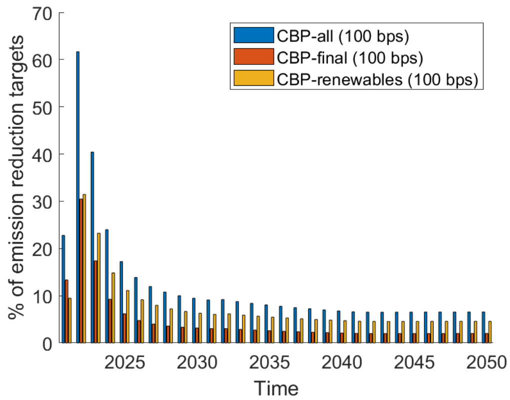
Under the CBP-renewables scenario investments are driven away from final and conventional power (sub)sectors towards renewables and green Transportation. Lower capital in final sectors is substituted by higher demand for other inputs of which oil, which in turn increases its price and emissions. More employed renewable capital would shift electricity supply away from conventional power, which decrease the output and the demand of other production factors by conventional power sources triggering a decrease in coal and gas prices and their emissions. The net effect on total emissions under this scenario is negative as showed in panel (9b). The total supply of electricity increases reducing its price and triggering higher demand for final production and consumption. With regard to distributional effects, under this scenario as capital becomes scarce and more expensive for most final sub-sectors, labor will be reallocated towards renewables, green Transportation, and brown Real-estate (substitution effect). CB intervention under this scenario will induce a sooner switch towards, and higher market shares of green Transportation only, while the remaining of green sub-sectors witness an adverse modest impact on their market shares. Accordingly, a CB intervention that targets the power sector could induce a feedback effect that speed up the transition in the Transportation sector and hinder the transition in the remaining final sectors. Finally, the effect on price levels is positive over the transition period under this scenario with a maximum CPI increase of 9.5 bps in 2031, and a rise of 3.9 bps in 2050.

The emerging conclusion from this analysis is that in order to achieve the maximum impact of CB intervention on emissions, it should be implemented on green and renewable (sub)sectors at the same time. Noting that, the studied scenarios are not enough to draw a conclusive conclusion on the effectiveness of sectorally differentiated CB's policy. Other sector-specific differentiated policy scenarios could possibly improve over the CBP-all policy that we have considered.

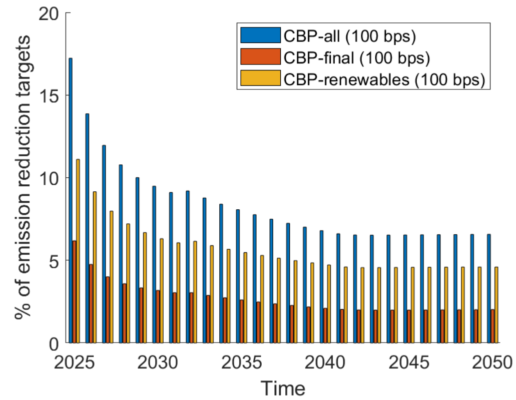
4.3 The contribution of green central bank interventions to achieve the climate goals

In order to have an indication of the contribution of green central bank intervention to achieve climate goals, we compare in this subsection the obtained relative effects on total emissions with similar effects under the Ambitious Climate Action (ACA) scenario.

Figure (10) presents the percentage decrease in emissions under different CBP scenarios (with 100 bps level). The two panels in this figure plot the same information but in different scales and time horizons. Panel (10a) extend from 2021 to 2050 while panel (10b) extend from 2025 till 2050. Depending on the scenario, this figure illustrates that the potential contribution of green central bank intervention in achieving climate goals could range from



(a) Scenario contribution to climate targets (2020-2050).



(b) Scenario contribution to climate targets (2025-2050).

Figure 10: The average annual contribution over the transition period is 12.24%, 4.7%, and 7.58% under CBP-all, CBP-final, and CBP-renewables scenarios.

2.02% (under CBP-final in 2050) to a top of 61.65% (under CBP-all in 2023). The average annual contribution over the transition period is 12.24%, 4.7%, and 7.58% under CBP-all, CBP-final, and CBP-renewables scenarios respectively. Noting that the strongest quantitative contribution of the CB intervention is in the early years of the transition when the carbon tax would still be at a low level. Moreover, it worth mentioning that the yearly effects under CBP-final, and CBP-renewables do not add up to those under CBP-all. That is, adding up the policies would not add up the effects, which means that a heterogeneous policy between final or renewable sectors would induce heterogeneous effects. A cost benefit assessment is needed to conclude if such contribution is worthwhile or not. However, under the assumption that CBs are doing some supervisory and monetary policies (capital requirements and collateral frameworks) anyhow, and the monetary policy goal of price stability is not negatively affected, we can argue that the costs are minimal. Then a 4.7% - 12.24% step towards the climate goal is substantial.

Noting here that the contribution of a CB intervention that results in reducing the cost of capital by less or more than 100 bps follows from our finding in section 4.2 and panel (9a), which show that such contribution is approximately proportional to the policy level implemented, at least under our benchmark calibration.

Finally, we emphasize here that the reported effects on emissions are possible ex-post first order effects without accounting for current or inter-temporal second or third order effects which could increase or mitigate the reported policy contribution to climate action.

4.4 Sensitivity analysis

Like any quantitative analysis that relies on theoretical modeling and numerical calibration, our reported results are sensitive to chosen parameters. Annex 1 described in detail how each of the model parameters is calibrated and motivated. In this subsection, we mention a couple of those parameters and reflect on how our reported results would be quantitatively affected. In Appendix B we test the model benchmark initial period equilibrium results for sensitivity to main parameters. We express this sensitivity as the elasticity of a key output variables with respect to the parameters. That is, we report the ratio between the percent change in those endogenous variables and the percent change in the parameter. We report these elasticities for energy prices and marginal productivity of capital across sectors as those are main variables that governs emissions and capital dynamics in our scenarios. This analysis is mainly focused on productivity parameters and substitution elastcities.

Reported transition effects across sectors highly depend on calibrated sector-specific substitution opportunities (elasticities of substitution) between green and brown varieties. All things equal, higher values for these elasticities mean an easier substitution between varieties and thus higher quantitative reaction of demand and stronger reduction on fossil fuel prices as green varieties are less dependent on fossil fuel. This would induce a higher quantitative reduction in emissions. Table (2) in Appendix B manifests this effect and quantifies it for energy prices. It reports a negative elasticity for all energy prices with respect to the elasticity of substitution between green and brown varieties, which would induce a stronger decrease in energy prices after a certain shock. For example, an increase in the elasticity of substitution of all final sectors by 10% would induce a decrease in energy prices by 0.008% for the price of electricity, 0.001% for coal, 0.004% for gas, and by 0.044% for the oil price.

Similarly, transition effects depend on calibrated sector-specific substitution opportunities between different energy sources. Higher substitution elasticities for green sub-sectors makes these sectors relatively more flexible to move towards cheaper inputs and become more competitive relative to brown ones, thus we expect a sooner and deeper switch towards green varieties. Tables (3) and (4) report the elasticity of the marginal productivity of brown and green capital with respect to different parameters. These tables show that an increase in the elasticities of substitution between energy sources for green sub-sectors are positive for almost all green and brown sub-sectors[6]. However, the quantitative impact is much stronger for green sub-sectors which would translates in higher shares of new investments for these sub-sectors after a certain shock, hence a sooner transition. Moreover, a rise in these elasticities would induce a positive effect on all energy prices.

The impact of an increase in the substitution opportunities between different different power sources is positive on gas and oil prices and negative on electricity and coal prices. The increase in this elasticity would mitigate the competitive position for different power sectors and brings their prices closer to each other which triggers a reallocation of investments from power towards final sectors, which are more dependent on gas and oil inducing a rise in their demand and prices.

Notable quantitative reactions are seen in the oil price. As brown sub-sectors become more productive in their use of fossil fuels, their demand for these inputs decreases triggering a decrease in their prices with a higher quantitative reaction in the oil price (elasticity of -2.7). Differently, if brown sub-sectors become more productive in their use of electricity, the reaction of energy prices is negative with an exception for the oil price which witness a positive effect (elasticity of 2.1) triggered by an increase in demand from brown sub-sectors as more new investments are reallocated toward these sub-sectors.

Finally, the results on the first order emission reductions are based on the used price elasticities of fossil fuel supply. Higher values for these elasticities will strengthen the assumed

[6]With an exception for brown Transportation where effect of higher σ_{ig}^{E} is negative.

supply response and trigger higher reductions in reported emissions. Moreover, emission reductions are sensitive to emission intensities of different fossil fuel sources. These intensities are expected to become lower over the transition period driven by cleaner technologies and the employment of Carbon Capture and Storage (CCS) technologies. Our analysis assumed similar intensities across all scenarios. We note that if lower emission intensities for ACA scenario were assumed, the effect of the same assumed carbon tax rate will be lower and the reported policy contribution to climate action under CBP scenarios would be higher over the transition period.

5 Conclusion and prospects for future research

This study investigated the potential effects of green CB policies on the energy transition taking into account possible inter-sectoral and general equilibrium effects. We identified one supervisory and three monetary tools at the disposal of central banks that can be used for a green purpose, namely: Capital requirements, the Collateral Framework, Asset Purchase Programmes, and TROs. We specified the link and described the mechanism by which those instruments affect the cost of capital of different investments and we surveyed available empirical evidence to quantify the effects these tools have on the cost of capital. We then used our GEMST-1 model with green sectors and sector-specific capital stocks to quantify the transition and general equilibrium impacts of greening CB's aforementioned instruments towards green and renewable sectors. These impacts were evaluated across sectors and between transition scenarios.

Results show that a uniform reduction in the cost of capital for targeted (sub)sectors will play a positive role in reducing emissions and speeding up the transition as it channels investments towards these sectors. However, the quantitative impacts depend on the sectoral coverage of such a policy. Our analysis shows that in order to achieve the maximum impact of this policy, it should be implemented on both green and renewable sectors at the same time. An intervention that targets renewable sectors only will induce spillover effects that could hinder the transition for most final sectors. Quantitative impacts across sectors differ according to their dependencies on different production factors. We note that all reported results are based on an assumed targeted uniform 100 bps reduction in cost of capital across (sub)sectors. Induced effects would be of course different if this assumption is relaxed and central banks target specific final or renewable (sub)sectors or if they use different rates for targeted sectors.

Our study concludes that green monetary and supervisory policy can make a positive contribution that amount to 4.7% - 12.2% of the needed emission reductions under an ambitious climate action scenario. However, at the same time, this effect is limited in comparison to what is needed, and since a differentiation in the cost of capital of 100 bps can already be considered ambitious, our results indicate that whereas central banks can play a substantial/significant role it should be seen as complementary, supportive, to fiscal and regulatory efforts.

Prospects for future research

The novelty of our model is the differentiation between green and brown final sub-sectors along with introducing sector-specific capital stocks which allows us to differentiate the cost of capital across sectors while capturing at the same time the emerging feedback loops through energy prices. However, like any other model based theoretical analysis, our model has some limitations that should be addressed in future research tackling similar research questions. First, as we have a one region model, calibrated on a world economy, effects that emerge across regions through trade channels are not covered in our analysis and the regional nature of monetary interventions is not accounted for. Second, our results are based on a model with high sectoral aggregation, which does not allow for an accurate definition of green sub-sectors. Third, our analysis of emission impacts is based on the assumption that changes in fossil fuel prices would have supply implications. However, as we do not model the responsiveness of fossil fuel supply explicitly in the model, our results on emissions can be interpreted as ex-post first order effects. That is our analysis does not account for possible second and third order impacts that could emerge from fossil fuel supply responsiveness. Endogenizing the supply of fossil fuel is high on our agenda for future research.

Finally, as a general policy conclusion, our study identified four options that central banks have to change the capital costs between green and brown sectors. It is important to choose one or more combinations of these instruments that would yield the maximum impact on capital costs. A relevant question for future research would be: how should central banks design a policy or policy combination that trigger the maximum change in capital cost? And what instruments can be used in good economic times when there is no monetary stimulus needed? Additionally, future research agenda could focus on integrating the financial sector in a general equilibrium setup as this would capture the full mechanism by which these tools propagate in the economy.

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Appendix A: Policy effects under CBP-final scenario

We analyze in this Appendix the results under CBP-final scenario. We assume under this scenario that the central bank intervention takes place in the final sectors only. That is the shock is a reduction in the cost of capital for green sub-sectors by 100 basis points. This scenario highlight a case where CB's intervention deviates from the market neutral principle. Such analysis would help understanding the potential differences and emerging feedback loops between final and power sectors. Moreover, it allows for comparing the effectiveness of different specifications of CB's green intervention. We focus in our analysis on main differences in impacts described under CBP-all.

Effects on the transition

Capital stocks in final sub-sectors witness similar qualitative effects as described under CBP-all scenario, quantitatively, however, these effects are different, where the relative decrease in brown capital stocks is marginally less than that under CBP-all scenario and the relative increase in green capital stocks is marginally more across all final sectors. The reason of this difference is that the policy induces a reallocation of investments from brown and most of power (sub)sectors towards green and gas (sub)sectors. This effect is manifested in figure (11) which portrays the relative effect on capital stocks in power sectors across scenarios.

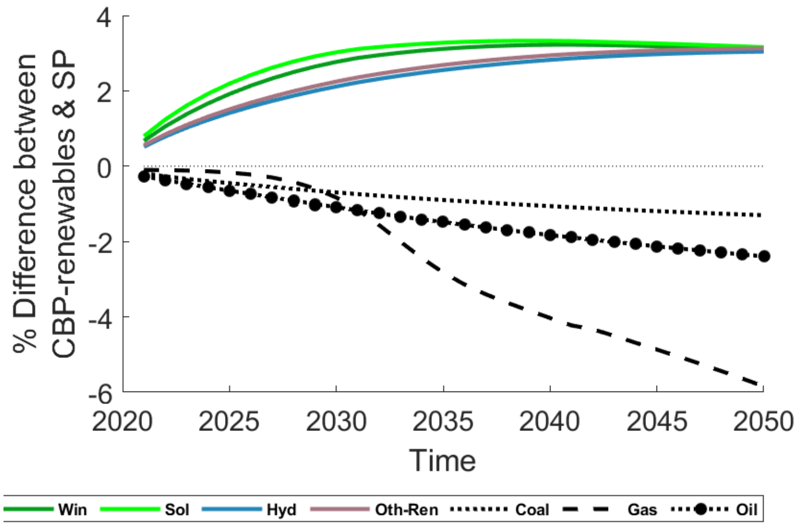
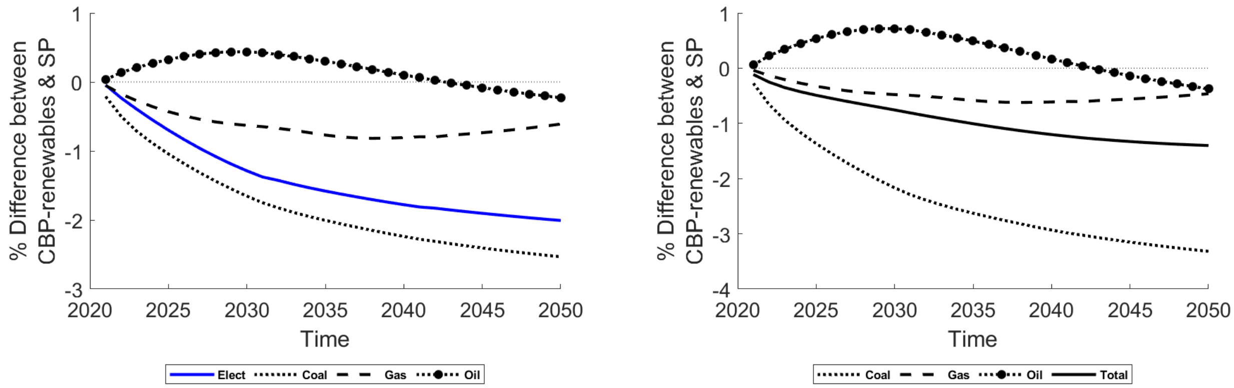


Figure 11: Difference in capital stocks between CBP-final and SP scenarios in different power sectors. Under CBP-final intervention we invest less in power sectors with an exception in the gas power sector.

This figure shows that the shock induced a relative decrease in allocated investments across renewables all over the transition period. The relative decrease become weaker over time and it is strongest for Solar, Hydro and Other renewables respectively. The impact on investments of the representative conventional power plants is not consistent over time. Both coal and oil power sectors witness lower investments in the first two decades of transition. Around 2042, the effect of the CB intervention on these sectors become positive mainly driven by the increase in electricity demand by green sub-sectors. The gas power sector witnesses a relative decrease in the first two years of transition followed by a relative increase that reach 2.1 % in 2050. However, it should be noted that this effect is small in absolute terms since the share of gas in the electricity mix is quite small as seen in the left panel of figure (2).

Effect on energy prices and emissions

One other important effect under this scenario is on energy prices and emissions. Figure (12) shows the expected impacts on these variables under CBP-final scenario relative to SP benchmark.



(a) Difference in energy prices.

(b) Difference in emissions by source.

Figure 12: CBP-final intervention induces a reduction in total emissions and oil prices along with an increase in all other energy prices.

Panel (12a) of this figure reports relative changes of prices for different energy sources over the transition period. The effect on the oil price is qualitatively similar to that described under CBP-all scenario in figure (5). Oil price shows a negative relative impact over time which tops -1.43 % in 2050. Oil demand from corresponding power sector increases to substitute for the lower capital stocks, however, the net effect on the price of oil is driven mainly by the decrease in oil demand by brown sub-sectors. Similarly for the coal price, there is a lower demand from the brown sub-sectors and a higher demand from the corresponding coal power sector. However, the net effect of these opposing powers is negative in the early years of transition. After 2028 the net effect on coal price turns positive until 2050. Conversely, the price of gas witnesses a relative rise over the transition horizon following higher investments in their gas fired power plant. From the supply side of the electricity market, the reduction in investments in most power sectors induces a negative net effect on total electricity supply. From the demand side, the shock reallocate investments toward green sub-sectors, which are more electricity dependent, triggering a positive demand for electricity, while having at the same time a reduction in demand from brown sub-sectors. The net effect on electricity price is positive as illustrated by the relative rise in the electricity price over the transition period between CBP-final and SP scenarios.

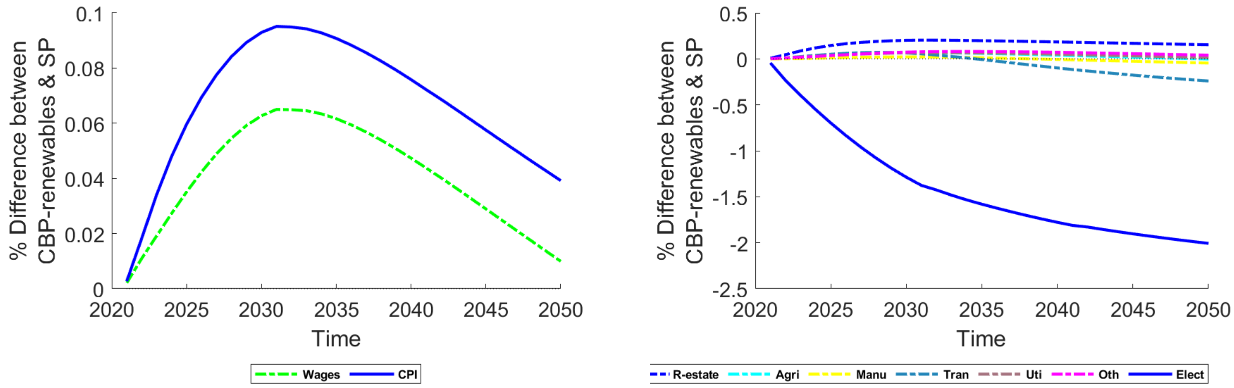
Panel (12b) illustrates the relative impact on emissions by source. As indicated before these impacts are ex-post first order effects and stem from relative effects on energy prices. Accordingly, we see that the decrease in emissions from oil are mitigated by the increase in coal and gas emissions. The aggregate relative effect is negative with a total reduction peak of -2.04% in 2042.

As the CB intervention drives investments away from most power sector under this scenario, these sectors substitute the loss of capital by labor and other inputs. Accordingly, the shock would trigger a reallocation of labor and other inputs away from brown sub-sectors and towards green and power (sub)sectors. Noting that the effect on labor demand by the renewable sectors start negative driven by the lower output of these sectors. However, this demand recovers within the second decade of transition as the lower capital stocks are substituted by more labor. This substitution is strongest in the coal power sector as labor become relatively cheaper than other production factors (both capital and coal prices increase for this sector).

Accordingly, a reduction in capital cost for green sectors only would induce a reallocation of labor and other mobile resources from final brown sub-sectors toward power and green (sub)sectors where the quantitative effect depends on labor intensity across these (sub)sectors.

Effects on market shares and price levels

Under this scenario, green market shares have similar relative qualitative effect to that described under CBP-all scenario. However, the quantitative effect differ across final sectors and over time. More precisely, the effect is stronger for Utilities & Construction green sub-sector and weaker for the green Transportation sub-sector especially after 2035. The main conclusion is that CB intervention in final sectors only would boost the transition for these sectors along a positive feedback effect the benefit the gas power sector.



(a) Difference in wages and CPI.

(b) Difference in prices for final consumption.

Figure 13: Under CBP-final intervention there is an overall rise in price levels.

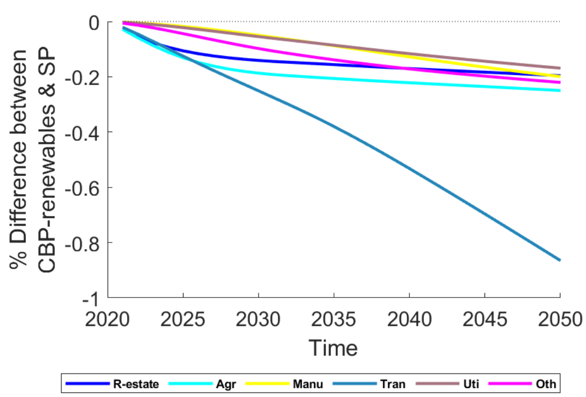
With regard to the relative effect on price levels. Qualitatively these effects are similar to those described under CBP-all scenario, however, the quantitative effects are different over time. This difference can be seen by comparing figure (13) with figure (8). These figures show that a reduction in the cost of capital for green sub-sectors only would induce a lower relative increase on CPI in the transition periods compared the increase under CBP-all scenario. This difference is mainly driven by a lower relative increase in real-estate price along with a more expensive electricity for final consumption under CBP-final. The highest increase of 0.106% (10.6 bps) in CPI is reached in 2042.

Appendix B: Policy effects under CBP-renewables scenario

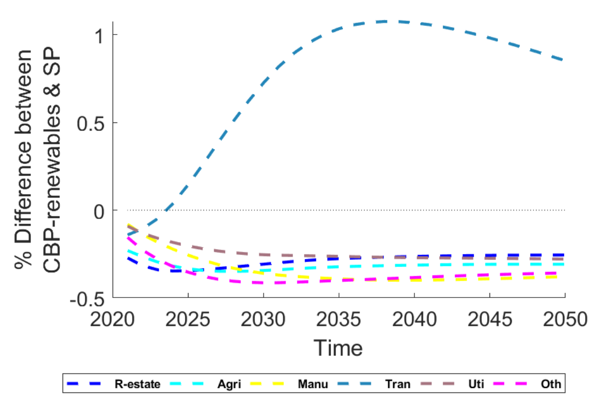
In this Appendix we investigate the relative effects under CBP-renewables scenario. In this scenario we assume a central bank intervention that results in lower cost of capital of 100 bps for the renewable power sectors only. As before, we analyze different impacts relative to the SP scenario as a benchmark.

5.0.1 Effects on transition

Relative effects on capital stocks in the power sectors are qualitatively similar to those in described in figure (2), quantitatively however, the relative increase in renewable sectors investments is stronger, while the relative decrease for conventional power sectors is weaker. This is mainly because of a reallocation of investments towards renewable sectors on the expense of final and conventional power sectors. This reallocation is manifested by a relative decrease in capital stocks in almost all final sectors in figure (14).



(a) Difference in brown capital stocks.



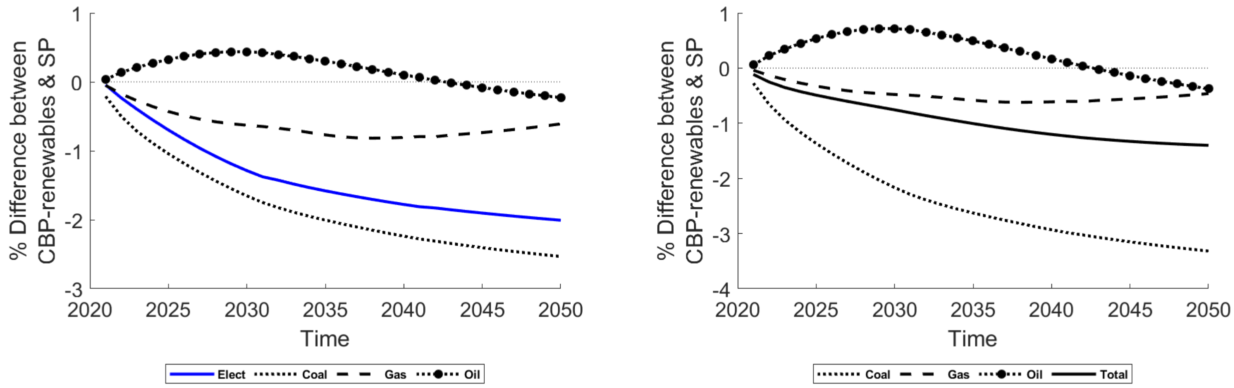
(b) Difference in green capital stocks.

Figure 14: Under CBP-renewables intervention we invest less in all sub-sectors with an exception of green Transportation.

Panel (14a) reflects the relative reduction in all brown sub-sectors with a deeper effect over time and highest relative effect for the brown Transportation that reaches -0.86% in 2050, followed by Agriculture, Real-estate, the Other sector, Manufacturing and Utilities and Construction respectively. Noting that these effects differ across sector over time. Panel (14b) of this figure illustrates the relative effect on green capital stocks over time. All green sub-sectors seem to be negatively affected except for green Transportation which benefit from the CB intervention. This sector does not witnesses a symmetric effect over time, rather it experience a relative maximum reduction of -0.14% (or 14 bps) in the first three years of the transition after which the effect turns positive with a maximum of 1.075% in 2042. This asymmetry in relative effects over time is mainly driven by how oil and electricity prices are being affected by the shock. The more expensive oil become the higher the induced substitution from brown to green Transportation. The remaining green sub-sectors have a relatively constant relative decrease over time that ranges between -0.09% (for Manufacturing and Utilities & Construction in 2021) and -0.38% (for the Manufacturing in 2050) over time.

Effect on energy prices and emissions

We move now to analyze relative effects on energy prices and emissions which are summarized in figure (15). In panel (15a) we see that coal and gas prices experience a relative decrease over the transition period mainly driven by lower demand from their respective power sectors following a decrease in new investments in these sectors. The switch towards renewables in the power sector increases their competitive position and substitute for the decrease in output by conventional power plants. The net effect on electricity supply is positive driving a lower price for electricity and higher demand by all final sectors . The decrease in electricity and coal prices shows a steep negative trend over time until it reaches -2% and -2.53% in 2050, for electricity and coal prices respectively, while the price of gas reaches a maximum relative decrease of -0.82% in 2038. Conversely, the oil price follows a positive trend in most of the transition periods that is mainly driven by an increase in demand from brown final sub-sectors which dominates the demand reduction by the oil power sector. These final sub-sectors witness higher production cost with lower capital stocks which induce a substitution towards oil in their production processes.



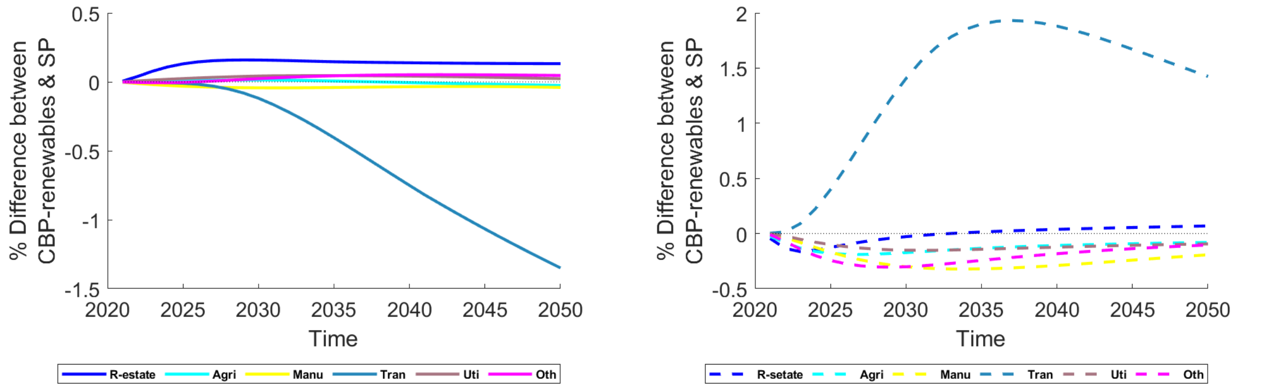
(a) Difference in energy prices.

(b) Difference in emissions by source.

Figure 15: CBP-renewables intervention induces a decrease in prices and emissions from all energy sources with an exception of Oil for most of the transition period.

With regard to emissions, panel (15b) shows a decrease in total emissions under this scenario that reaches a maximum of -1.4% in 2050 relative to the SP benchmark.

Effects of the CB's intervention on the demand of labor and other inputs under this scenario would reallocate these resources towards renewables, green Transportation and some brown sub-sectors. As capital become relatively lower in brown sectors, its price increases and most of these sectors substitute capital with labor and other inputs as well. This effect is evident in panel (16a). This panel also shows that labor demand increases by most brown sub-sectors except for Transportation and Manufacturing. In the Manufacturing sector, both green and brown sub-sectors decrease their demand for labor and other inputs following a fall in the total output of this sector. Brown Transportation is dominated by higher market shares of green varieties, and accordingly, the effect of the shock on the output of this sub-sector is negative and the demand of labor and other inputs by this sub-sector follows.



(a) Labor demand change by brown sub-sectors. (b) Difference in labor demand by green sub-sectors.

Figure 16: Under CBP-renewales intervention labor will be reallocated towards renewables, green Transportation and some brown sub-sectors

The last mentioned effect can be also seen by higher labor demand by only green Transportation in panel (16b) while other green sub-sectors lose in term of market shares as illustrated by figure (17).

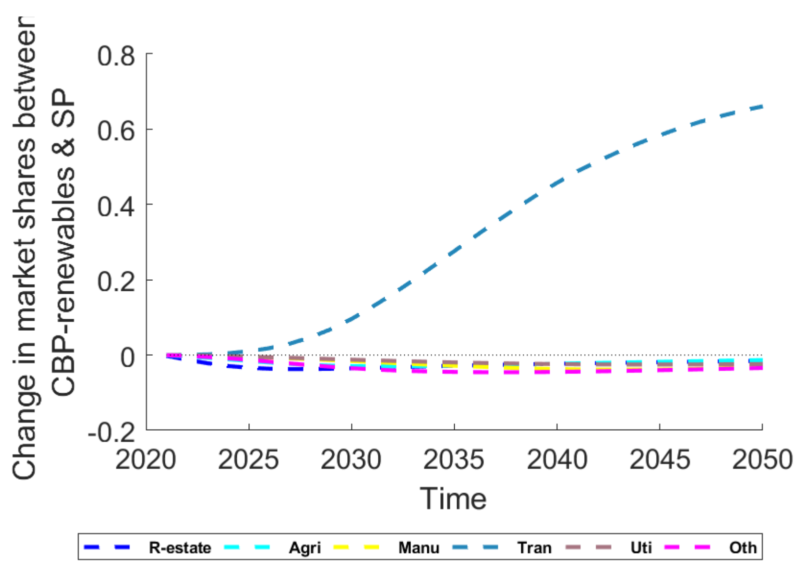
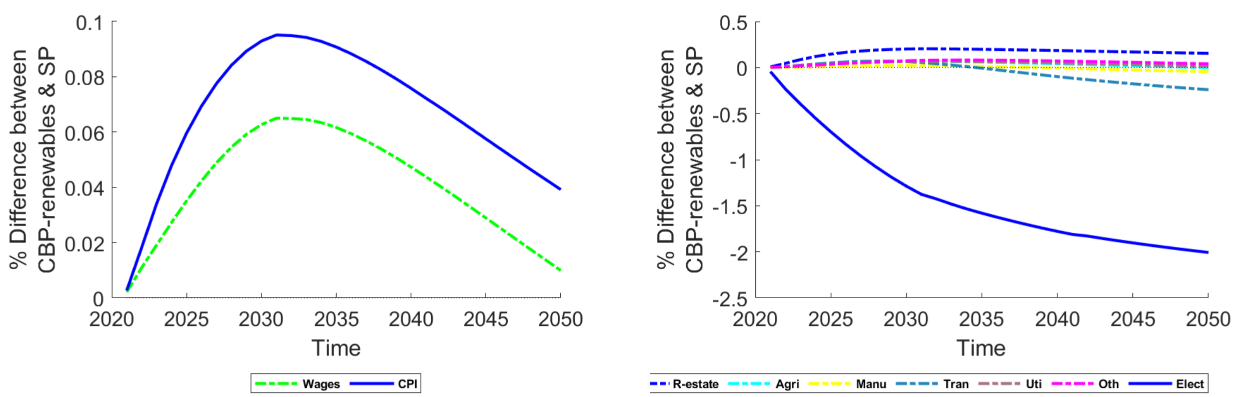


Figure 17: Change in market shares of green sub-sectors between CBP-renewables and SP scenarios. Under CBP-renewables intervention green sub-sectors lose market shares with an exception of the Transportation sector.

Accordingly, we can conclude that a shock of lower capital cost for renewable sectors only would induce a feedback effects that slow down the transition in final sectors as this shock would benefit mainly brown sub-sectors. The only exception of this effect is the Transportation sector where the intervention speed up the transition towards the green varieties. Quantitatively, these effects are are somehow modest with a maximum increase in market shares of green Transportation reaches 0.66% in 2050, and a maximum relative decrease for green sub-sectors is materialized in the 'Other' sub-sector with -0.045% in 2040.

Effects on price levels

Finally, we report relative effects on price levels under this scenario. Figure (18) reports in panel (18b) a relative increase in almost all final sectors except for Transportation and Manufacturing after 2035. Consequently, the net effect on price levels is positive over the transition period under this scenario with a maximum CPI increase of 9.5 bps in 2031, and a rise of 3.91 bps in 2050 as shown by CPI graph in panel (18a).



(a) Difference in wages and CPI.

(b) Difference in prices for final consumption.

Figure 18: CBP-renewables intervention induces an overall rise in price levels.

Appendix D: Sensitivity of results to main parameters

In this appendix we test the model benchmark initial period equilibrium results for sensitivity to main parameters. We express that as the elasticity of a key output variables (energy prices and marginal productivity of capital across sectors) with respect to the parameters. That is, we report the ratio between the percent change in those endogenous variables and the percent change in the parameter.

Table 2: Sensitivity of energy prices with respect to main parameters

Parameter	Energy prices			
	Electricity	**Coal**	**Gas**	**Oil**
CES between final goods (σ)	0.0940	0.1724	-0.1520	-0.2110
CES between green and brown varieties (σ_i)	0.0943	0.1726	-0.1518	-0.2335
CES between electricity and fossil fuels for brown sub-sectors (σ_{ib}^{E})	-0.0172	0.1385	-0.1785	1.2987
CES between different fossil fuel sources for brown sub-sectors (σ_{ib}^{F})	0.0559	0.1746	-0.2650	0.5441
CES between electricity and fossil fuels for green sub-sector (σ_{ig}^{E})	0.3026	0.4448	0.0617	0.1631
CES between different fossil fuel sources for brown sub-sectors (σ_{ig}^{F})	0.1347	0.2319	-0.1193	0.0201
CES between different electricity sources (σ^{EL})	0.0145	0.0776	-0.0713	-0.1108
Productivity of fossil fuels for brown varieties (λ_{ib}^{F})	0.2172	0.1593	-0.1962	-2.8927
Productivity of electricity for brown varieties (λ_{ib}^{EL})	-0.2148	0.0022	-0.3000	1.9170
Productivity of coal for brown varieties (λ_{ib}^{X})	0.0952	-0.0076	-0.1507	-0.2262
Productivity of gas for brown varieties (λ_{ib}^{Z})	0.0664	0.1887	-0.3625	0.2556
Productivity of oil for brown varieties (λ_{ib}^{O})	0.2425	0.3250	0.0140	-3.2672
Productivity of fossil fuels for green varieties (λ_{ig}^{F})	0.1436	0.2218	-0.1046	-0.2177
Productivity of electricity for green varieties (λ_{ig}^{EL})	0.2721	0.3561	0.0204	-0.1780
Productivity of coal for green varieties(λ_{ig}^{X})	0.0961	0.1623	-0.1503	-0.2254
Productivity of gas for green varieties (λ_{ig}^{Z})	0.1210	0.2070	-0.1276	-0.1670
Productivity of oil for green varieties (λ_{ig}^{O})	0.1163	0.1978	-0.1300	-0.2825

Parameter	**Energy prices**			
	Electricity	**Coal**	**Gas**	**Oil**
CES between different production factors in renewable power production(σ_{ELr})	0.0673	0.1523	-0.1711	-0.1663
CES between different production factors in conventional power production(σ_{ELf})	-0.1309	4.1139	-0.0265	0.1428
Productivity of capital for renewable power (λ^k_{ELr})	-0.3207	-0.1314	-0.4452	0.7650
Productivity of capital for conventional power (λ^k_{ELf})	-0.8764	1.8969	-0.0398	1.7740
Productivity of labor for renewable power production (λ^l_{ELr})	0.0929	0.1711	-0.1530	-0.2234
Productivity of labor for conventional power production (λ^l_{ELf})	0.0891	0.1800	-0.1487	-0.2176
Productivity of other inputs for renewable power production (λ^s_{ELr})	0.0909	0.1697	-0.1544	-0.2184
Productivity of other inputs for conventional power production (λ^s_{ELf})	0.0874	0.1737	-0.1432	-0.2169
Productivity of fossil fuel for conventional power production (λ^f_{ELf})	-0.3748	-1.6295	-0.7098	1.0323

Table 3: Sensitivity of the marginal productivity of brown capital with respect to main parameters

Parameter	Marginal productivity of brown capital (r_{ib})					
	Else	Real estate	Agriculture	Manufacturing	Transportation	Utility and Construction
CES between final goods (σ)	-0.0011	-0.0110	0.0019	0.0053	0.0255	0.0023
CES between green and brown varieties (σ_i)	-0.0017	-0.0022	-0.0024	-0.0005	0.0243	0.0012
CES between electricity and fossil fuels for brown sub-sectors (σ_{ib}^E)	-0.0314	-0.0310	-0.0270	-0.0271	0.0455	-0.0501
CES between different fossil fuel sources for brown sub-sectors (σ_{ib}^F)	-0.0138	-0.0142	-0.0118	-0.0108	0.0393	-0.0190
CES between electricity and fossil fuels for green sub-sector (σ_{ig}^E)	0.2297	0.2287	0.1963	0.1999	-0.3056	0.3779
CES between different fossil fuel sources for brown sub-sectors (σ_{ig}^F)	0.0418	0.0410	0.0325	0.0286	0.0546	0.0752
CES between different electricity sources (σ^{EL})	-0.0006	-0.0009	-0.0007	0.0004	0.0100	0.0007
Productivity of fossil fuels for brown varieties (λ_{ib}^F)	0.0243	0.0266	0.0135	0.0150	-0.0789	0.0383
Productivity of electricity for brown varieties (λ_{ib}^{EL})	-0.1616	-0.1495	-0.1558	-0.1697	-0.0621	-0.2815
Productivity of coal for brown varieties (λ_{ib}^X)	-0.0008	-0.0015	-0.0010	0.0011	0.0213	0.0025
Productivity of gas for brown varieties (λ_{ib}^Z)	-0.0184	-0.0177	-0.0178	-0.0179	0.0255	-0.0286
Productivity of oil for brown varieties (λ_{ib}^O)	0.0430	0.0437	0.0315	0.0356	-0.0850	0.0713
Productivity of fossil fuels for green varieties (λ_{ig}^F)	0.0451	0.0439	0.0371	0.0355	0.0140	0.0794
Productivity of electricity for green varieties (λ_{ig}^{EL})	0.1682	0.1591	0.1600	0.1602	-0.0297	0.2880
Productivity of coal for green varieties(λ_{ig}^X)	0.0001	-0.0005	-0.0003	0.0012	0.0222	0.0042
Productivity of gas for green varieties (λ_{ig}^Z)	0.0237	0.0225	0.0198	0.0185	0.0420	0.0449
Productivity of oil for green varieties (λ_{ig}^O)	0.0190	0.0184	0.0154	0.0181	-0.0081	0.0346

Parameter	**Marginal productivity of brown capital (r_{ib})**					
	Else	**Real estate**	**Agriculture**	**Manufacturing**	**Transportation**	**Utility and Construction**
CES between different production factors in renewable power production(σ_{ELr})	-0.0008	-0.0015	-0.0010	0.0006	0.0180	0.0020
CES between different production factors in conventional power production(σ_{ELf})	-0.0039	-0.0041	-0.0028	-0.0012	-0.0119	-0.0080
Productivity of capital for renewable power (λ^k_{ELr})	0.0041	0.0056	0.0024	-0.0050	-0.0213	-0.0005
Productivity of capital for conventional power (λ^k_{ELf})	0.0066	0.0103	0.0054	-0.0092	-0.1018	-0.0118
Productivity of labor for renewable power production (λ^l_{ELr})	-0.0008	-0.0014	-0.0009	0.0013	0.0210	0.0025
Productivity of labor for conventional power production (λ^l_{ELf})	-0.0008	-0.0011	-0.0007	0.0014	0.0206	0.0025
Productivity of other inputs for renewable power production (λ^s_{ELr})	-0.0006	-0.0012	-0.0008	0.0013	0.0209	0.0026
Productivity of other inputs for conventional power production (λ^s_{ELf})	-0.0005	-0.0011	-0.0008	0.0013	0.0203	0.0026
Productivity of fossil fuel for conventional power production (λ^f_{ELf})	0.0080	0.0102	0.0049	-0.0063	-0.0199	0.0040

Table 4: Sensitivity of the marginal productivity of green capital with respect to main parameters

Parameter	Marginal productivity of green capital (r_{ig})					
	Else	Real estate	Agriculture	Manufacturing	Transportation	Utility and Construction
CES between final goods (σ)	0.0008	-0.0104	0.0095	0.0145	0.0004	0.0047
CES between green and brown varieties (σ_i)	0.0062	-0.0016	0.0417	0.0580	-0.4144	0.0124
CES between electricity and fossil fuels for brown sub-sectors (σ_{ib}^E)	-0.0344	-0.0317	-0.0448	-0.0619	-0.1711	-0.0579
CES between different fossil fuel sources for brown sub-sectors (σ_{ib}^F)	-0.0136	-0.0141	-0.0148	-0.0192	-0.0549	-0.0203
CES between electricity and fossil fuels for green sub-sector (σ_{ig}^E)	0.2575	0.2376	0.3316	0.4063	1.2421	0.4346
CES between different fossil fuel sources for brown sub-sectors (σ_{ig}^F)	0.0546	0.0460	0.0809	0.1124	0.0834	0.0884
CES between different electricity sources (σ^{EL})	0.0002	-0.0006	0.0029	0.0045	-0.0033	0.0018
Productivity of fossil fuels for brown varieties (λ_{ib}^F)	0.0302	0.0278	0.0526	0.0507	-0.2084	0.0521
Productivity of electricity for brown varieties (λ_{ib}^{EL})	-0.2007	-0.1712	-0.2573	-0.3436	-0.5791	-0.3242
Productivity of coal for brown varieties (λ_{ib}^X)	0.0010	-0.0008	0.0069	0.0104	-0.0037	0.0049
Productivity of gas for brown varieties (λ_{ib}^Z)	-0.0192	-0.0185	-0.0215	-0.0383	-0.1290	-0.0296
Productivity of oil for brown varieties (λ_{ib}^O)	0.0514	0.0464	0.0820	0.1015	-0.0620	0.0885
Productivity of fossil fuels for green varieties (λ_{ig}^F)	0.0557	0.0483	0.0788	0.1063	0.1353	0.0916
Productivity of electricity for green varieties (λ_{ig}^{EL})	0.2016	0.1793	0.2287	0.2918	0.5566	0.3211
Productivity of coal for green varieties(λ_{ig}^X)	0.0023	0.0002	0.0088	0.0147	-0.0024	0.0069
Productivity of gas for green varieties (λ_{ig}^Z)	0.0321	0.0262	0.0469	0.0667	0.0372	0.0521
Productivity of oil for green varieties (λ_{ig}^O)	0.0229	0.0196	0.0360	0.0454	0.0919	0.0414

Parameter	Marginal productivity of brown capital (r_{ib})					
	Else	**Real estate**	**Agriculture**	**Manufacturing**	**Transportation**	**Utility and Construction**
CES between different production factors in renewable power production(σ_{ELr})	0.0008	-0.0009	0.0057	0.0086	-0.0077	0.0040
CES between different production factors in conventional power production(σ_{ELf})	-0.0054	-0.0045	-0.0105	-0.0184	-0.0130	-0.0106
Productivity of capital for renewable power (λ^k_{ELr})	0.0028	0.0053	-0.0079	-0.0198	-0.0547	-0.0043
Productivity of capital for conventional power (λ^k_{ELf})	-0.0022	0.0075	-0.0374	-0.0692	-0.0436	-0.0256
Productivity of labor for renewable power production (λ^l_{ELr})	0.0010	-0.0007	0.0069	0.0107	-0.0039	0.0049
Productivity of labor for conventional power production (λ^l_{ELf})	0.0010	-0.0005	0.0068	0.0105	-0.0037	0.0048
Productivity of other inputs for renewable power production (λ^s_{ELr})	0.0012	-0.0005	0.0068	0.0106	-0.0040	0.0050
Productivity of other inputs for conventional power production (λ^s_{ELf})	0.0012	-0.0004	0.0066	0.0103	-0.0033	0.0048
Productivity of fossil fuel for conventional power production (λ^f_{ELf})	0.0073	0.0100	-0.0048	-0.0179	-0.0765	0.0002

Table 5: Sensitivity of the marginal productivity of renewable capital with respect to main parameters

Parameter	Marginal productivity of renewable capital (r_{ELr})			
	Wind	**Solar**	**Hydro**	**Other renewables**
CES between final goods (σ)	0.4080	0.5451	0.3606	0.3627
CES between green and brown varieties (σ_i)	0.4083	0.5454	0.3608	0.3630
CES between electricity and fossil fuels for brown sub-sectors (σ_{ib}^E)	0.2834	0.4219	0.2385	0.2406
CES between different fossil fuel sources for brown sub-sectors (σ_{ib}^F)	0.3708	0.5082	0.3240	0.3261
CES between electricity and fossil fuels for green sub-sector (σ_{ig}^E)	0.6200	0.7612	0.5724	0.5746
CES between different fossil fuel sources for brown sub-sectors (σ_{ig}^F)	0.4497	0.5877	0.4023	0.4044
CES between different electricity sources (σ^{EL})	0.1844	0.2451	0.1632	0.1641
Productivity of fossil fuels for brown varieties (λ_{ib}^F)	0.5508	0.6858	0.5001	0.5022
Productivity of electricity for brown varieties (λ_{ib}^{EL})	0.0726	0.2100	0.0298	0.0319
Productivity of coal for brown varieties (λ_{ib}^X)	0.4094	0.5465	0.3619	0.3641
Productivity of gas for brown varieties (λ_{ib}^Z)	0.3883	0.5251	0.3409	0.3431
Productivity of oil for brown varieties (λ_{ib}^O)	0.5675	0.7030	0.5169	0.5191
Productivity of fossil fuels for green varieties (λ_{ig}^F)	0.4591	0.5970	0.4115	0.4136
Productivity of electricity for green varieties (λ_{ig}^{EL})	0.5913	0.7310	0.5431	0.5453
Productivity of coal for green varieties(λ_{ig}^X)	0.4102	0.5474	0.3628	0.3649
Productivity of gas for green varieties (λ_{ig}^Z)	0.4358	0.5733	0.3883	0.3904
Productivity of oil for green varieties (λ_{ig}^O)	0.4310	0.5684	0.3834	0.3856

Parameter	**Marginal productivity of renewable capital (r_{ELr})**			
	Wind	**Solar**	**Hydro**	**Other renewables**
CES between different production factors in renewable power production(σ_{ELr})	0.4187	0.5335	0.3551	0.3573
CES between different production factors in conventional power production(σ_{ELf})	0.1799	0.3214	0.1384	0.1405
Productivity of capital for renewable power (λ^k_{ELr})	0.7702	0.9345	0.7358	0.7381
Productivity of capital for conventional power (λ^k_{ELf})	-0.5716	-0.4156	-0.5937	-0.5917
Productivity of labor for renewable power production (λ^l_{ELr})	0.4200	0.5696	0.3743	0.3764
Productivity of labor for conventional power production (λ^l_{ELf})	0.4031	0.5404	0.3558	0.3580
Productivity of other inputs for renewable power production (λ^s_{ELr})	0.4562	0.5476	0.3844	0.3865
Productivity of other inputs for conventional power production (λ^s_{ELf})	0.4014	0.5387	0.3542	0.3563
Productivity of fossil fuel for conventional power production (λ^f_{ELf})	-0.0594	0.0871	-0.0945	-0.0925

Table 6: Sensitivity of the marginal productivity of conventional power capital with respect to main parameters

Parameter	Marginal productivity of conventional power capital (r_{ELf})		
	Coal	**Gas**	**Oil**
CES between final goods (σ)	0.1968	-0.1207	0.3175
CES between green and brown varieties (σ_i)	0.1971	-0.1204	0.3178
CES between electricity and fossil fuels for brown sub-sectors (σ_{ib}^E)	0.0760	-0.3518	0.1935
CES between different fossil fuel sources for brown sub-sectors (σ_{ib}^F)	0.1602	-0.0506	0.2794
CES between electricity and fossil fuels for green sub-sector (σ_{ig}^E)	0.4042	0.0664	0.5289
CES between different fossil fuel sources for brown sub-sectors (σ_{ig}^F)	0.2375	-0.0715	0.3587
CES between different electricity sources (σ^{EL})	0.0898	-0.0540	0.1439
Productivity of fossil fuels for brown varieties (λ_{ib}^F)	0.3362	0.2440	0.4621
Productivity of electricity for brown varieties (λ_{ib}^{EL})	-0.1304	-0.6493	-0.0152
Productivity of coal for brown varieties (λ_{ib}^X)	0.2037	-0.1195	0.3189
Productivity of gas for brown varieties (λ_{ib}^Z)	0.1764	0.1172	0.2965
Productivity of oil for brown varieties (λ_{ib}^O)	0.3484	0.0008	0.4803
Productivity of fossil fuels for green varieties (λ_{ig}^F)	0.2470	-0.0709	0.3684
Productivity of electricity for green varieties (λ_{ig}^{EL})	0.3765	0.0550	0.4998
Productivity of coal for green varieties(λ_{ig}^X)	0.1994	-0.1181	0.3197
Productivity of gas for green varieties (λ_{ig}^Z)	0.2239	-0.0918	0.3450
Productivity of oil for green varieties (λ_{ig}^O)	0.2192	-0.0993	0.3405

Parameter	Marginal productivity of conventional power capital (r_{ELf})		
	Coal	**Gas**	**Oil**
CES between different production factors in renewable power production(σ_{ELr})	0.1717	-0.1518	0.2921
CES between different production factors in conventional power production(σ_{ELf})	0.0130	-0.7862	0.1594
Productivity of capital for renewable power (λ^k_{ELr})	-0.1954	-0.6106	-0.0793
Productivity of capital for conventional power (λ^k_{ELf})	-0.0824	-1.9165	0.1210
Productivity of labor for renewable power production (λ^l_{ELr})	0.1959	-0.1216	0.3166
Productivity of labor for conventional power production (λ^l_{ELf})	0.2048	-0.1180	0.3259
Productivity of other inputs for renewable power production (λ^s_{ELr})	0.1940	-0.1240	0.3146
Productivity of other inputs for conventional power production (λ^s_{ELf})	0.1982	-0.1121	0.3155
Productivity of fossil fuel for conventional power production (λ^f_{ELf})	-0.1736	0.8166	-0.1266

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